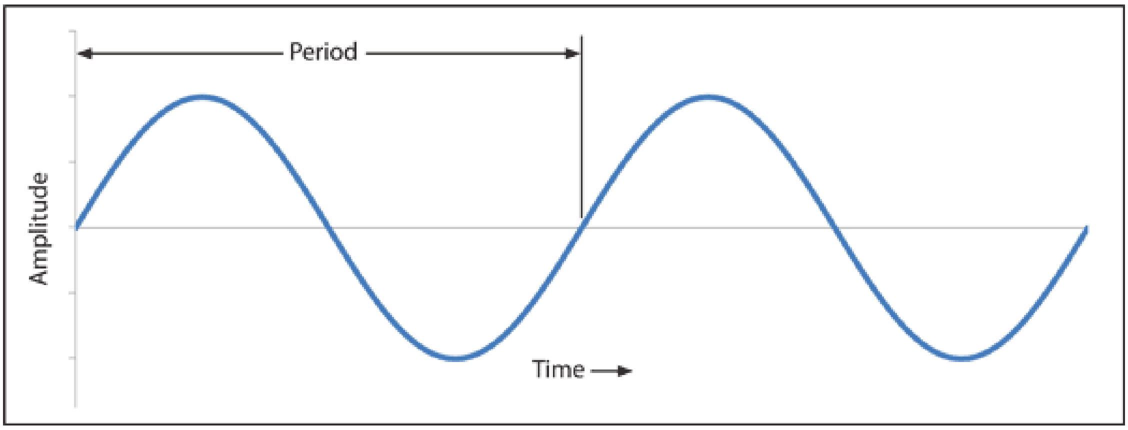
Frequency Measurement and Calibration Techniques

Some definitions need to be understood, the relationship of time and frequency.

Time is a measure of an event start to finish, with alternating current, the wave starts and ends (380 deg.) one cycle event, the measured time from when it starts to when it ends, is the **period**.



A cycle measured in Hertz, is defined as 1 period per second (t)
thus Frequency is the reciprocal of the time taken to complete one cycle.

$$f = 1/t$$

Making frequency measurements, can be done using several methods, one is to beat one frequency against the other known frequency (Heterodyne), this result in a mix, a sum and a difference of the two frequencies, the difference creates a null when the two frequencies, are the same (zero beat).
This method is often used in equipment utilizing marker oscillators, such as found in non PLL radios to calibrate the VFO.

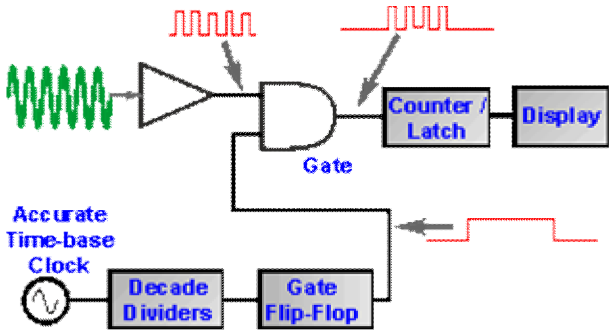
Frequency Resolution

The heterodyne method, best achievable resolution is +/- 1 Period or one Hertz, in modern applications this is not accurate enough, modern radios that use phase locked loop technology, the PLL and following band mixers requiring more accurate frequency adjustment of these oscillators' if incorrectly adjusted the result will have many unwanted results, from PLL step to final frequencies errors . To calibrate this type of system the reference must be at least 10 times better than the frequency under test, so the resolution of the testing equipment must follow this requirement.

Frequency Stability short term, long term

Stability is that figure of drift, in an oscillator, causing a change in frequency due to ambient temperature or aging, temperature will cause short term drift, aging causes long term drift.
The types of drift errors are expressed as parts per million (PPM), attention must be paid as this can be misleading, for a given PPM value the higher the oscillator frequency, less will be the stated drift, (1PPM at 1 MHZ is a greater figure of drift compared to 10 MHz). Aging of quartz crystals cause deviation from the cut frequency, this is known as long term stability, usually a predictable outcome, however the short term stability, is more important, the ability of the oscillator to reach a stable frequency, with accuracy in a short period of time is desirable. Long term Stability due to aging, is not so important as the error and changes are very small, if the error is know this can be applied to the measurement under test as a correction, if the oscillator is part of a frequency counter or external reference, however if this error is large enough, it should be calibrated against an outside reference standard.

Frequency Counter



We understand that the frequency is a direct relationship to a Period (t), we can measure one period or a number of periods and take an average. Instruments that measure just one period are very complex and expensive, but will also express another error, called Jitter. Jitter is that when a wave is shifting less than one period (Phase Change) Measuring more than on period, any error due rapid drift (Jitter) is averaged, jitter will cause a count error in the least significant digit adding to the inaccuracy of the count, to overcome this the longest sampling time is selected, ignoring the last digit in the count will provide an accurate measure, ideally oscillators should have no Jitter, but in PLL designs this is not achievable when we have uneven division of the output frequency comparing to the reference. Lets assume that the signal under test is deviating by 1/2 a cycle of jitter, sampling 100 cycles 1% will be Jitter, but if we sample 1000 cycles the jitter will now be 0.1% thus the more resolution (More Samples) more accurate the result will be, as long as you ignore the very last digit in the count. Understanding sampling time with its relationship to inaccuracy is a very important factor when using digital frequency counters.

The basic frequency counter sampling, or counting is done using an accurate timed gating, in the above diagram the gate is opened, counting the number of edge triggered events up to when the gate is closed, the above diagram shows that the input sine wave signal is converted to a square wave, the count start by edge triggering, closing the gate at a predetermined time (Sampling time), the result, is related to the gating time, we know how many pulsed and the allowed past the gate in a known time, the count can be directly displayed as frequency.
Any error in this kind of measuring system is largely due to the Time Base Clock, plus any sampled signal jitter, but there is another, because we are dividing the sampled signal, the very last digit in the count will have a +/- 1 count in the best case, on some counters this figure can be greater. Understanding the instrument is important if you are calibrating to a high order of accuracy.
Note that for higher frequencies, prescalers are used, these divide the high frequency to one that can be measured, and such systems increase the error in the resulting measurement by the factor of the division.

Time Base Clock stability

Radios and Instruments, frequency accuracy is dependent on the clock oscillator, the short term and long term stability are very important, crystal oscillators drift with age and temperature, short term drift can be compensated with the use of a thermistor compensating against the cause of temperature, many radios and Temperature Compensated Oscillators (TXO) use this technique, however this method does not compensate against long term drift due to aging.
The other more accurate short term stability methods is to use an oven, the crystal housing is maintained at a constant temperature, usually higher that the highest possible ambient temperature encountered, this allows for short term accuracy with no ambient temperature drift.
Thermistor compensated oscillator usually provide stability and accuracy of 2.5 PPM
Oven Controlled from 10^{-5} to 10^{-4} The reason for not stating PPM is that with this kind of oscillator the long term stability is around 1 to 2 PPM per year, with short term stability less than 1 PPM. Oven controlled is the best in stability both short term and Long term, a more expensive solution, usually found in high end equipment.

How do we calibrate

If you have lots of money, you send your radio or instrument to a workshop that hopefully has equipment to adjust your equipment, the level of accuracy is largely dependent of what is used for calibration. No guarantee that the workshop measuring equipment is on frequency, depends on when it was calibrated and can have an error, unless the workshop is NATA certified (National Association of Testing Authorities) then you will have a calibration that is accurate.
Modern radio equipment will employ a Phase locked Loop VFO any drift in the oscillator will result in minimal inaccuracies, 200 Hz on VHF that equates to approximately 1.6 PPM error can be tolerated, but on an HF radio using SSB this error equates as 58 PPM I chose such numbers to show that at lower frequencies the oscillator drift can have a larger effect.

How can we as amateurs calibrate our equipment, or confirm that we are on frequency, I recently measured two factory supplied FTM100D Radios, I found that one was 200 Hz low the other 200 Hz high, so when the two radios talked to each other, the error was the sum of the two.
400 KHz off frequency, a fair error. The above example is bad enough, what about others?
Today no one seems to pay attention to their frequencies accuracies, largely in the belief that the equipment been used will not change, this is very notable with those using digital radios, digital modes are less forgiving to frequency errors, resulting in bad distorted audio.

If you have lots of money you can either purchase a good quality frequency counter or a service monitor, these are designed to hold good accuracy for length of time having good long term stability and frequency resolution. Eventually even this will require calibration by a NATA certified workshop.

So back to the question, how do we calibrate with out spending lots of money.
For our purpose to be with in 1 Hertz is good enough, an HF radio can be calibrated against one of the time signal stations like WWV, even an AM broadcast station is good enough as their frequency is locked against a frequency standard either a rubidium or cesium master clock, the problem is that you will require something to beat against those signals, the SSB oscillator in an HF radio is good enough, however they are also subject to age drift, and could be off frequency, comparing USB with LSB will give a good indication of how accurate that oscillator is, but you are still taking a guess, averaging the errors out will get you close, nothing wrong with this, as long as you are on the indicated frequency when transmitting, your error will be with in 100 Hertz, this a very long winded method, but doable.

With the higher frequencies, we can beat using the 1st IF frequency, you will need an oscillator running at this frequency and zero beat, you will need a reference frequency to compare against for accuracy, this fixes the receiver and if a PLL radio it will also adjust the TX frequency, To be

more accurate a frequency counter is the minimum requirement, you can adjust your signal generator using the counter, even then you are back to the fact that you calibration is as good as your counter calibration.
Note that PLL radios the final frequency can be multiplied via harmonic multiplier, so a small error at the oscillator can result in a large error at the operating frequency, the other technique used is to mix the PLL with another oscillator to the final frequency, so you have two oscillators to calibrate, in this the PLL error will result in a frequency stepping error, and the other in a final frequency error.

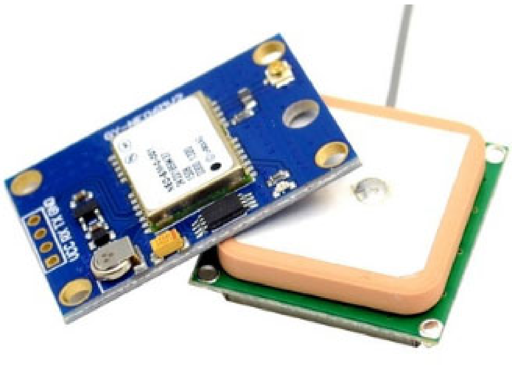
If your frequency counter has good short and long term stability, only needs to be periodically calibrated, compensating for aging. if your frequency counter has a known degree of inaccuracy calibration of all other devices such as marker oscillator or signal generator can be adjusted against your frequency counter. The counter becomes you reference.

There is a cheaper way

As amateurs we are inventive and think outside the square, In the past there have been circuits developed, using a phase locked 10 MHz oscillator against WWV, some even got locked to the local TV station, I remember using the line frequency 15625 KHz to calibrate my frequency counter, in the knowledge that TV stations used a cesium beam references, for many years these solutions provided the Radio Amateur the means having a frequency reference to calibrate equipment against.

Things have changed, propagation on HF is negligible WWV are hard to receive, TV stations have gone digital, the signals are not suitable to use for our calibration purposes, not a lot left to use..
Hold on there is, we can use the GPS system, there are many GPS satellites above us, all with high accuracy clocks, locked against a master atomic clock here on earth.

There exists cheap modules allowing you to derive a signal that is as stable as the on the on board satellite clock.
A company called u-blox makes devices called NEO M series, there are You Tube videos that show projects to construct using GPS locked frequency reference source.



The other solution, thanks to the proliferation of cellular phones, repeater towers requiring a very accurate clock, a GPS locked system is used, called GPS disciplined Oscillator.
As part of the maintenance schedule these oscillators are been replaced well with in their service life, sold as disposable equipment, making a cheap reference device, providing a 10MHz signal, accurate to 10^{-12} This is as good as a rubidium standard.
These units have a temperature controlled oscillator whose output is divided down providing a one pulse per second, this is compared with the GPS signal also divided down to one pulse per second, every second, the phase of the two pulses are compared and a correction is applied to the

onboard oscillator, locking the oscillator frequency to the satellite, resulting in a very accurate short term and long term 10 MHz reference signal, never needing calibration.

There are several seller that have used these units providing a box and GPS antenna, sold on eBay, note that the active part is second hand, you have no knowledge of how old or what life is left, the problem is that as these age, the oscillator can drift past what the compensation mechanism can adjust, in time the unit will fail due to aging.

There are units that have adopted the same principle in providing an accurate frequency, using new components, some can be adjusted from 400 Hz to 810 MHz. using the provided software, making an ideal frequency reference source for the shack.
One can dial a reference frequency co calibrate against as well as a standard for your test equipment.

Hope this article helps in understanding what is involved in accurate frequency calibration. providing methods and solutions, the use of these GPS locked units is a very cheap way to calibrate both your radio and your test equipment.

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