Precise Time and Frequency, LLC
an LGL Group company

Frequency, Time, and Timing Handbook

Introduction

This handbook is intended as a handy quick reference guide to those people that are in some way involved in developing equipment or systems that rely on frequency or time characteristics in order to correctly function.

The book endeavors to outline some of the important concepts and relationships between frequency and time, and bring together a summary of some useful formulas and references that are used as an integral part of everyday design work in time and frequency applications.

It is hoped that for those people who spend only a small (albeit critical) portion of their time concerned with designing or integrating frequency or timing references into larger overall systems, this book will provide a convenient and handy reference.

It is not intended as a comprehensive reference for the "gurus" who are advancing the frontiers of science through development of state of the art atomic clock technology etc. and undoubtedly already have access to far more comprehensive reference material than could possibly be included here.

The section on applications gives a few examples of how to relate the required output specifications for particular applications to the requirements for a precision frequency or time reference source. Many systems use more than just the parameters quoted e.g. Network Time Protocol (NTP) or IRIG time code for setting absolute time in related equipment, and highly accurate (<100ns) one pulse per second signals for synchronization of events.

Also many systems are required to provide very high up time and use redundant system components to insure continuous operation even in the event of an equipment failure. There are a number of alternative approaches to providing such systems, and some of the more common approaches have also been addressed.

Finally, although this is not intended as a high profile marketing tool, the liberty has been taken of including the current Precise Time and Frequency short form catalog at the end of the book, to give some additional information on the types of equipment available to implement some of the requirements covered.

It is hoped that you will find the book both interesting and useful, and any feedback (positive or negative !) that will help to improve the content is welcomed.

David Briggs
President, Precise Time and Frequency, LLC.

Contents

1. What is Frequency, Time, and Timing

a. Basic Concepts

In order to provide a definition of time, first the general concept of frequency will be addressed. In simple terms, frequency is the repetition rate of an event, i.e. how often does the event occur. This really encompasses pretty much any type of event (e.g. how often does the train leave from Boston to New York) however for the purposes of this document it will be assumed that we are talking about the frequency of pulses or waveforms of electrical energy.

In short then, the “frequency” of a waveform is defined by how fast it is repeating, usually referred to in “Hertz” (abbreviated as Hz). If a waveform is repeating at a rate of exactly one hertz, it is repeating once per second (historically frequency was referred to in “cycles per second”, so one hertz is one cycle per second).

The concept of time then, is the accumulation of a number of events, in other words if an event is occurring at a frequency of one hertz, then the accumulation of ten events represents a time period of ten seconds. This may seem trivial, but is actually very important in understanding the relationship between frequency and time. Effectively time is proportional to the integral of frequency, which becomes significant when trying to understand the time errors created by frequency errors.

As time is derived from frequency, the effects of a frequency error and its impact on time are critical to this understanding.

Timing (as opposed to “time”) generally refers to the interval of time between events.

b. Constant Frequency Offset Error

If a frequency source is in error by a constant ten per cent, the effect of this on time is to produce a linearly increasing error. Taking the example of a one hertz frequency source above, if the source is high in frequency by ten per cent (i.e. the actual frequency is 1.1 Hz) then the time interval between occurrences is actually 1second / 1.1 Hz = 0.90909' seconds. If then the source is believed to be at 1Hz the observer would count ten occurrences and believe that 10 seconds has elapsed, however for a 10% error, ten occurrences would actually represent 10x0.90909 or approximately 9 seconds of elapsed time, and so the observer would be in error by approximately one second. Unlike the frequency error, which is static (remains at 0.1 Hz), the time error does not stay at one second, but increases as the elapsed time increases, so that after 100 events, the time error is 10 seconds.

The graphs below show the relationship between a static offset frequency error, and the resultant time error it produces.

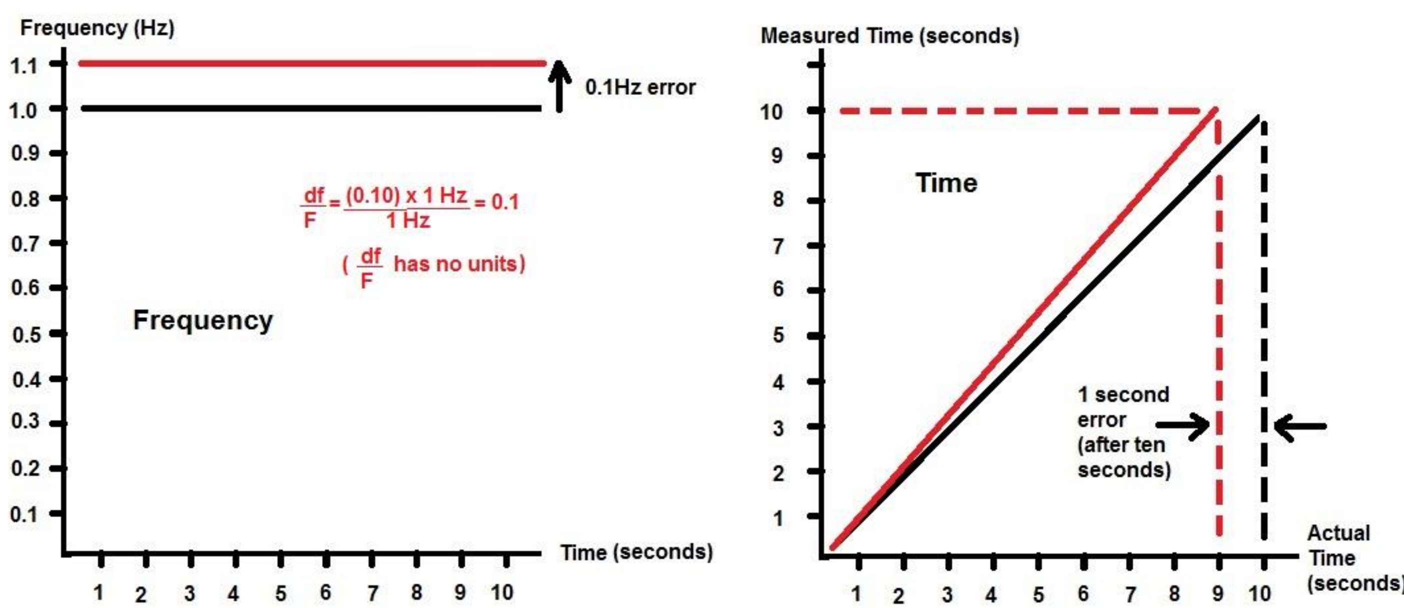


Figure 1. Relationship between Constant Frequency offset error and time

Although apparently trivial, this concept is critical in understanding the impact of frequency error on time errors, as will been seen in the next section.

c. Linearly Increasing Frequency Error

Although the static frequency example above is useful for understanding the relationship between frequency and time errors, in the real world it is more usual that frequency error will be varying over time. In practice a typical quartz oscillator will almost certainly have a drift (often referred to as “aging”) component, where the frequency error is gradually increasing (or decreasing) in a relatively linear fashion with elapsed time.

As the time error is an integral of the frequency error, the result of this linearly changing frequency error on the time error, is that the rate of change of time error changes with elapsed time, creating a non-linear effect on the time error.

Mathematically the time error at any given point after time zero (the time at which the measurement is started) can be approximated by the following equation;

$$T_e = T_i + Y_o \times T + 0.5 \times \frac{dy}{dt} \times T^2$$

where;

$Y_o = \frac{df}{F}$ = initial fractional frequency error (i.e. the error divided by the frequency)
T_e = time error
T_i = initial time error (synchronization error, if you like) at T = 0
Y_o = linear time error caused by the initial frequency offset
$\frac{dy}{dt} = \frac{df/F}{dt}$ = rate of change of frequency error (aging rate)
T = elapsed time

In using this equation, it is important to keep the units consistent, generally most straightforward if done by using seconds, and hertz.

An example for a typical quartz oscillator frequency source is shown below

For an oscillator with nominal frequency of 10MHz (10 x 10^6 Hz), and initial frequency error of 1 Hz (i.e. actual frequency is 10,000,001 Hz), and an aging rate of 2 x 10^{-7} (df/F)/day the time error generated in one day would be calculated as follows;

Ti = 0 (we will assume we synchronize to start with, if not we would just add this value to the end result)

df/F = 1 / 10 x 10^6 = 1 x 1 x 10^{-7} = 1 x 10^{-7}

Y_0 = df/F = 1 x 10^{-7}

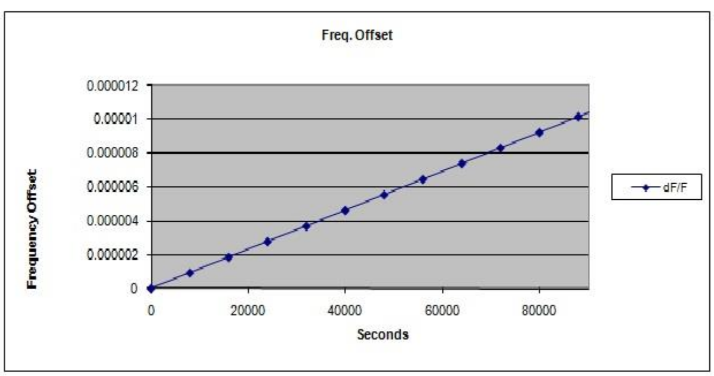
dy/dt = 2x10^{-7} / day = 2 x 10^{-7} / 86400 seconds
= 2.314 x 10^{-12} / second

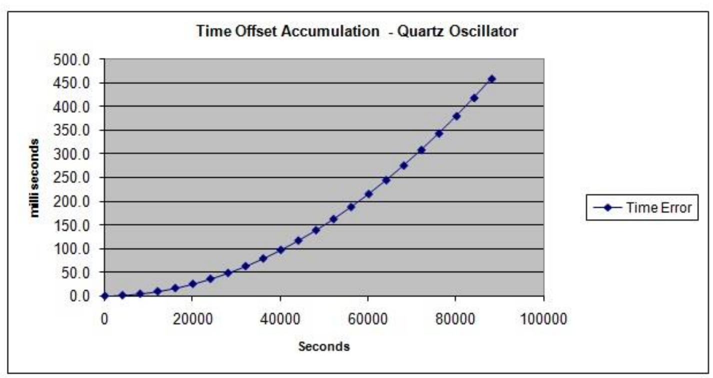
T = 1 day = 86,400 seconds

so;

T_e = 0 + 1 x 10^{-7} x 86400 + 0.5 x 2.314 x 10^{-12} x 86400 x 86400
= 0 + 0.00864 + 0.00864 = 0.01728
= 17 milli seconds time error after one day

The graphs below show the non-linear (parabolic) effect of increasing time error with linear increasing frequency error;





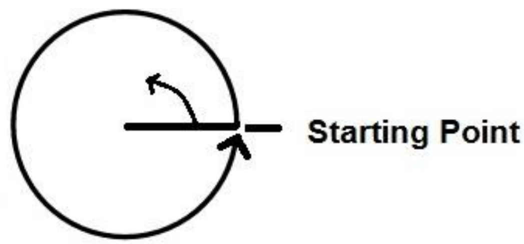
A Linear frequency error produces a non-linear time error

Note: In the graphs above aging rate was increased to 1 x 10^{-5} per day in order to clearly demonstrate the non-linear effect.

2. Critical Parameters

   a. Definition of a "Pure" Frequency

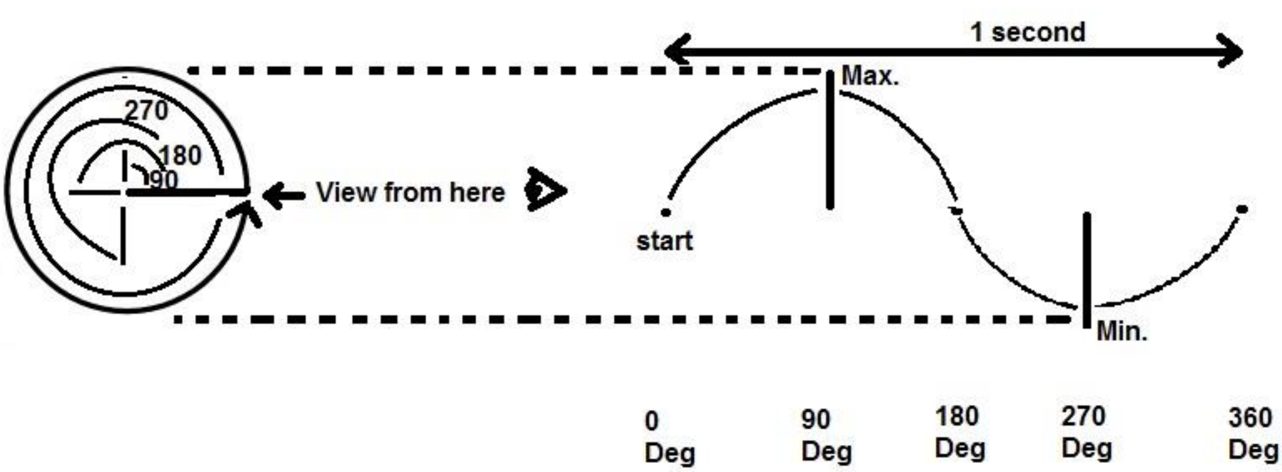
   Before addressing the parameters that are critical in an application requiring a precision frequency reference, it is worth defining what is meant by a "pure" frequency. A pure frequency is one that has just a single frequency component. In practice this can be imagined as a single spoke of a wheel rotating at an exactly constant speed. Each time the spoke passes the starting point, one cycle has been completed, therefore for a representation of 1Hz (i.e. one cycle per second) the spoke would complete a revolution and pass the starting point in exactly one second, see below;



If one rotation takes one second then the frequency of rotation is 1Hz

   In order to describe this frequency in electrical terms we describe the progression of the rotation in terms of the angle of rotation, which for one cycle is exactly 360 degrees. The length of the spoke is a representation of the amplitude of the electrical signal, and more specifically if we observe the spoke rotating from the side, we would see the length of the spoke increasing and decreasing in a non-linear fashion.

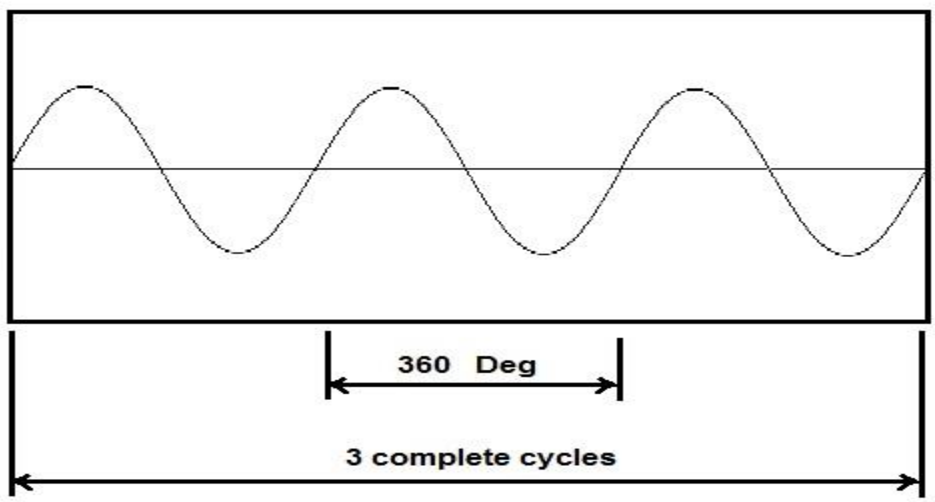
   The following diagram demonstrates this;



The non-linear progression of the amplitude can be exactly described by the sine of the angle of rotation with a maximum peak (length) at the top of the rotation and a minimum at the bottom of the rotation, as shown in the diagram.

In fact, for the signal frequency to be in its purest form, it must follow an EXACT sine wave (or its orthogonal component, the cosine wave). If the signal is not an exact sine wave, i.e. if the signal contains distortion or unexpected bumps or dips, then by definition it contains more than just one frequency, and it is these unwanted frequencies that contribute to the generally unwanted perturbations of stability and phase noise described in the following sections.

The figure below shows the more familiar representation of a pure sine wave when observed on an oscilloscope.



b. Frequency Accuracy, Stability

i. Accuracy

Accuracy in frequency terms can be an amazingly ambiguous term. In general frequency accuracy is considered in terms of how well the average frequency matches another frequency reference standard over a period of time, e.g. 100 seconds. Unfortunately, this description by itself really has little or no meaning in the practical world, as a signal could be highly accurate against an alternate precision reference when averaged over 100 seconds, but could vary wildly in an instantaneous fashion.

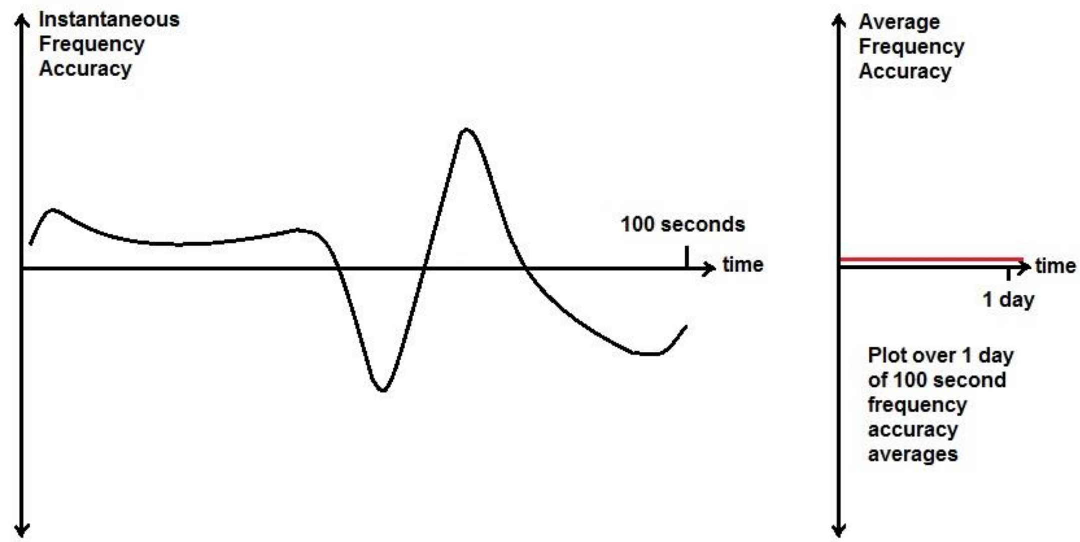
If we revert to the wheel spoke example, for an average rotation frequency of 1Hz, the wheel would make 100 rotations in 100 seconds. However if the frequency of rotation is unstable (i.e. varying wildly) it could well be that the wheel made 70 rotations in the first 50 seconds, and only 30 rotations in the last fifty seconds.

The reason that this is critical, is that if the number of wheel rotations were used to measure a parameter such as ten seconds of elapsed time, by counting 10 rotations, the result would be very different if taken during the first 50 rotations or the second 50 rotations, and both would return an answer that was wrong.

In summary, the level of instability in signal frequency, has a direct impact on the usefulness of the frequency accuracy stated over a given averaging time.

In order to deliver useful accuracy in real time, a signal must also be stable, to equal or better than the accuracy figure stated, over the averaging time for which the accuracy figure is quoted.

This is demonstrated by the figure below, that shows a wildly varying value that actually has a very high accuracy when averaged over a long period of time.



Precision is related to the resolution (or settability) that can be achieved in setting and measuring a given frequency. A frequency that can be set in steps of 0.01 Hz, can be set more *precisely* than one that has setting steps of 0.1Hz.

ii. Stability / Wander

For reasons outside of the scope of this document, the stability of a frequency signal is generally described by a special averaging technique to determine a measure referred to as Allan Variance, or it's square root called Allan Deviation.

Allan variance $\sigma_y^2(\tau)$ is defined as

$\sigma_y^2(T) = <\sigma_y^2(2, T, T)>$ The "<>" brackets represent a time average (τ)

which is conveniently expressed as

$$\sigma_y^2(\tau) = \frac{1}{2} < (\tilde{y}_{n+1} - \tilde{y}_n)^2 > = \frac{1}{2\tau^2} < (x_{n+2} - 2x_{n+1} + x_n)^2 >$$

where τ is the observation period, $\tilde{y}_n$ is the *n*th fractional frequency average over the observation time τ.
The samples are taken with no dead-time between them, which is achieved by letting

$T = \tau$

Whereas stability is expressed in terms of averaging time, e.g. stability at 100 seconds, wander is a more general term that is effectively a combination of all stability measurements from averaging times of 0.1 seconds up.

iii. Measuring Accuracy and Stability

In order to take measurements of the accuracy and stability of a frequency reference it is necessary to have a known frequency reference that has better accuracy and stability than the device under test.

Typically for precision frequency measurements a reference such as a cesium frequency standard would be used as this provides both an accurate (better than 1 x 10^{-12}) and stable (typically better than 3 x 10^{-12} at 100 seconds) signal.

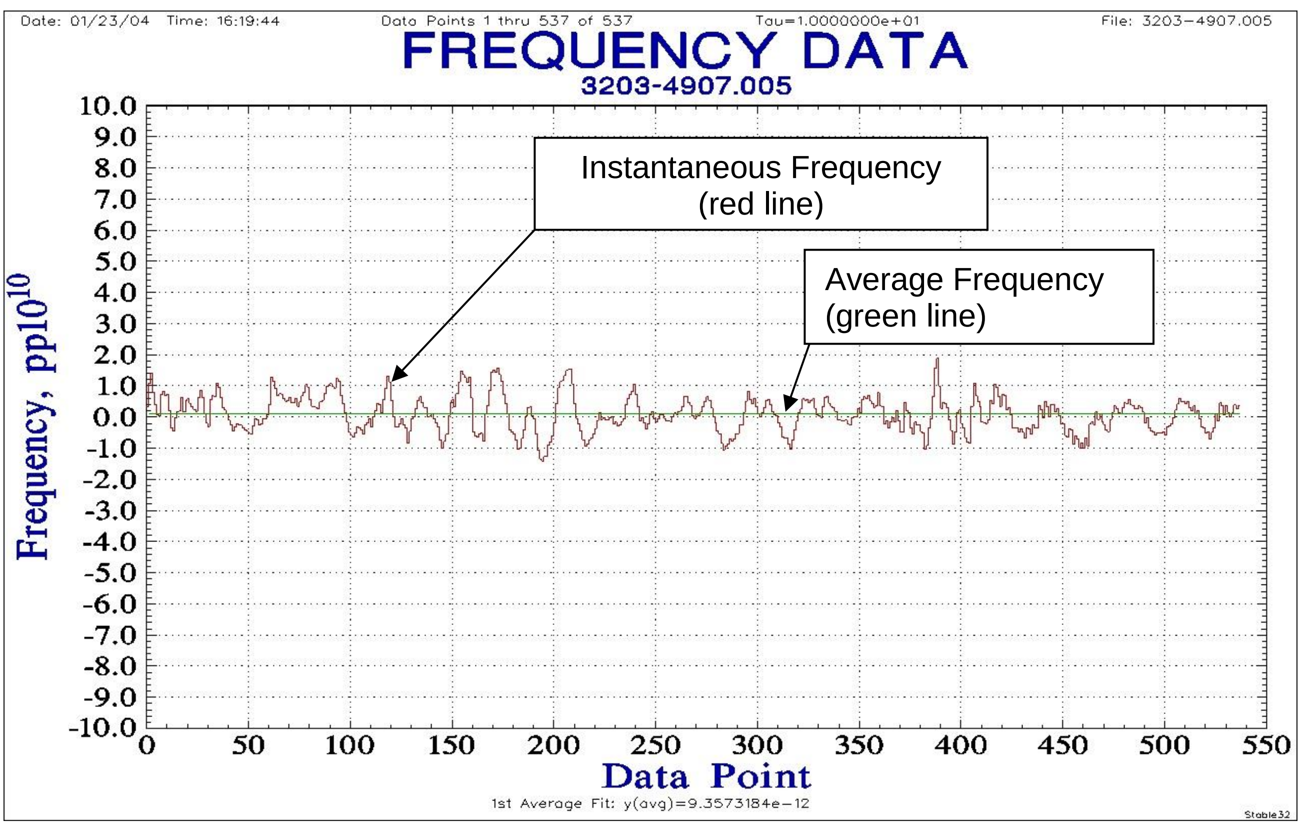
A suitable alternative would be a GPS disciplined rubidium standard, which when locked to the GPS signal will give a comparable accuracy, and actually slightly better short term stability than a cesium standard.

Measurements can be made by recording the change of phase of the reference versus the unit under test over fixed intervals of time (1, 10 100 seconds etc.) and then performing the calculations according to the Allan variance formula.

The phase measurement is usually made by using a one pulse per second signal from each of the frequency sources (reference and unit under test) derived by dividing down the frequency of the sine wave signal.

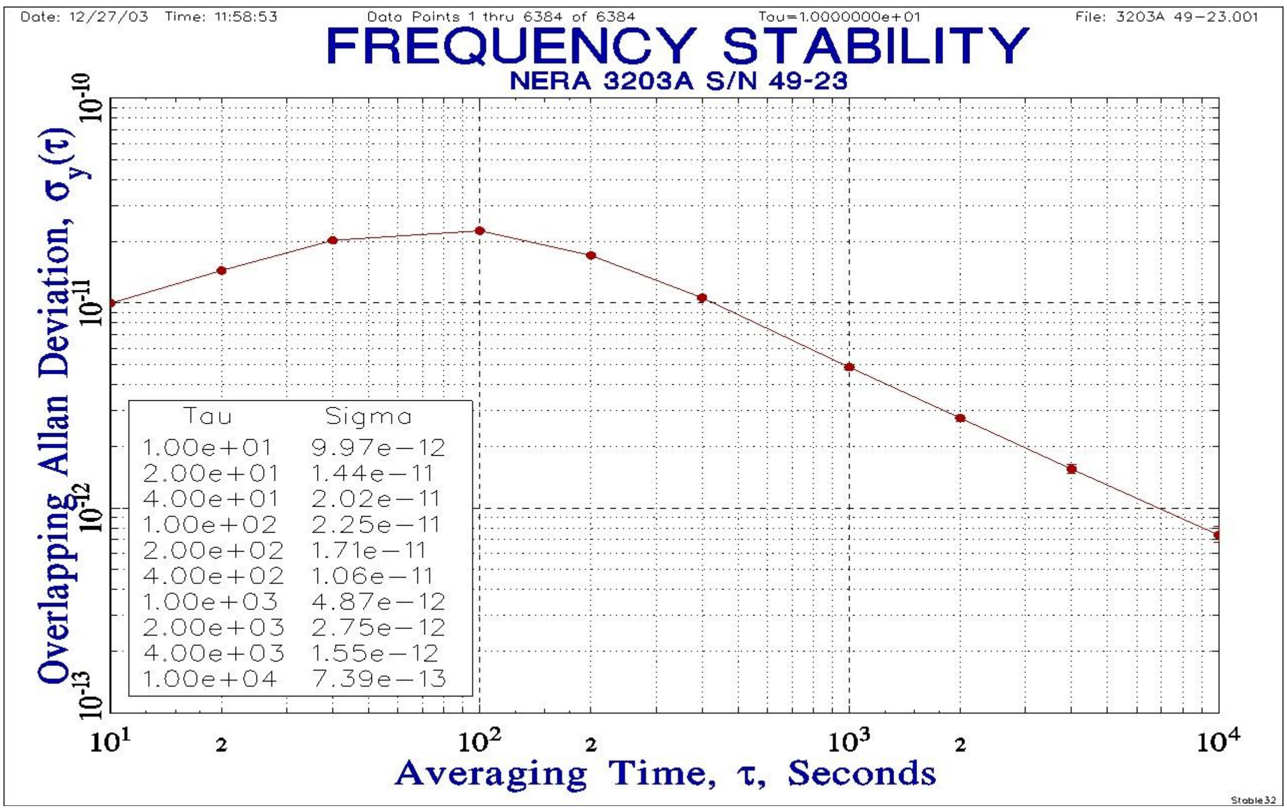
Once the measurements have been taken, there are commercially available software programs (e.g. stable, available from Hamilton Technical Services, www.wriley.com) that will accept a text data file, perform the necessary calculations and provide graphical output of frequency accuracy and stability.

Typical accuracy and stability plots produced by the “Stable” program are shown below. Note, it is usual to plot the fractional frequency (df/F) or frequency “offset” from the nominal (carrier) frequency rather than the absolute frequency, as this technique provides many times the resolution enabling the user to observe small errors in the frequency.



As can be seen from the graph, although instantaneous frequency variations are of the order of 2 x 10^{-10}, the average frequency error is actually 9 x 10^{-12} .

The graph below shows a typical stability plot for a similar frequency source.



From the above plot it can be seen that the worst stability is at around 10^2 seconds (i.e. 100 seconds) where the curve peaks at approximately 2 x 10^{-11}. In this case, the absolute best frequency accuracy that could be measured instantaneously would therefore be 2 x 10^{-11}, however in practice the error would probably be around 5 to 10 times worse than that due to other noise factors (as also shown on the previous frequency accuracy graph).

c. Phase Noise / Jitter

Phase noise is another way of measuring stability of a frequency source, but whereas Allan deviation is measured in the time domain, usually for variations from 0.1 seconds up, phase noise is measured in the frequency domain usually from 10Hz up, which in the time domain equates to 0.1 seconds down..

Thus phase noise is used to describe shorter term (higher frequency) noise rather than stability which is generally used to describe longer term (low frequency) noise.

Typically phase noise will be expressed in decibels (dB) per Hertz (Hz) relative to the carrier signal. For an absolutely pure single frequency sine wave the phase noise figures would be minus infinity (- ∞), however in the real world, typical figures for excellent frequency sources would rarely be better than -170dB below the carrier frequency (written as -170dBc/Hz where the “c” refers to the carrier), which in any case is VERY small.

Jitter is another measure similar to phase noise, but like the wander term mentioned above, jitter is a combined measure of all phase noise characteristics from 10Hz upwards.

The mathematical definitions for phase noise and jitter are described below, however in practice these values would generally be taken from the manufacturer’s data sheet for the particular frequency source, or directly measured. It is fairly straightforward to calculate the equivalent jitter given phase noise values at several frequency offsets from the carrier frequency, however it is not possible to calculate the phase noise at various offset frequencies from the carrier from a jitter value, as to do so would require additional information on the individual jitter component frequencies, which in general is not readily available.

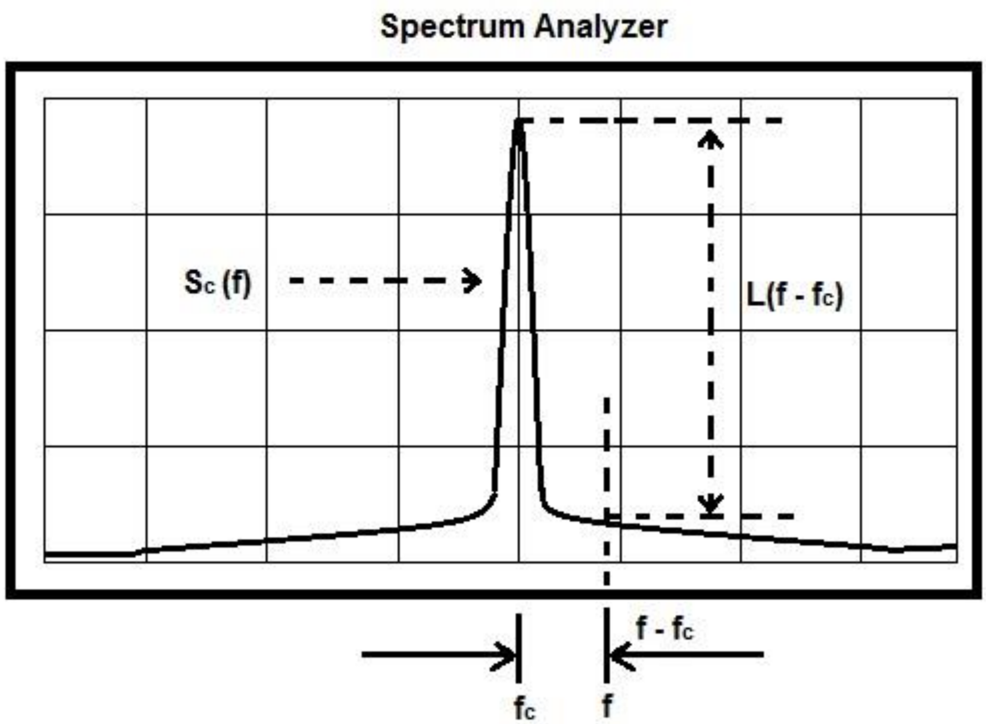
Also at the end of this section, some useful equations are provided that allow calculation of the effects of multiplying a carrier with specified phase noise characteristics up to a higher frequency, and what the resultant (theoretical) phase noise characteristics will be at the higher frequency.

Again in practice, these calculations return the best that can be achieved (from a mathematical standpoint) but in practice actual results will be slightly worse due to additional noise factors added by the multiplication circuitry.

i. Relationship between phase noise and jitter

To understand the definition of the phase-noise spectrum L(f), the power spectrum density of a clock signal, $S_C(f)$, is first defined. The $S_C(f)$ curve results when the clock signal is connected to an instrument such as a spectrum analyzer.

The phase-noise spectrum L(f) is then defined as the attenuation in dB from the peak value of $S_C(f)$ at the carrier frequency, f_C, to a value of $S_C(f)$ at f, the frequency offset from the carrier for which it is desired to express the phase noise component. The definition of L(f) is demonstrated by the figure below.



The equation for calculation of phase noise is;

$$L(f - f_c) = 10 \log [S_c(f) / S_c(f_c)] \quad \text{in dBc}$$

where;

L(f) represents the ratio of the signal power level of the carrier frequency *(f_c)* and the power level of the phase noise component at the offset frequency *(f)*, expressed in dBc, and is always negative, e.g. -80 dBc (assuming the phase noise component is of less amplitude than the carrier frequency !)

S_c is the power spectrum density of the signal.

Jitter can be defined in terms of either the peak jitter, that is the maximum period between the ideal cycle period and the actual cycle period, or root mean square (rms) jitter which is a representation of an average jitter value.

In mathematical terms, jitter (J) can be described as:

J = T – To where To is the ideal period and T is the actual period.

For rms jitter, this simply expands to:

$$J_{rms} = \sqrt{\langle J^2 \rangle}$$

where $\langle J^2 \rangle$ is the sum of the squares of J for each cycle over the measure period.

To calculate jitter from a given table of phase noise the following equation is used:

$$J_{rms} = \frac{1}{2\pi f_c} \sqrt{2 \sum_{i=1}^{i=n-1} 10^{\frac{y}{10}} \; f_i^{\frac{-x_1}{10}} \left(\frac{x_1}{10} + 1\right)^{-1} \left[f_{i+1}^{\frac{x_1}{10}+1} - f_{i-1}^{\frac{x_1}{10}+1} \right]}$$

where;

n = number of frequency offset elements in the phase noise table

$$x = \frac{\left(L(f_{i+1}) - L(f_i)\right)}{\left(log(f_{i+1}) - log(f_i)\right)}$$

y = $L(f_i)$

f_i = Frequency offset from carrier

An example of using this calculation is shown below;

For a 10MHz frequency source that has a phase noise characteristic of;

Offset from 10MHz carrier	Phase Noise	(i)
10 Hz	-125dBc/Hz	1
100 Hz	-155dbC/Hz	2
1000 Hz	-162dBc/Hz	3
10000 Hz	-162dBc/Hz	4

First we calculate x_i and y_i

x_{i1} = (-155 – (-125)) / (log 100 – log 10) = -30 / (2 – 1) = -30

x_{i2} = (-162 – (-155)) / (log 1000 – log 100) = -7 / (3 – 2) = -7

x_{i3} = (-162 – (-162)) / (log 10000 – log 1000) = 0 / (4 – 3) = 0

y_{1i} = -125 y_{2i} = -155 y_{3i} = -162 y_{4i} = -162

Now substituting the above values into the equation ;

$$J_{rms} = \frac{1}{2\pi f_c} \sqrt{2 \sum_{i=1}^{i=n-1} 10^{\frac{y}{10}} \; f_i^{\frac{-x_1}{10}} \left(\frac{x_1}{10} + 1\right)^{-1} \left[f_{i+1}^{\frac{x_1}{10}+1} - f_{i-1}^{\frac{x_1}{10}+1} \right]}$$

Calculate the sum for each value of i first;

$i_1 = 2\ (10^{-125/10} \times 10^{-(-30/10)} \times (-30/10 + 1)^{-1}\ [100^{-(-30/10+1)} - 10^{-30/10+1}\ ])$
$= 2\ (3.16 \times 10^{-13} \times 1000 \times -0.5\ [0.0099]\ )$
$= 2\ (3.16 \times 10^{-10} \times -0.5 \times 9.9 \times 10^{-3}\ )$
$= 3.130677 \times 10^{-12}$

$i_2 = 2\ (10^{-155/10} \times 100^{-(-7/10)} \times (-7/10 + 1)^{-1}\ [1000^{-(-7/10+1)} - 100^{-7/10+1}\ ])$
$= 2\ (3.1623 \times 10^{-16} \times 25.11886 \times 3.3333 \times [\ 3.96221\ ]$
$= 0.20982 \times 10^{-12}$

$i_3 = 2\ (10^{-162/10} \times 1000^{-(-0/10)} \times (-0/10 + 1)^{-1}\ [10000^{-(-0/10+1)} - 1000^{-0/10+1}\ ])$
$= 2\ (6.30957 \times 10^{-17} \times 1 \times 1 \times [\ 9000\ ]$
$= 1.1357226 \times 10^{-12}$

Now substituting the above values into the equation ;

$$J_{rms} = \frac{1}{2\pi f_c} \sqrt{2 \sum_{i=1}^{i=n-1} 10^{\frac{y}{10}} \; f_i^{\frac{-x_1}{10}} \left(\frac{x_1}{10} + 1\right)^{-1} \left[f_{i+1}^{\frac{x_1}{10}+1} - f_{i-1}^{\frac{x_1}{10}+1} \right]}$$

$$J_{rms} = \frac{1}{2\pi f_c} \sqrt{\left[(3.130677 + 0.20982 + 1.1357226) \times 10^{-12} \right]}$$

$$= \frac{1}{2\pi f_c} \sqrt{\left[4.4762196 \times 10^{-12} \right]} = \frac{1}{2\pi f_c} \; 2.11570 \times 10^{-6}$$

$$= 1 / 6.283185 \times 10^{7} \times 5.71422 \times 10^{-6} = 0.15915 \times 10^{-7} \times 2.11570 \times 10^{-6}$$

$$= 0.03367 \times 10^{-12} \qquad = 0.03367 \text{ pico seconds jitter}$$

In practice, there are a number of utilities immediately available on the internet that will accept phase noise values and return a result in rms jitter. Links to a couple of these are shown below;

http://jittertime.com/resources/pncalc.shtml
http://www.raltron.com/cust/tools/osc.asp

ii. Calculation for Equal (Phase) Noise Sources

When taking Phase Noise measurements of a frequency source against a precision reference, it is important to note that the measured value also contains noise contribution from the reference itself.

If the unit under test is itself a precision source it can be difficult to find a reference that gives superior performance. If both sources are of the same performance, this addition returns results that are 3dBc worse than either frequency source independently.

For example, if an oscillator under test has a phase noise performance at 10Hz offset from a 10MHz carrier of -125dBc/Hz, and a 10MHz reference source is used that also has a phase noise figure of -125dBc/Hz at a 10Hz offset, the resultant measurement will return a value of -122 dBc/Hz at 10Hz offset due to the noise contribution from the reference.

The equation for calculating additive phase noise is shown below;

$$\mathcal{L}_{fm} = 20\,log_{10}\sqrt{\left[10^{\frac{\mathcal{L}_{fm1}}{10}} + 10^{\frac{\mathcal{L}_{fm2}}{10}}\right]}$$

For two sources that have phase noise of -125dBc/Hz at a 10Hz offset from the carrier this will result in;

$$\mathcal{L}_{fm} = 20\,log_{10}\sqrt{\left[10^{\frac{-125}{10}} + 10^{\frac{-125}{10}}\right]}$$

$$\mathcal{L}_{fm} = 20\,log_{10}\sqrt{[3.16 \times 10^{-13} + 3.16 \times 10^{-13}]}$$

$$\mathcal{L}_{fm} = 20\,log_{10}\sqrt{[6.32 \times 10^{-13}]}$$

$$\mathcal{L}_{fm} = 20\,log_{10}(7.935 \times 10^{-7})$$

$$\mathcal{L}_{fm} = -121.989 \text{ dB/Hz}$$

Therefore the difference from the original -125dBc/Hz value

125 – 121.989 = 3.011dB (i.e. almost exactly 3 dBc worse than the individual sources)

iii. Calculation for equivalent phase noise at multiplied frequencies

In many applications, for example satellite communications, a lower frequency (e.g. 10MHz) precision reference is used (for accuracy, stability and noise reasons) and then multiplied up to a higher frequency (e.g. 200MHz) for the up/down converter.

In this case, although typically the phase noise figures for the source will be quoted around 10MHz, it is often useful to know what the equivalent phase noise impact is at the higher frequency.

The equation for calculating this is similar to that for calculating equal noise sources (described above), and is shown below;

$$\mathcal{L}_{fm} = \mathcal{L}_{fm\ base} + 20\ log_{10}\ n$$

Where n = frequency multiplication factor

e.g.

for a 10MHz reference with -125dBc at 10 Hz offset, multiplied up to 200 MHz

$$\mathcal{L}_{fm} = -125dBc + 20\ log_{10}\ 20$$

$$\mathcal{L}_{fm} = -125dBc + 26\ dBc$$

$$\mathcal{L}_{fm} = -99dBc$$

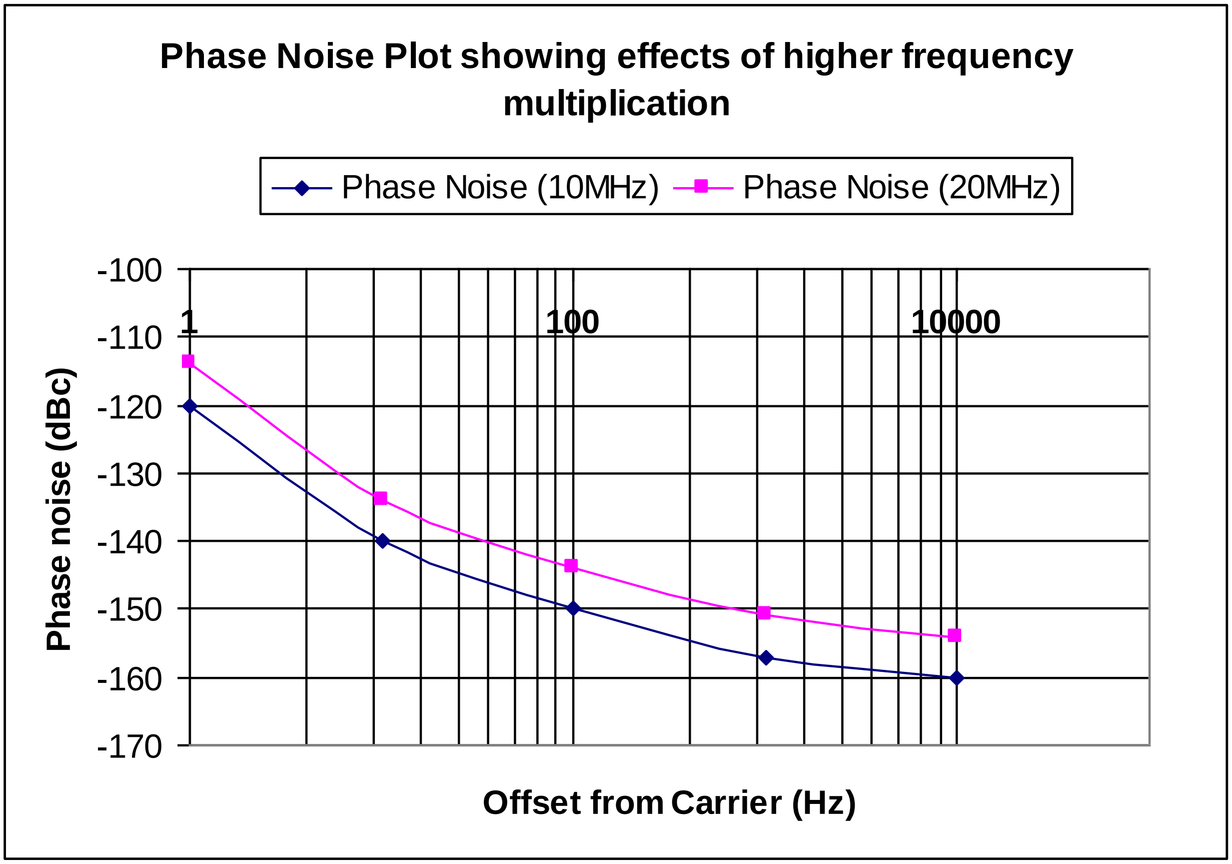
The overall effect is to raise the whole phase noise plot by a fixed amount (in the above case by 26dBc/Hz).

This is also important when reading specifications for frequency sources, as in some cases, where a frequency reference is generating two frequencies, e.g. 5MHz and 10MHz, phase noise will be quoted at the lower frequency.

For this example, if phase noise is quoted at 5MHz, it will by definition be $20\ log_{10}\ 2$ = 6dB worse at 10MHz.

i.e. -125dBc/Hz phase noise at 10Hz offset from 5MHz = -119dBc/Hz at 10MHz

This is demonstrated by the graphical plot below;



d. Harmonic / Non-Harmonic Noise Effects

In the context of precision frequency sources, harmonic noise is a noise “spur” (i.e. a narrow frequency band) at a frequency offset that is an exact multiple of the main frequency (carrier) being generated, e.g. for a 10MHz carrier frequency, a noise spur at 20MHz would be harmonic noise. The most common and obvious noise spurs tend to occur at integer multiples of the carrier, and this noise is typically generated directly from signal processing of the carrier itself.

Non-harmonic noise on the other hand, is noise superimposed on the main carrier signal at frequencies unrelated to the carrier frequency itself, and this non-harmonic noise is generally derived from other noise sources in close proximity to the precision frequency source, e.g. a mains power supply is likely to inject 60Hz (US) or 50Hz (Europe) noise from the line supply onto the frequency signal, or a switching power supply is likely to inject high frequency switching noise onto the precision frequency reference.

Careful electronic, and physical design together with shielding can keep these noise effects to a minimum, and fairly good signal to noise values for a carrier frequency of 10MHz would be <-40dBc (i.e. 40 dB down from the carrier signal) for harmonics and <-80dBc for non-harmonics.

i. Calculation for equivalent harmonic/non-harmonic noise at higher frequencies

As with phase noise, the effect of multiplying the carrier frequency to a higher frequency, also applies to any harmonic/non-harmonic noise present.

Harmonics at the higher frequency = $20 \log_{10} n$ x Harmonics at lower frequency
Where n = multiplication factor

e.g. for a 10MHz source with -80 dBc non-harmonic noise

noise at 100MHz = $20 \log_{10} 10 = 20 \times 1 = 20$dBc worse at 100MHz

so the same noise spur when multiplied to 100MHz will be -80+20 = -60dBc

e. Propagation Delays.

With increasing precision being delivered to many timing applications, often down to tens of nano seconds (1×10^{-9} seconds) or even less, it is important to consider the effects of propagation delays.

Electro magnetic signals travel through unshielded copper conductors at approximately 96% the speed of light. In shielded conductors (e.g. coaxial cable) the speed is somewhat less at approximately 66% the speed of light.

0.96 x 299,792,458 meters per second = 287,800,759 meters per second
0.66 x 299,792,458 meters per second = 197,863,022meters per second

therefore, time taken to travel 1 meter is
1/287,800,759 = 3.47×10^{-9} seconds or 3.47 nano seconds
Or
1/197,863,022 = 5.05 nano seconds/meter respectively

It can be seen therefore that if looking for an accuracy of 50ns, the propagation delays start to become a significant factor on the overall design, contributing up to a 10% offset for a one meter length.

f. Phase Matching

A number of applications require precise phase matching between precision frequency outputs, and it can be seen from the above, that even when these outputs a re generated from the same frequency reference, care must be taken to avoid errors due to physical layout causing signals to travel different distances.

This is generally achieved by insuring that from the position the original signal is split (into two or more lines) the physical distances travelled, together with the line impedances of the separate paths (usually implemented as “transmission lines” for RF signals) must be very carefully matched.

In addition any additional inline active/passive components must be selected to avoid unmatched propagation delays. If close attention is paid to this it is possible to design distribution amplifiers that can take one (e.g. 10MHz) RF input and provide up to 12 (or more) outputs that are matched to within <0.25nano seconds.

g. Temperature Effects.

No discussion on propagation delays would be complete without considering the effects of temperature.

As mentioned above, propagation delays through copper conductors can be of the order of 5 nano seconds per meter. As with most materials, copper has a coefficient of temperature expansion which causes its length to change with temperature.

Again, with high precision applications, this variation must be taken into account. For copper, the approximate temperature coefficient of linear expansion is 17×10^{-6} per degree Celsius.

As shown in the last section, for a 10 meter length of copper cable at 20 degrees Celsius, the propagation delay will be approximately 50 nano seconds

If that same cable is heated to a temperature of 30 degrees Celsius, its physical length will change by $10 \times 17 \times 10^{-6} = 17 \times 10^{-5}$ meters

$17 \times 10^{-5} \times 5 = 85 \times 10^{-5} = 0.85$ pico seconds

Referring back to the sections on wander and jitter, clearly on a high quality signal that has a jitter of only 0.033 pico seconds, a variation of 0.85 pico seconds due to temperature effects could be significant, however due to the (generally) slow pace of temperature changes the effect is more of a wander characteristic than jitter.

Having said this, in fact, temperature is probably the single most important contributor to unwanted noise and error effects, and maintaining precision equipment at constant temperature will significantly improve performance.

h. Transmission via sine waves versus digital signals

Often precision signals must be transmitted over significant distance to synchronize various items of instrumentation. In this case it is important to note the difference between using sine waves as opposed to digital waveforms for transmitting the synchronization signals.

A digital signal can be produced from a sine wave by causing an active comparator (or amplifier) to switch very fast as the sine wave crosses a preset amplitude threshold.

This is convenient for clocking signals, where the signal is to be used to drive logic (e.g. TTL, CMOS) components to generate additional functions (dividers, counters etc.) however in the process of producing the square wave the waveform by definition contains many additional higher frequencies (in particular the leading and trailing edges contain very high frequency components). In addition, these signals do not necessarily have an equal mark to space ratio and are usually DC coupled (that is, referenced to 0V level as a “low” and some voltage e.g. 5V as a “high).

The result of this is that if the signal is to be transmitted any significant distance, it is much more difficult to “match” the transmitting and receiving ends of the signal, as the matching must hold true for all the frequencies contained in the waveform in order to avoid injecting distortion on the waveform, which in turn increases the noise/jitter of the signal.

Also, unless the digital signal is of an exactly equal mark / space ratio, any AC coupling will result in an unbalance positive/negative going signal, making the receiving end more complicated.

For these reason it is far preferable to transmit a signal in sine wave form, and only convert it at the point of use, as in this way the transmission line can be designed to introduce minimal distortion onto the transmitted signal, and the signal can be easily AC coupled, avoiding problems associated with different reference points at the transmit/receive ends.

3. Typical Specifications for Applications

The following specifications are meant as a guide only, but are intended to give the reader some basic guidelines for specifying precision frequency and time references. Specifications for individual applications are bound to vary somewhat according to the specific demands of the application, e.g. the actual transmit/receive frequencies and data rates specified for a SatCom application in a particular project may vary according to the band being used and the required bandwidth to cater for the traffic to be carried.

The following specifications refer to a precision 10MHz reference being used as a reference for the application, often to produce an intermediate frequency

SatCom (e.g. Ku band, 12 to 18 GHz)

Accuracy
Frequency accuracy of <2 E -12 over a 24 hour period

Stability

100 seconds	< 5 E -11
10000 seconds	< 1 E -12

Phase noise at transmission frequency (12 GHz to 18GHz)

10 Hz	-30 dBc
100 Hz	-60 dBc
1,000 Hz	-70 dBc
10,000 Hz	-80 dB
100,000 Hz	-90 dBc

Assuming a transmission frequency at the top of the range of 18 GHz the above figures relate to a phase noise of a 10MHz reference as being $20 \log_{10} (1800)$ better i.e. 65.1 dBc better, giving:

Equivalent phase noise requirement at 10MHz

10 Hz	-95.1 dBc
100 Hz	-125.1 dBc
1,000 Hz	-135.1 dBc
10,000 Hz	-145.1dBc
100,000 Hz	-155.1 dBc

Mobile WiMax (e.g. range 2.5 to 3.8 GHz)

Frequency accuracy of <2 E -12 over a 24 hour period

Stability	
100 seconds	< 5 E -11
10000 seconds	< 1 E -12

Phase noise at transmission frequency (2.5 GHz to 3.8GHz)	
10 Hz	-40 dBc
100 Hz	-75 dBc
1,000 Hz	-95 dBc
10,000 Hz	-95 dBc

Assuming a transmission frequency at the top of the range of 3.8 GHz the above figures relate to a phase noise of a 10MHz reference as being 20 $\log_{10}$ (380) better i.e. 52 dBc better, giving;

Equivalent phase noise requirement at 10MHz	
10 Hz	-92 dBc
100 Hz	-127 dBc
1,000 Hz	-147 dBc
10,000 Hz	-147dBc
100,000 Hz	-147 dBc

TV and Digital TV Broadcasting (54 to 805 MHz)

Typical transmitter specs;

Frequency range 174 MHz to 240 MHz, in 8 kHz increments

Phase noise at transmission frequency

10 Hz	-50 dBc
250 Hz	-60 dBc
1,000 Hz	-72 dBc
2,000 Hz	-78 dB
10,000 Hz	-92 dBc
100,000 Hz	-112 dBc

Assuming a transmission frequency at the top of the range (i.e. worst case) of 240 MHz the above figures relate to a phase noise of a 10MHz reference as being $20 \log_{10} (24)$ better i.e. 28 dBc better, giving;

Equivalent phase noise requirement at 10MHz

10 Hz	-78 dBc
250 Hz	-88 dBc
1,000 Hz	-100 dBc
2,000 Hz	-106 dBc
10,000 Hz	-120 dBc
100,000 Hz	-140 dBc

4. Redundancy Schemes

The previous sections have all related to provision of precision frequency/timing references and the specific parameters of interest to insuring the desired quality of signal.

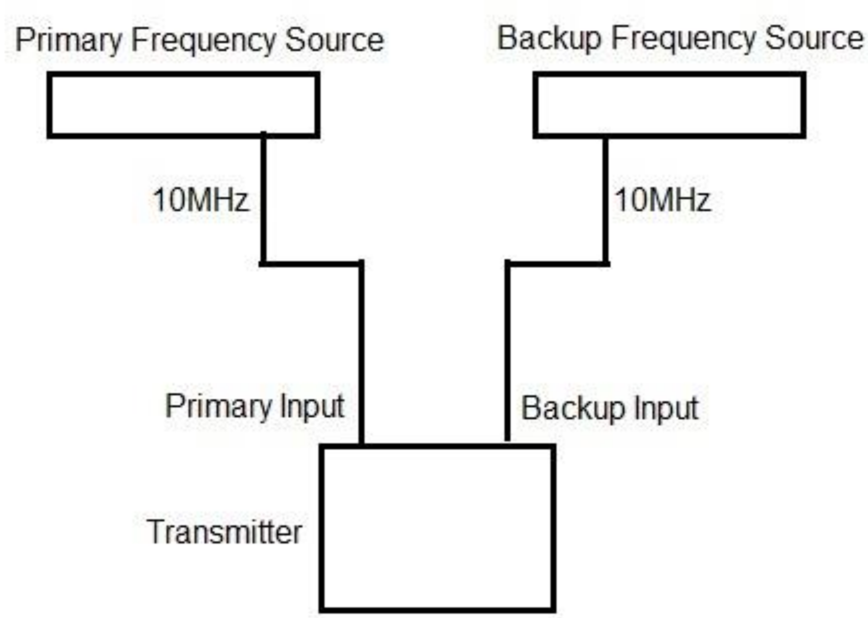
In practical application however there is another aspect to system design that requires this performance to be provided with very high (continuous) availability even in the event of individual system component failures.

This is generally achieved by designing redundant systems. That is systems that include back-up system elements in case a primary system element fails.

There are a number of ways of implementing these redundant systems, and several examples are shown below.

a. Simple Redundancy

In its simplest form, a redundant system will comprise two sources, one as a primary source the other as a backup, shown below.



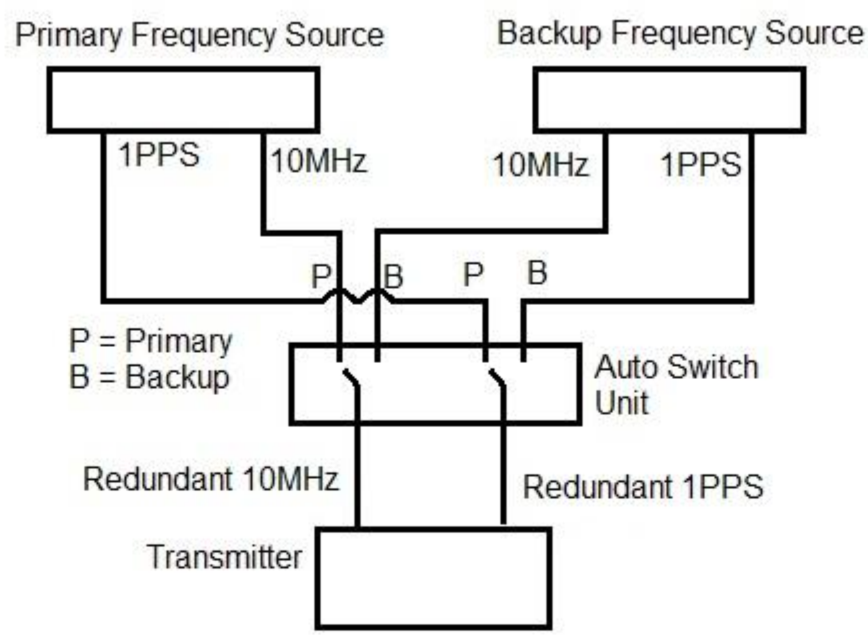
This scheme requires the transmitter (or receiver or both) to accommodate redundant inputs (which is usually the case). The transmitter (receiver) may also include internal redundant amplifiers and in some cases redundant antennas.

It is rare to see such a simple implementation as in general there are additional items of equipment required in the system implementation that also require frequency references and often timing (1PPS) and time (IRIG B /NTP) references and therefore a more comprehensive system implementation is required.

b. Redundancy with Automatic Switching

The next diagram shows a slightly more comprehensive implementation that includes a special redundancy Auto Switch to automatically switch from Primary source to Backup source in the event of failure. The system also shows an additional redundant 1PPS signal used for timing synchronization purposes.

This type of approach is required where the transmitter (or other equipment) has only one input and does not make provision for primary and backup inputs.

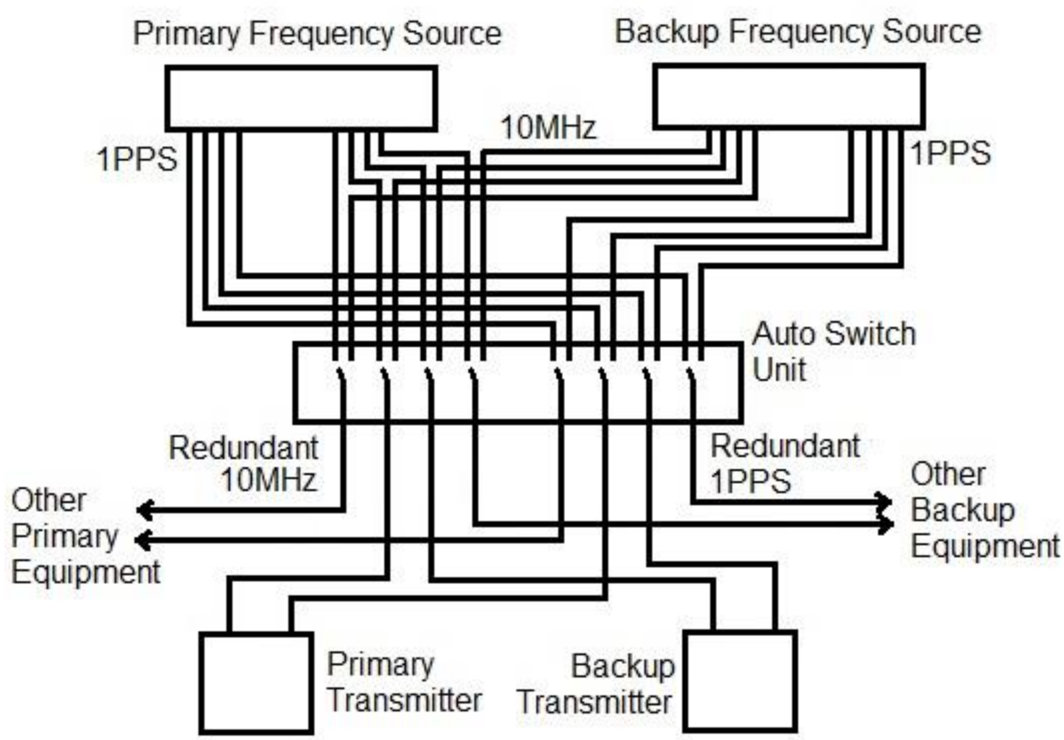


One factor to remember in this type of implementation is that in order to be redundant, with no single point of failure, the Auto Switch unit itself must be “failsafe”. This is usually achieved by insuring the Auto Switch unit utilizes some sort of mechanical switching (e.g. a mechanical latching relay) that will continue to pass the last selected signal in the event of switch failure, or even power loss.

c. Redundancy with Auto Switching and Multiple Outputs

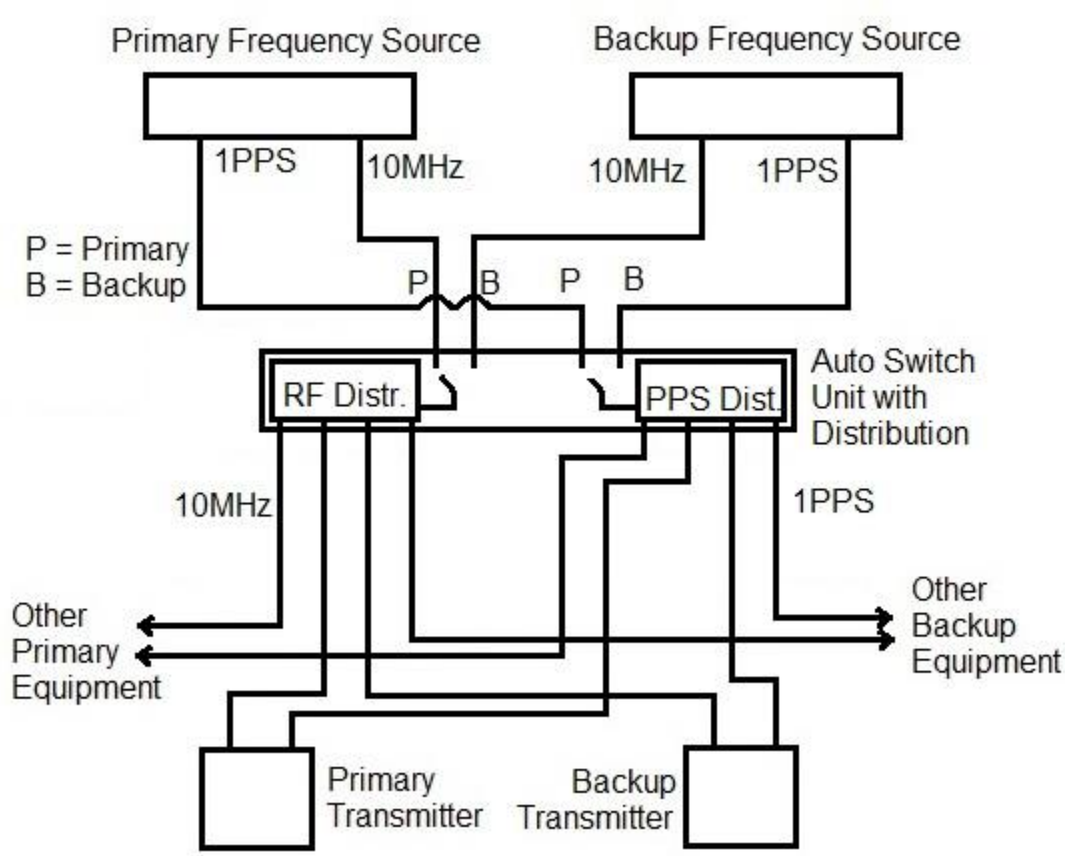
Where the system being implemented is a truly fully redundant system, with primary and backup transmit/receive elements, a solution is required that not only provides automatic switching from primary to back, but has to provide multiple switched primary and backup inputs.

One solution is a more comprehensive implementation of the above architecture, as shown below.



The above solution tends to become very complicated if more distributed signals are required to drive additional equipment, and also requires multiple frequency and timing outputs from the frequency sources themselves, which can become expensive.

An alternative approach to this is shown in the figure below.

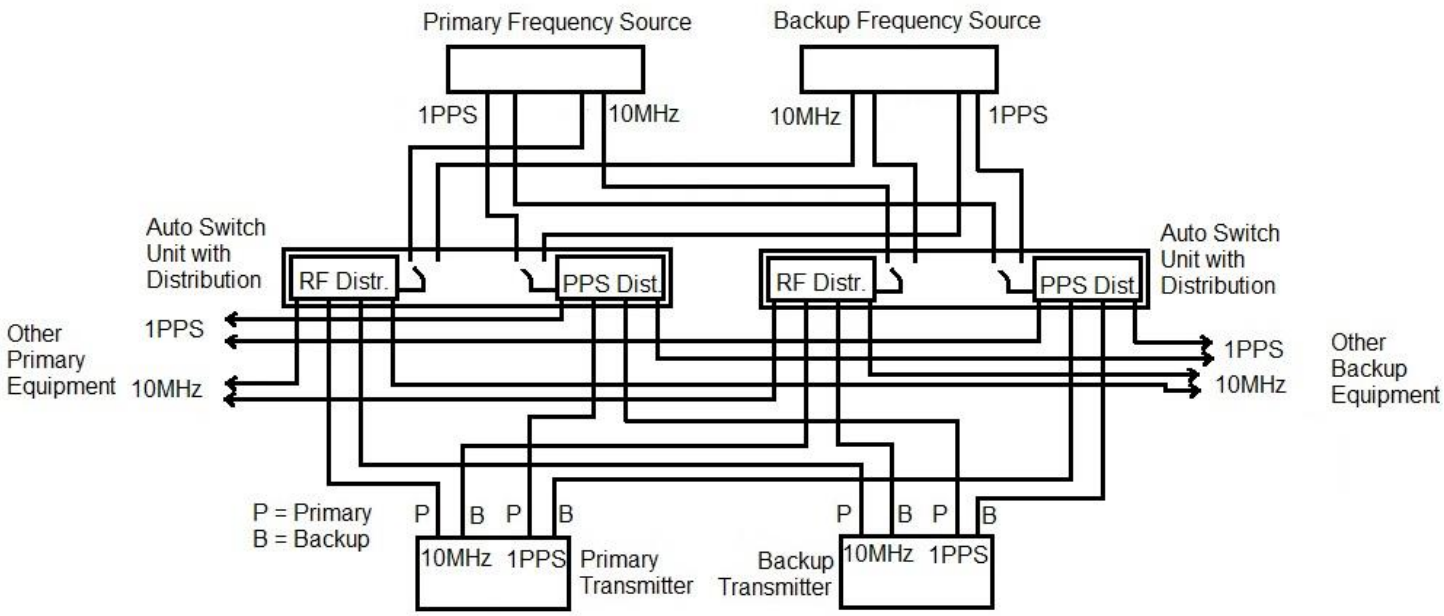


This approach has the advantage that it is much simpler, however there is a potential single point failure in the distribution elements.

Due to the inherent high reliability of the signal distribution, this is sometimes acceptable. If not there is a slightly more complex system that avoids this drawback shown in the next section

d. Redundancy with redundant Auto Switching and Distribution

The following scheme expands on the previous approaches and provides signal distribution within the Auto Switch units while maintaining a philosophy of no single point of failure. This configuration solution has been provided by Precise Time and Frequency, Inc. to many installations over the past 8 years.

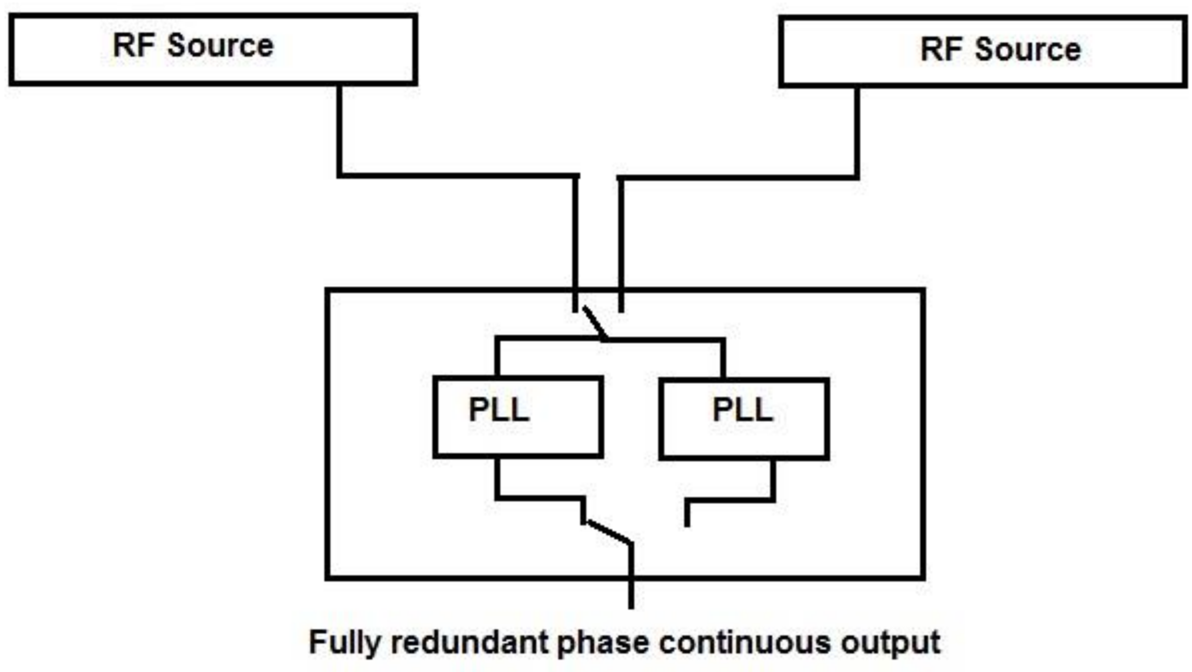


As all elements in the system are redundant and also have both primary and backup inputs, the above solution provides an extremely robust and reliable solution to those installations where equipment uptime is of primary concern.

e. Redundant switching with phase continuous switchover

In addition to the above schemes there are occasionally requirements for redundancy switching between sources, but avoiding phase jumps during the switchover. There are a number of solutions to this, generally involving the use of phase locked oscillators that are steered by the input sources to provide a smooth transition, however to maintain full redundancy these systems become quite complex (and expensive).

A simple example of this is shown below:



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