What is Quantization Error?

Understanding the Error Inherent in a GPS Receiver

The Trimble Resolution T embedded GPS Timing Receiver and the Trimble Acutime 2000 "Smart" GPS clock offer the long-term accuracy of an atomic clock at a small fraction of the price, making them a very attractive solution for synchronizing wireless basestations and Location Measurement Units (LMU). Increasing accuracy requirements for Location Based Services (LBS) techniques such as Time Difference of Arrival (TDOA) has engineers pushing the accuracy envelope of low cost GPS timing receivers. One of the major accuracy improvements engineers can address is quantization error removal. This paper will discuss quantization error; what it is, how it affects total accuracy, and how to remove it.

Quantization Error: *Errors due to Oscillator Speed*

Most electronic devices including GPS receivers rely on a microprocessor to bring them to life. In turn, microprocessors rely on the steady flow of data through their circuits. This flow is referred to as the speed of the computer and is measured in MHz. A single cycle of this frequency is usually referred to as a clock-cycle, and every instruction and calculation happens on a clock-cycle. Even the reporting of a PPS must occur on a clock-cycle.

The limitation of having to report the PPS on a clock cycle introduces an error called quantization error. This error is inversely proportional to the speed of the clock; i.e., the higher the clock frequency, the smaller the quantization error.

In the case of the Resolution T and the Acutime 2000 the internal clock frequency is 12.504 MHz, so clock cycles occur 12,504,000 times a second. If you take the inverse of 12.504 MHz, you get 80 nanoseconds. This means there is a period of 80 nanoseconds between clock cycles.

Another way to think of this is there is a blackout period of 80 nanoseconds where a GPS receiver is unable to report a PPS. GPS timing receivers typically place the PPS on the nearest clock cycle. For example, if a receiver determined that a PPS ideally would come out 50 nanoseconds after a clock cycle, then the receiver will wait and report that PPS on the next clock cycle. If the receiver determined the PPS was 30 nanoseconds after a clock cycle, then it would advance it to report on that earlier clock-cycle. In this case it would come out 30 ns early. This 80-nanosecond gap introduces an error of $\pm$40 nanoseconds, see figure 1.

The Trimble Resolution T uses a high-precision, fixed frequency oscillator as the timing source to down-convert and decode the GPS signal and to generate a PPS output signal. Since a fixed-frequency oscillator is used, the Resolution T must place the PPS output on the clock edge that it determines is closest to UTC or GPS. **The difference in time between the clock edge used to generate PPS and the where the Resolution T has determined where the PPS should be placed is referred to as the PPS quantization error**. The magnitude of the PPS quantization error will be up to one-half the period of the fixed frequency oscillator. The oscillator frequency is 12.504 MHz which is equivalent to a period just under 80 nanoseconds. **By using both clock edges, the quantization error on the Resolution T PPS output is between ±20ns.**

Quantization error is illustrated below. The top waveform represents the 12.504 MHz clock. The Resolution T output must be placed on one of the edges of this clock. The middle waveform represents the UTC/GPS on-time mark as determined by the receiver's electronics. The bottom waveform represents the Resolution T PPS output which is output on the clock edge closest to the actual UTC/GPS on-time mark.

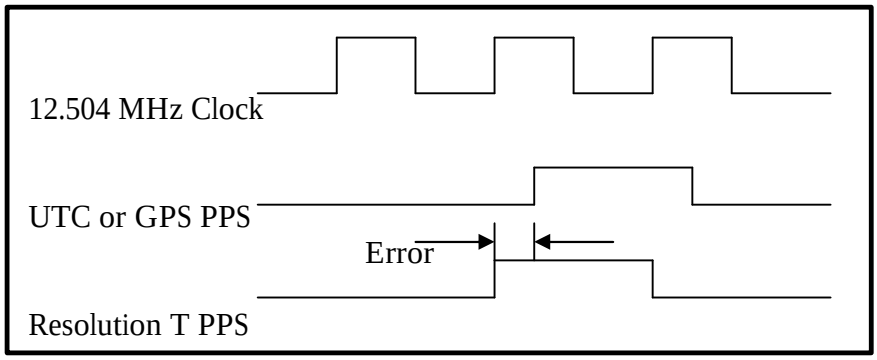

Figure 1—PPS Quantization Error

The amount of quantization error present on each PPS output pulse is reported in TSIP packet 0x8F-AC. This quantization error information can be used to reduce the effective amount of jitter on the PPS pulse.

Accuracy Improvement

Trimble typically specifies timing accuracy as a 1-sigma value. For the Resolution T and Acutime 2000, the 1-sigma values[1] for quantization error are:

Model	Clock Speed	Accuracy(1 sigma)	Quantization Error Removed (1 sigma)
Acutime 2000	12.504	50 nanoseconds	23 nanoseconds
Resolution T	12.504 MHz	<15 nanoseconds	<5 nanoseconds

These numbers generally represent the overall accuracy of the GPS receiver. There are other errors, but these are usually small in comparison to Quantization Error and have little effect on overall accuracy.

Elimination of the Quantization Error

The Resolution T and the Acutime 2000 allow for the removal of the Quantization Error by reporting a packet (0x8F-AC) that states the offset from the nearest clock edge. The user can then subtract this difference from the reported clock edge.

Using the Quantization Error

One common application for the Resolution T involves phase locking an oscillator to the Resolution T PPS output. This technique keeps the frequency of the oscillator precisely in tune with the GPS system. The diagram on the following page shows a typical PLL (phase locked loop) where the PPS signal from the Resolution T is used as the reference.

[1] Oscillator Granularity has a uniform distribution; that is, there is an equal chance of any offset between 0 and $\pm$40 nanoseconds. The 1-sigma value of a uniform distribution is the distribution range divided by the square root of 12. In the case of the Resolution T this is $80ns/(12)^{1/2}$.

In the diagram the quantization error received from the Resolution T is used to reduce the phase error signal. The phase error at node “A” is the raw phase error which includes the effects of quantization error. Node “B” is the quantization error reported by the Resolution T. Node “C” is the phase error with the quantization error subtracted from the raw phase error at node “A”. In this example, reducing the phase error helps to minimize the jitter on the PLL’s clock output.

Important Note: The Trimble Thunderbolt and other custom Trimble GPS disciplined clocks do not have Quantization Error. The PPS is reported directly from the oscillator, so it is not necessary to wait for a clock edge. The receiver speeds up or slows down the oscillator so that the PPS falls on time.

Phase lock loop (PLL) Clock