High Performance
GNS Disciplined
Frequency Reference Standards
Introduction

Over the past two decades, the dependability and availability of the Global Positioning Satellite (GPS) system has improved to the point where GPS disciplined frequency references are the solution of choice for most precision frequency reference applications.

Performance that in many cases exceeds that of the de facto frequency standard, the Cesium Atomic Clock, is now realizable at a fraction of the cost. The introduction of the European based Galileo system, currently with four satellites available, but due to have a full complement of 30 satellites in operation by 2019, will serve to augment the capability to provide low cost, high performance systems even further.

In addition, there are other Global Navigation Satellite Systems currently either already in use or under construction. Specifically the Russian Glonass system, that like GPS has been operational since the early 1980’s, and a new Chinese system called Beidou (or sometimes referred to as Compass), that is currently partially operational, with 10 satellites, in the Asia-Pacific region and is expected to have 35 satellites offering full Global capability by 2020.

The generalized term for referring to these systems is Global Navigation Satellite system, or GNS system.

Finally, in addition to the basic Satellite Systems, there are currently a number of "augmentation" systems designed to provide independent validation and reference to the main satellite systems. Examples of such systems are the US Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), and various other systems designed to enhance accuracy and reliability of the basic satellite systems.

Basic Operation

While all of these systems have a primary function of providing precise positional information, due to the basic theory of operation of the systems, they all also provide precise timing information (that is in any case required to calculate precise position).

The principle of operation of a GNS based frequency standard, is to receive and decode the incoming satellite signal, and use it to provide a highly accurate pulse, repeating exactly once per second, referred to as a "One Pulse per Second" (1PPS) signal. There is also a different approach that is sometimes used, that uses the actual received carrier frequency as the control signal for another local oscillator, usually referred to as a "Carrier Phase Disciplined Oscillator".

GNS satellites orbit the Earth at a distance of around 12,000 miles, and therefore by the time the satellite signal reaches the Earth's surface it is very small, around -130dBm. Environmental and atmospheric effects can cause small variations on travel time for the received satellite signals, and therefore the resulting 1PPS signal can be somewhat "noisy" with an instantaneous accuracy of anywhere from 50 nano seconds to 150 nano seconds.
For some applications such as Network Time Protocol Servers (NTP servers) this accuracy is more than sufficient, as the overall system accuracy of around 5 to 10 milli seconds is dominated more by the actual network than the timeserver.

For many applications however, this level of accuracy is simply not sufficient, and therefore designers go to great lengths in order to realize the absolute best performance possible from the satellite reference.

The diagram on the cover of this paper shows performance of a Precise Time and Frequency, Inc. (ptf) GPS disciplined frequency standard, and shows a 24 hour average frequency accuracy of <2E-15 (also with a measured 24hr stability of <6E-13, not shown).

In theory, a properly implemented hybrid 1PPS/Carrier Phase system could provide the ultimate performance in a time and frequency reference, however, in practice with careful implementation, a 1PPS based system can provide a highly accurate frequency and time reference, and the carrier phase technology would simply add complexity and cost without providing any additional realizable benefit.

The following sections discuss some of the critical issues that must be addressed in order to realize the absolute best from a 1PPS disciplined frequency standard.

GNS Receiver

In order to decode the incoming GNS signal, a GNS receiver is used. There are many different receivers available, that vary in size, shape and performance, but in general they all use the same basic principal. An antenna receives the very low power GNS signal, usually provides some initial amplification (typically around 30dB), and feeds the signal to the front-end RF circuitry of the receiver.

Internally, the receiver generates a predetermined signal waveform, a pseudo random code, and tries to match, or correlate, this to an identical waveform in the incoming signal. This initial "locking" phase of the receiver continues until the matching code is found. The time it takes to achieve this can a very unpredictable and is dependent upon many factors, including:

- The age of the internally held "Almanac", that provides the receiver vital information on which satellites are expected to be where, and when.
- Availability of an accurate position for the receiver (so that it knows which satellites it should be expecting to see).
- The number of simultaneous satellites in view
- The length of time each satellite is in view

These are just a few of the variables that can affect acquisition time. From just these few examples it is clear that asking how long a receiver takes to lock is like asking how long is a piece of string.
Once the receiver has locked to at least one satellite, it then begins the process of locking to additional satellites in view. The first task is to determine accurate position for which a minimum of four satellites in view is required. For a single constellation (e.g. GPS) there can be a maximum of satellites in view of around 10 to 12. Most current receivers can process at least 12 simultaneous satellite channels, and more recently with the introduction of additional satellite systems, some receivers can process up to 70 channels simultaneously.

After obtaining an accurate physical position, the receiver then goes about the task of precisely determining the correct position (in the time domain) for the 1PPS pulse.

Once determining where in the time domain the 1PPS edge should go, the receiver then has the task of presenting this in the most accurate way possible. Dependent upon particular model, the receiver engine uses an internal oscillator with a frequency in the range 12MHz to 30MHz. Due to this internal frequency, the receiver has a finite "quantization error", or positioning point on which it is able to place the edge.

i.e. the receiver must determine the closest internal clock edge to the "ideal" 1PPS position and output the 1PPS on this edge.

In practice, because the internal oscillator is not synchronized to the 1PPS, the output time domain position of the 1PPS changes slightly each cycle relative to where the actual position should be, until the current clock edge is not any more the closest one and the 1PPS output "flips" to the next pulse edge. This effectively generates a "saw-tooth" waveform of the actual output position relative to the ideal output position; see the diagram below.

![Diagram showing saw-tooth waveform](image)

Most receivers report the amount of the error for each pulse, which allows compensation of the generated error.
Disciplined Oscillator

To provide a high quality RF output (usually 10MHz sine wave) for use in communications, timing, metrology, and other critical applications, at a minimum a system will use a high performance Oven Controlled Crystal Oscillator (OCXO). Typically, the single most important parameter of the oscillator is close-in stability in the frequency domain, usually referred to as phase noise.

The better the oscillator performance, the lower the phase noise, specified in dBc/Hz (decibels relative to the carrier in a 1Hz bandwidth). For high-speed communications, high data throughput applications, this parameter is critical for data synchronization. The more stable this signal, the faster achievable throughput.

A reasonable value for this parameter for a 10MHz OCXO would be -120dBc/Hz at an offset from the carrier frequency (10MHz) of 10Hz. A good value would be -125dBc. If necessary to achieve even better performance, use of an Ultra Low Noise Oscillator (ULNO), can give values of -150dBc/Hz at 10Hz, decreasing to around -170dBc/Hz at a 1000Hz offset from the carrier. Oscillators with this level of performance however, can range in price from one thousand to several thousand dollars.

For those communications gurus that think in terms of rms jitter rather than phase noise, the above phase noise numbers convert to;

<table>
<thead>
<tr>
<th>Phase Noise (10MHz Carrier)</th>
<th>Equivalent rms jitter (pico seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Hz Offset</td>
<td>10000Hz Offset</td>
</tr>
<tr>
<td>-120dBc/Hz</td>
<td>-160dBc/Hz</td>
</tr>
<tr>
<td>-125dBc/Hz</td>
<td>-165dBc/Hz</td>
</tr>
<tr>
<td>-150dBc/Hz</td>
<td>-170dBc/Hz</td>
</tr>
</tbody>
</table>

In order to optimize the benefits of both the long-term stability and accuracy of the GNS system and the short-term performance of the OCXO, the two systems must now be carefully combined to preserve the best features of both worlds. At this point, all of the elements for realizing a great performance frequency reference standard exist, however without great care it is downhill all the way from here. Unfortunately, it is far easier to throw away this performance than it was to develop it in the first place.

In essence, the principle is simple. Divide the OCXO 10MHz by 10,000,000 to generate a 1PPS signal, and then compare this 1PPS with the GNS generated 1PPS signal and drive the phase difference between them to zero.

Before getting started however, it should be remembered that we are endeavoring to achieve accuracy and stability in the order of:

0.000000000001 i.e. 1E-12, or even better. Sometimes including the zeros is helpful in remembering the significance of the numbers!
Phase Measurement

The simplest form of phase measurement between two pulses is to drive a digital counter with a high speed clock (say 10MHz or 100MHz), start the counter on one (say the OXCO 1PPS) pulse and stop it on the other (GNS 1PPS) pulse. The number of counts between the start and stop then represents the phase difference between the two pulses.

Typically, a 10 MHz or 100MHz clock would be used for the high speed clock, however this does give limit the resolution on the measurement to either 100ns for a 10MHz clock or 10ns for a 100MHz clock. Using a technique of looking at the clock half cycles, the doubling the resolution, to give 5ns for a 100MHz clock. This is the method used on a number of existing systems, and whilst this is a reasonably good resolution, when trying to remove saw-tooth granularity errors of the order of 10ns, 5ns becomes significant.

For the new generation of precision clock currently under development by ptf, a new technique is deployed that uses an interpolator to measure the granularity caused by the non-synchronous edges of the clock and the pulses being measured. The interpolator charges a capacitor for the period represented by the quantization error, and then discharges it one thousand times more slowly, effectively amplifying the error by one thousand. Using this method, the system can be run on a 10MHz clock (reducing timing errors within the FPGA) and still provides phase measurement resolution of $100 \times 10^{-9} / 1000 = 100 \times 10^{-12}$ or 0.1 nano seconds.

Having achieved such a level of phase accuracy, it now becomes feasible to remove the saw-tooth error generated by the by the receiver itself, as described in the GNS Receiver section above. Removal of the error is possible by reading the messages from the receiver, one of which provides the error between calculated 1PPS position and actual output 1PPS position due to the internal clock quantization.

Oscillator Control

There are many things to consider when designing the oscillator control loop. The most important factor is;

- What is the turnover point between the chosen oscillator stability versus GNS?

The circumstances of a particular application are what determine the performance requirements of the internal oscillator (primarily phase noise) and therefore in turn the answers to the above questions. In order to cover the range of performances required, ptf offers six different performance levels of oscillator.
Performance options include; a basic Temperature Compensated Crystal Oscillator (TCXO), High Performance and Ultra High Performance Oven Controlled Crystal Oscillators (OCXO and ULNO), and high performance Rubidium Atomic Oscillators.

First, consider the GNS Receiver output without disciplining a high quality local oscillator. The normal method of viewing time-domain stability data is an Allan Deviation plot, see below.

![GNS Stability Graph](image1)

GNS systems are excellent references in the long term, with a noise characteristic which is basically white phase noise. The GNS plot gives a straight line heading down to a noise floor of approximately $1 \times 10^{-14}$. In the short term (one second), however performance is quite poor due to short-term noise effects.

![OCXO Stability Graph](image2)

A good OCXO will give far superior performance in the short term (more than 100 times better) but will not perform very well past around 100 seconds due to the "aging" (long term drift) effect of the crystal.
Now if we combine the two plots we can see a cross-over point at few hundred seconds, see below;

This tells us that, for this oscillator, we want the oscillator control loop to have minimal influence on the oscillator below 300 seconds, and that the disciplining should have maximum effect beyond this point.

At this point it should be noted that the above plots refer to the system in steady state condition and not during start-up or after some externally generated perturbation.

The elapsed time on the bottom (X) axis simply reflects the time from starting the measurement, not time from switch-on.
The ideal characteristic for this oscillator is shown by the blue line in the diagram. Disciplining to the GNS signal begins just as the oscillator characteristic begins to turn up. This allows the excellent close-in phase noise and short-term stability characteristics of the oscillator to be used while the long term performance is determined by the GNS receiver.

Not all oscillators, even those of the same manufacturer and model, have identical characteristics, and therefore in practical terms there is always some degree of compromise to cover a range of responses.

There are two main aspects to implementing the ideal control.

First, due to the fairly substantial level of phase noise of the GNS signal, a low pass filter is applied to the incoming phase variations to attenuate them. This is a one-pole low-pass filter described by the equation;

\[ H(s) = \frac{1}{(\tau_1 s + 1)} \]

where:

\[ s = \text{laplace operator} \]
\[ \tau_1 = \text{time constant} \]

The overall difference equation used for controlling the oscillator is;

\[ Y_n = a_1 Y_{n-1} + a_2 (X_n + X_{n-1}) \]

where:

\[ a_1 = \frac{(2\tau_1 - T)}{(2\tau_1 + T)} \quad \text{and} \quad a_2 = \frac{T}{(2\tau_1 + T)} \]

and T = sampling rate, which is one second in all cases.
For a detailed explanation of these equations, please refer to an earlier paper;

**Design Considerations for Optimizing Stability in GPS Disciplined Frequency Standards**

Suffice it to say here that for a good quality OCXO the required loop bandwidth is around 1mHz which gives a loop time constant of $\frac{1}{2\pi f}$ or approximately 159 seconds in this case.

The first graph shows performance of an actual good quality OCXO in a steady state with a 159 second loop time constant (1mHz loop bandwidth).

By taking this graph, and superimposing it on the GNS response graph (green line), it can be seen that the control loop is doing its job as designed.
It is important to note that although this gives an optimal response for the steady state case, using the rule of thumb that reaching 90% of final value will take around 5 x the loop time constant, if a large perturbation occurs it can take many minutes for the instrument to settle.

To compensate for this, it is advisable to have at least one, if not two, additional modes of operation that will provide a more rapid, if somewhat less accurate, response when the phase error is large, switching to the fine control only when phase errors are small.

**Delivering the Signal**

Having taken such tremendous care to produce an optimal RF signal that is stable in frequency (<2E-11 at 100 seconds), very low phase noise(<-125dBc at 10Hz offset), and very accurate (<1E-12 over 24 hrs), it is critical to insure we preserve these characteristics in providing the signal on an output that is available to the user.

The most common causes of degradation to the signal are;

- Poor power supplies, injecting noise/instability
- Low grade buffer amplifiers, with insufficient slew rates to deliver the required signal level (usually 13dBm/1vrms)
- Poor layout routing digital and analog signals too close resulting in crosstalk
- Insufficient attention to ground planes on circuit board layouts

If careful attention is given to all of the above, the output signal will very closely reflect the performance of the high quality oscillator. Typically, the output impedance will be 50 ohms, and is supplied on a BNC type connector which allows further connection via high quality, 50 ohm coaxial cable, further insuring signal quality to point of delivery.