Receiver Frequency Standards

Optimizing Indoor GPS Performance

Larry D. Vittorini and Brent Robinson

WHILE ORBITING GPS satellites use atomic frequency standards to generate the ranging signals, most GPS receivers can determine position using only a simple frequency standard: a quartz crystal oscillator. Mass-produced quartz crystal oscillators are found in virtually every piece of electronic equipment, from wristwatches to GPS receivers. Oscillators contribute only a fraction of a receiver's manufacturing cost and have helped reduce consumer cost for a basic receiver to less than $100.

The common consumer GPS product sold today, however, will generally not function indoors and will have difficulty dealing with signal blockage from buildings and foliage. In recent years, engineers have developed receivers that will perform satisfactorily even with multipath-corrupted and severely attenuated signals such as those found indoors. This month's column examines the quartz crystal oscillator's role as a frequency standard in a GPS receiver and how certain characteristics of these mass-produced devices can limit performance for indoor use. — R.B.L.

GPS was never intended for indoor environments, and indeed, the relatively weak satellite signals do not readily lend themselves to use in such environments. The Federal Communications Commission's E911 mandate has spurred significant effort in the GPS community to apply its combined expertise to solve this dilemma.

Although manufacturers are successfully pushing the limits of physics with sophisticated hardware and signal processing, trade-offs must be made when deciding how best to optimally apply available resources to detect, acquire, and then track the attenuated and multipath-corrupted signals resulting from transmission around and through concrete and steel building structures. Furthermore, although wireless networks can potentially provide timing and ephemeris assistance to an embedded GPS receiver, some fundamental business, technical, and performance challenges continue to drive GPS manufacturers' desire to not only minimize their dependence on network aiding, but also improve location reporting performance and robustness.

This article discusses some of the fundamental choices receiver designers face and how the performance of the receiver's oscillator can affect those choices. Test results illustrate the vulnerability of weak signal acquisition to behaviors exhibited by mass-produced cell phone temperature-compensated crystal (xtal) oscillators (TCXOs).

Fundamentals

The lure of ever-increasing microprocessor throughput and geometrically increasing gate counts crammed into ever-decreasing areas can be so seductive one might forget that the best solutions are often simple as well as efficient. Huge correlator arrays are excellent for searching large swaths of code phase for multiple satellites very quickly, but they are of little value in solving the fundamental problem weak signals present: relatively long observation periods are necessary to reliably detect them. So-called block processing, relying on frequency domain techniques, will encounter analogous constraints. Although some researchers suggest that exotic signal processing techniques can overcome these limitations, the resulting increased algorithmic complexity is usually less than desirable in practical commercial systems and architectures and still may not solve the problem.

Signal processing (SP) improvements can help offset attenuation problems at the expense of increased hardware complexity, higher power dissipation, and ultimately, size and cost. But an improved receiver frequency reference will have a positive effect on both life-cycle cost (LCC) and performance as well as improve receiver robustness.

Systems Challenges

Although most system architects recognize that frequency standard behavior in any radio system is a key to attaining optimal performance, overreliance on silicon and software solutions can foster a propensity to dismiss the fundamental trade-offs involved.

Every system component is subject to cost scrutiny, but the oscillator is perhaps not the best place to compromise performance. Improving effective oscillator performance by focusing key manufacturing and technology advancements will pay tangible dividends in the overall receiver LCC.

Acquiring and tracking GPS signals in environments where signals are attenuated 10–30 dB from ideal outdoor conditions distills into relatively simple concepts and two key concerns about the physical environmental challenges of modern building structures: high signal attenuation and dynamic range effects and numerous multipath mechanisms. This article focuses on the first item; the second is in the domain of SP architecture and algorithms.

Attending to signal attenuation seems relatively straightforward from an SP perspective: extend the coherent and/or noncoherent integration periods to recover the lost signal-to-noise ratio (SNR). But the signal attenuation problem is further exacerbated by unpredictable attenuation profiles, bringing into play the Gold spreading codes' cross-correlation side-lobe characteristics and the much larger expected dynamic range. This manifests itself by further complicating detection of the true code phase peak.

Requirements Overview

System architecture trade-offs significantly influence receiver design, and oscillator performance pervasively affects overall system performance. In considering frequency accuracy and drift versus SP requirements, the trade-off involves SP hardware capability for frequency standard performance because the required processing is proportional to frequency error and drift (that is, SP load is dependent upon the number of correlator delay taps and/or Doppler frequency search bins, microprocessor throughput, and available memory). The two primary categories of oscillators used for GPS are internally compensated (TCXOs) and externally compensated (temperature-sensing oscillators [TSOs] or calibrated dual crystal oscillators [CDXOs]). This article does not discuss these oscillators at length but highlights some of the feature trade-offs.

The bottom line is that there is no magic bullet. Frequency-error handling must be designed into the system architecture. The variables include

- hardware: SP, microprocessor, memory, oscillator, real-time clock
- software: acquisition and tracking loop architecture and design, Kalman filter.

User Dynamics. Composite effective residual user dynamics determine receiver acquisition and track architecture options. User and oscillator dynamics (velocity, acceleration, and jerk [acceleration rate of change]) plus the availability of aiding determine loop design choices; that is, carrier and code tracking loop order and bandwidth. Similar considerations will dictate acquisition choices as well (coherent and noncoherent integration, etc.). Transient dynamics can exceed normal or typical velocity, acceleration, and jerk design values but normally only introduce temporary loss of lock when tracking GPS signals.

Indeed, oscillator dynamics induce disturbances to the acquisition and tracking processes that are equivalent to user dynamics, which include the receiver–satellite relative motion. Some commercial GPS receiver vendors shy away from specifying full operational dynamics and rarely acknowledge the oscillators' importance to overall performance. This is quite unlike the military world where continuous tracking, frequently in high dynamics and even without inertial aiding, is often mandatory, and the oscillators' contribution is recognized and accounted for during system design. Having said this, it is recognized that indoor GPS poses new constraints on the oscillator that haven't been necessary to consider previously.

Receiver Sensitivity

Receiver designers generally choose acquisition and track detection thresholds on the basis of a combination of dynamics, system hardware and software capability, and basic signal detection physics. The factors that influence detection thresholds include

- the predetection integration (PDI) or coherent integration period, which is generally limited to 20 milliseconds due to the 50 bits per second data rate, unless data aiding is used
- noncoherent summation (NCS) or dwell, typically 1 second during tracking
- probability of detection, the probability of identifying a true signal
- false-alarm rate, the probability of falsely identifying noise as signal.

GPS Acquisition/Track. Ultimately, nearly all systems intended for commercial use today, other than automotive uses, are unaided; therefore, the oscillator represents the most significant stress component to consider. These oscillator effects are primarily manifested as velocity and acceleration equivalents. But even jerk is manifested by the microjump phenomenon (see "Microjump Performance and E911" later in this article), which is not uncommon to some degree in virtually all unscreened AT (a common crystal cut angle with a cubic temperature characteristic) crystals available today, and one with largely unknown practical effects on performance expected in wireless applications.

Doppler Window. It is well known that extending the PDI over several data bits is more potent than noncoherent summation alone for detection, but it comes with a steep price: the Doppler window (the frequency-band containing GPS signals with the combined dynamics of satellite motion and user and clock dynamics) shrinks in direct proportion to the integration period, ultimately constraining the allowable frequency error and consequently the frequency rate of change as well.

Analysis shows that with a 20-millisecond PDI, the Doppler window allows no more than a trot (3.6 meters per second) from a pedestrian, for example, before oscillator frequency drift becomes a concern. Indeed, even for a stationary user conventionally de-

Frequency Standards

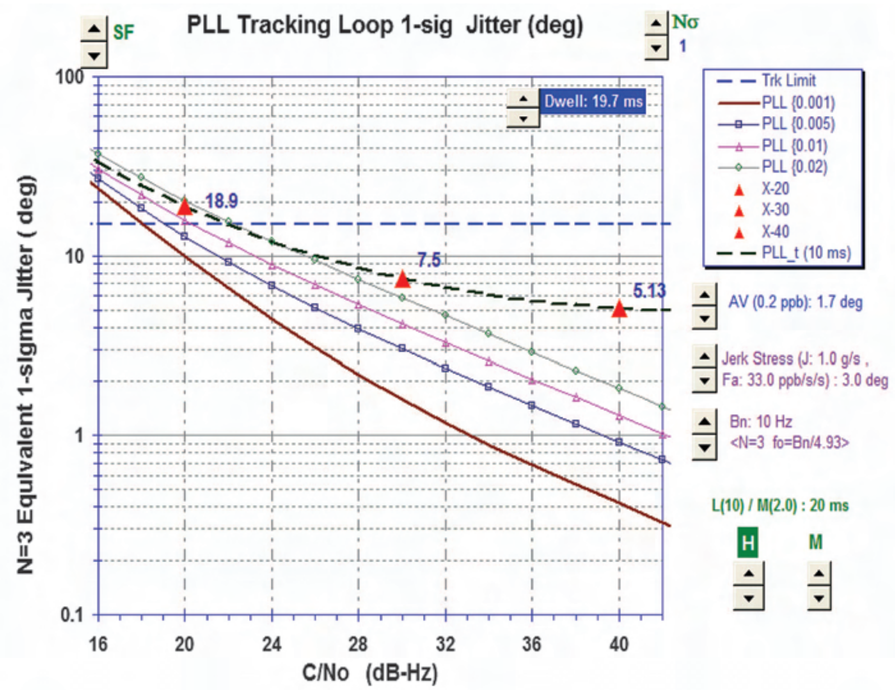
A frequency standard is a source of an electrical signal with a precise frequency. The central component of the frequency standard or oscillator is a resonator that vibrates or oscillates with a well-defined frequency when excited.

An external voltage applied across opposite faces of a piece of quartz crystal cut in a prescribed way causes the crystal to expand and contract depending on the polarity of the voltage. A crystal connected to an alternating voltage source will vibrate, generating an alternating voltage. These generated signals interact with the applied voltage in such a way that the vibrations and the resultant current flow are at a maximum at a particular frequency — the resonant frequency of the crystal, determined by the size of the crystal and how it is cut. Manufactured crystals are chemically very pure and have few crystallographic flaws.

Accuracy (how well the oscillator can be tuned to a specified frequency) and stability (how well it stays on frequency) determine oscillator quality. Oscillator stability is measured in terms of the relative change in its frequency over time.

A simple crystal oscillator (XO) does not provide a means for controlling the crystal's frequency variation as the ambient temperature changes. In a temperature-compensated crystal oscillator (TCXO), a thermistor generates a correction voltage to keep the oscillator's frequency more constant. TCXOs can reduce the frequency instability resulting from temperature effects by a factor of 4–20. In an oven-controlled crystal oscillator (OCXO), a miniature oven is used to maintain a stable temperature around the crystal, improving its inherent stability by factors of 1,000 or more and giving it short-term stabilities over periods shorter than approximately one hour of a part in 10^{12} or better.

While the very short-term accuracy and stability of quartz resonators is good, their long-term behavior is significantly surpassed by atomic frequency standards. – R.B.L.



▲**FIGURE 1** Phase lock loop tracking error as a function of GPS signal carrier-to-noise density. The curves illustrate the effects of four different predetection integration intervals (PDIs) from 1 to 20 milliseconds without a jerk stress and for the 10-millisecond PDI case when the loop undergoes a 1.0-g-per-second jerk stress. In each case, the dwell is 20 milliseconds.

signed TCXOs would have difficulty holding a drift rate of less than 2 parts per billion (ppb) per second required to extend the PDI past 80 milliseconds if a significant temperature gradient exists.

This set of conditions has a direct impact on oscillator performance because even temperature changes of much less than 1 degree Celsius can induce an equivalent acceleration that will result in "smearing" of the signal across several bins/taps during the integration period. This outcome reduces the probability the signal will pass the detection threshold, resulting in a missed detection. Ideally, one would like mass-produced TCXOs/crystals to have drift rates that approach 1 ppb/s, 10 times better than generally available today (see "Frequency Standards" sidebar).

Tracking Thresholds. To understand how dynamics can affect the tracking threshold, analytical models can clarify how the oscillator's performance can affect the carrier loop. Although many manufacturers use "snapshot" detection techniques that eschew conventional tracking loops, they generally produce noisier solutions. However, their performance can also be nearly completely described by looking at the acquisition process. The receiver tested uses a more conventional approach.

We constructed an Excel spreadsheet model of a second-order phase-locked loop (PLL) that accounts for both Allan Variance and microjump effects that manifest as a jerk. We assumed the standard 15-degree PLL jitter limit. As expected, bandwidth is inversely proportional to its ability to handle stress.

Combining the jerk stress model with a similar one for the square root of the Allan Variance (0.2 ppb at 1 second shown) allows one to compute total loop error jitter, as shown in **Figure 1**. We considered constant 20-millisecond dwell cases for PDIs of 1, 5, 10, and 20 milliseconds plus the effect of a jerk stress of 1 g (9.8 meters per second squared is standard Earth gravity acceleration or approximately 32.6 ppb/s) per second with a 10-Hz bandwidth. The 10-millisecond case, including all jitter effects, is highlighted, which results in a 2-dB degradation in loss-of-lock threshold. This also illustrates the value of noncoherent summation because there is a 2+ dB advantage for comparing 1- and 10-millisecond PDIs. (Note: this model does not include practical system losses that can total 3–5 dB.) However, in practice these designs, although capable of being upset, recover relatively quickly. Thus, our studies concentrated on the acquisition process, which is more critical when considering uses such as E911.

SNR. To recover GPS signals in high-attenuation areas such as those found indoors, SNR must be boosted to account for the signal loss incurred. **Table 1** summarizes several methods for boosting detected SNR.

Acquisition Sensitivity. The acquisition model used for the following examples is a Gaussian approximation rather than a true noncentral χ^2 (Chi-square) model and is deemed adequate for comparison purposes since we are interested in relative improvements. The actual carrier-to-noise density (C/N_0) thresholds will be 3–5 dB higher due to practical design considerations.

Figure 2A shows the effect of doubling the NCS period for a stronger signal case with a constant PDI of 1 millisecond and

TABLE 1 Choices for boosting signal-to-noise ratio

Extend the PDI interval	Extend the NCS interval
Improves SNR directly proportional to ratio of T	Improves SNR as a ratio of square-root of T
Only available if data aiding used	Much less sensitive to frequency drift/shift
Useful gain as squaring loss becomes significant	Gain attained under any signal condition
Dependent on chip spacing and code loop bandwidth	Use two-step detection process
Greatly reduced tolerance to frequency drift/shift and user dynamics	Requalify samples in gray area with longer NCS
	Combine above to suit conditions

5-, 10-, and 20-millisecond dwell periods to be on the order of 2 dB per octave change in dwell (NCS) length. As shown in **Figure 2B,** a low-SNR situation, we considered the case of a constant total dwell time of 2 seconds and variable PDI. There is a gain of nearly 4 dB/decade change in PDI length with constant dwell in extending the PDI from 20 to 200 milliseconds. This gain will diminish as SNR increases.

These two cases show how combining coherent and noncoherent samples diminishes the advantage of coherent integration alone and allows detection at lower SNRs without using an overly lengthy PDI, which constrains velocity error. Nevertheless, it is still desirable to use the longest PDI practical.

We may summarize the considerations related to the acquisition of weak signals as it relates to oscillator equivalent dynamics as follows: the advantage of a longer PDI diminishes when combined with longer dwells. There is a 4–4.5 dB/decade PDI gain with constant dwell for weak signals. As we have noted, the total velocity error budget is a major constraint in extending the PDI beyond 40 milliseconds. Although aiding can minimize this issue, the result is a higher burden on oscillator stability because a higher PDI dictates that one search proportionately more Doppler bins. However, newer architectures are capable of searching many bins in parallel, mitigating this constraint. Nevertheless, signal power can still migrate across bins during the detection period if the frequency is drifting or shifting. Overall, the best performance is obtained by judiciously combining PDI/NCS or using two-step detection, although residual dynamics will dictate a practical limit in the 60–200 millisecond range.

Only careful analysis will produce the best choices for the system design constraints. Overall, however, improved local oscillator performance will ensure maximum performance and potentially support more than a 5-dB threshold improvement over a PDI limited to 20 milliseconds or less.

Table 2 summarizes the effects of an improved oscillator on receiver architecture.

Frequency Reference Anomalies

Contrary to popular belief, mass-produced cell phone TCXOs can exhibit behaviors that degrade expected system performance in critical situations. One is an anomalous crystal-related behavior and the other a residual of low-cost compensation methods.

TABLE 2 Effects of improved oscillators

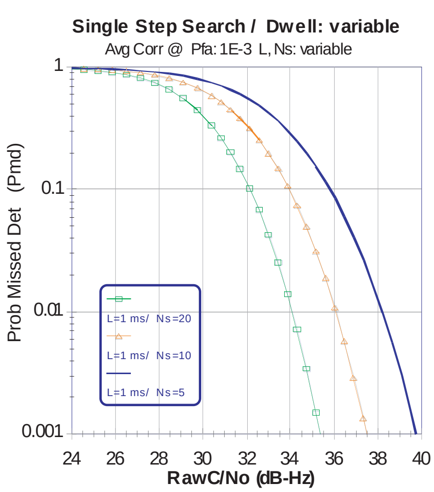
Conserves system acquisition resources
Requires less RAM for parallel search of Doppler bins and code-phase bins
Reduced software complexity (resolves bin-smearing due to apparent acceleration drift during acquisition)
More margin for dedicated signal processing and microprocessor resources
Reduced resource strain leaves more margin for "unintended consequences."

Microjump Performance and E911. A microjump (MJ) is a random abrupt change in frequency with a variety of causes, but it is most often associated with microscopic crystal blank surface contaminants and other manufacturing-related defects. Although MJs are commonly less than 10 ppb shifts occuring relatively infrequently, empirical evidence has shown their magnitudes can far exceed 10 ppb and even exhibit burst-like behavior during periods of more than ten seconds when subjected to temperature gradients, especially after coming from a cold soak — a condition easily achieved during winter in much of the world. Although current crystal manufacturing technology cannot completely eliminate the manufacturing defects that allow MJs to occur, recently developed postproduction screening processes appear to cull those most susceptible to this behavior and reject, on average, as many as 5 percent of the units tested. Work is ongoing to develop methods to improve MJ screening robustness.

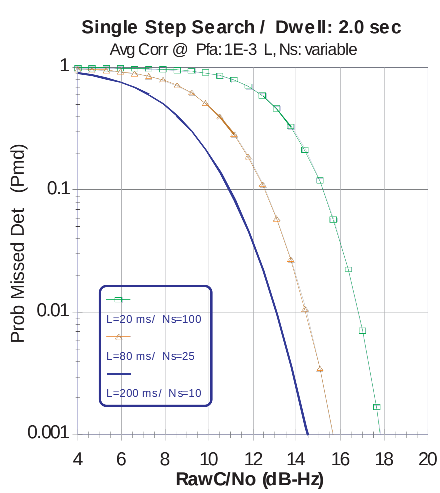
Although conventional wisdom dictates that for standard commercial GPS usage MJs present no more than a somewhat rare annoyance, this stance may be overly optimistic when it comes to a safety-critical application such as E911, which often involves a life-threatening situation.

The probability of a crystal "blip" or series of blips occurring throughout a short span resulting in a delay or denial of the transmission of location information intuitively dictates a much higher level of oscillator signal integrity — perhaps a novel concept but one that deserves our attention.

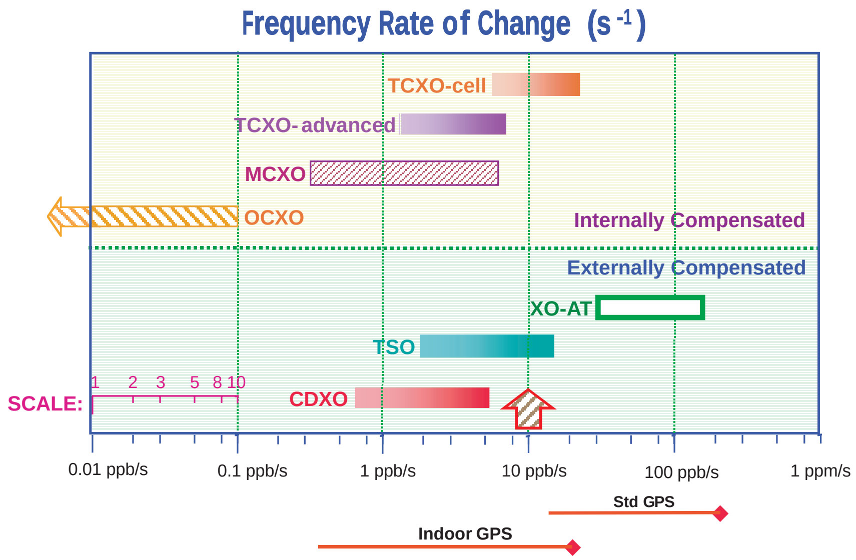
In stronger signal conditions, the receiver



▲ **FIGURE 2A** The probability of the missed detection of strong GPS signals as a function of carrier-to-noise density. The response for three noncoherent summation or dwell periods of 5, 10, and 20 milliseconds is illustrated. In each case, the predetection integration interval (L) is 1 millisecond. The dwell period is L, and Ns is the number of noncoherent samples.



▲ **FIGURE 2B** The probability of the missed detection of weak GPS signals as a function of carrier-to-noise density. The dwell period (L × Ns) was held fixed at 2 seconds, and the predetection integration interval (L) varied from 20 to 200 milliseconds.



▲ **FIGURE 3** Temperature-gradient performance of different types of crystal oscillator varies widely. TCXO: temperature-compensated; MCXO: microcomputer-controlled; OCXO: oven-controlled; XO: uncompensated; TSO: temperaturing sensing; CDXO: calibrated dual crystal oscillators.

can recover from an MJ with relative ease. However, as SNR decreases, the occurrence of an MJ event coupled with the need to use extended integration periods could make reacquisition significantly more difficult. Indeed, test results shown later in this article indicate that even a standard acquisition is vulnerable.

With tangible evidence that, even in a small percentage of cases (say less than 5 percent), such an event could prevent or delay reporting a caller's position, a tangible vulnerability and cause for concern could indeed arise with unscreened crystal oscillators.

Conventional TCXO Constraints. Conventional TCXO technology simply cannot respond to, nor compensate for, high-dynamic changes in frequency such as those caused by MJs and to a lesser degree, activity dips, which will degrade the compensation model fit, generally a 3rd-order polynomial model. Similar to MJs, dips are changes in frequency, but the difference is they always occur at approximately the same temperature (in a particular crystal design) but are much slower. This is a phenomenon largely associated with coupled modes in AT resonators (alternate, unsuppressed secondary resonances) and tends to be present in most crystals to one degree or another. The effect often worsens as the temperature gradient rises.

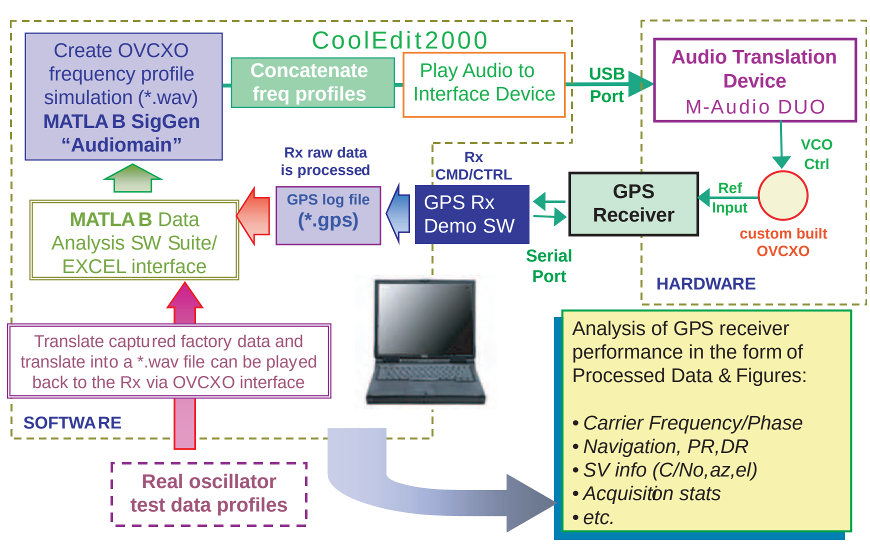
Although they are not normally fast enough to cause carrier or code loop loss of lock, activity dips nevertheless degrade the models' fit by consuming degrees of freedom to compensate the nominally 3rd-order crystal curve. Thus, minute temperature changes (much less than 1 degree Celsius) can result in an oscillator-induced apparent acceleration, limiting the ability to extend the coherent integration as desired. Gradient performance of cell phone TCXOs on the market today is on the order of 100 ppb per degree Celsius or 10 ppb/s (1/3 g). New technologies promise to improve on this by a factor of 4 to 10.

Insulating the search process from frequency drift and drift rate is thus a critical component in achieving optimal receiver performance. Figure 3 indicates how various frequency standard technologies vary in temperature-gradient performance.

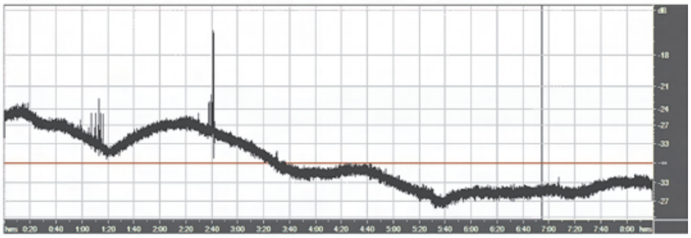
GPS Receiver Test Bed

We developed a GPS receiver test bed (GRTB) expressly to examine the effect of oscillator performance on receiver performance. For this study, a commercial off-the-shelf high-sensitivity receiver was tested in the acquisition mode to determine its sensitivity to the two key anomalous crystal behaviors: MJs and temperature-induced gradients presented by standard TCXO compensation methods. GPS signal power was uniformly controlled with a front-end radio frequency attenuator for the live-signal tests. Acquisition results were tabulated for high to medium-low signal conditions.

The test results presented generally used a 60-second reset of a warm start and determined successful acquisition to be one resulting in successfully reaching either a carrier or code-lock tracking state, including successful ephemeris collection for a minimum of four satellites. The next phase of this study will integrate a signal simulator



▲ **FIGURE 4** GPS receiver test bed data processor system block diagram.



▲ **FIGURE 5** An example of microjumps in a temperature-compensated crystal oscillator following a cold soak. The vertical scale is signal voltage into the oscillator in dB. The horizontal scale is time in hours and minutes.

with full scenario generation capability to improve the reliable collection of statistics and allow inclusion of the combined effect of user dynamics and oscillator characteristics simultaneously.

Test Methodology Overview. It was deemed prudent to begin with periodic profiles representative of real-world situations. These profiles were synthesized to allow a statistic for a given profile to be computed to establish performance over 100 acquisition resets for an acquisition event, at controlled intervals, to document acquisition sensitivity to that profile.

Figure 4 summarizes the test system, which includes the data processing software to process the raw data. Repeatable, periodic profiles effectively characterize their effect on the acquisition process. In this context, two primary cases were considered.

Temperature-Induced Gradient Effects. To effectively simulate the oscillator dynamics exhibited by TCXOs, it is helpful to collect information about the expected gradients that may be encountered in the integrated platform. One example, obtained from a cell phone manufacturer, suggests the frequent possibility of a sustained gradient in excess of 5 degrees Celsius per minute for tens of seconds. Of course, placement of the oscillator within the receiver will be important in any application because it determines how this temperature gradient is translated to the oscillator itself.

Microjumps: How Bad Can They Get? Studies of Rakon's database of production test data from all the major manufacturers as well as specific experiments and MATLAB analysis tools developed to characterize the data provide a salient example of an extreme case that occurs with a lower but tangible frequency in units stressed in dynamic temperature environments. These same units, when returned to room temperature, often look perfectly normal — indeed a cause for concern. Figure 5 shows an example of just how bad MJs can get under temperature stress with "bursty" events lasting minutes, with magnitudes from 50 to more than 100 ppb.

Temperature Gradient Profiles. Consider a temperature gradient of 6 degrees Celsius per minute (0.1 degree Celsius per second). One phone-board data set analyzed reveals that 10 ppb/s (1/3 g) frequency rates of change with random changes in slope direction may be typical. The test profiles selected to simulate this behavior consist of triangular waveforms with amplitudes ranging from 2 to 32 ppb for a 60-second period, simulating the effect of temperature gradients on an installed oscillator during warm-up and cool-down periods.

Microjump Profile. We determined that jumps much larger than 10 ppb in temperature transition are completely feasible. Furthermore, it appears that more than 10 percent of these jumps could be much worse during cold soaks, sometimes with burst-like behavior. The test profiles we selected to simulate this behavior consisted of square waves with 2–32 ppb peak magnitudes and periods ranging from 10 to 100 seconds.

Test Results

The summary charts in Figures 6–8 clearly illustrate the receivers' acquisition failure rate (F/R) sensitivity to ramps, square waves, and combinations of a range of simulated MJ magnitudes and frequency gradients with signal power attenuated to less than an effective C/N_0 of 30 dB-Hz with unattenuated conditions supplying the baseline. Acquisition performance was notably degraded in the weaker signal conditions tested, which were a fair bit stronger than the minimums at which indoor receivers are expected to perform (14–16 dB-Hz). Note: 25–32 dB-Hz was considered a "mid-range C/N_0" for these tests.

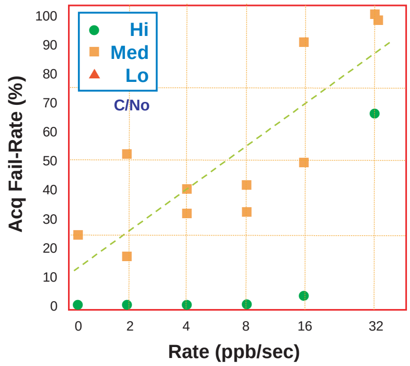
TABLE 3 Summary of low-cost frequency standard choices

Crystal Types – Pros/Cons
Standard mount with circular blank
Constrains total package size reductions
Low vibration sensitivity
Strip resonators
Much smaller, lower cost
Current designs — higher vibration sensitivity
Internally Compensated Choices (0.5–2.5 ppm)
2-port thermistor: conventional approach
Analog IC: newer, higher performance
Least squares polynomial model

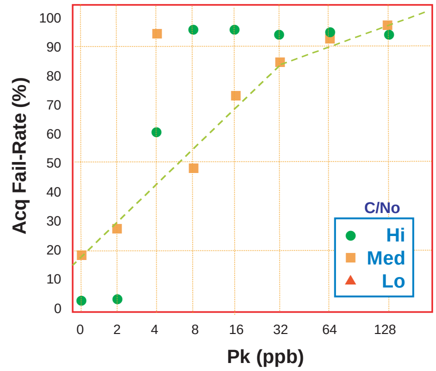
Externally Compensated Options (< 0.25 ppm)
Open loop
Aid code/carrier loops
Kalman filter methods
Other
Technology options
Dual crystal (AT/Y) cuts
Temperature sensed (silicon sensor)

There was little sensitivity to acceleration ramps up to appproximately 0.5 g (16 ppb/s) for signals greater than 36 dB-Hz. However, with the signals attenuated to the 25–32 dB-Hz range, even low acceleration profiles had F/Rs greater than 25 percent, rising steadily as the acceleration increased. The point is that a TCXO can exhibit these effects. As shown in Figure 7, the profile has a fixed 60-second period with variable magnitudes. The F/R quickly rose as magnitude increased, even for higher signals. Finally, Figure 8 shows a combination of simulated MJ activity (square waves) overlaid on a 1/3-g acceleration profile. Performance degraded significantly above 2-ppb magnitudes for cases of both 40- and 60-second square wave periods.

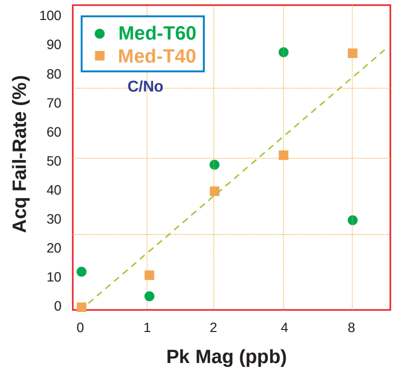
Test Results Summary. The GRTB system exercises receivers in a unique manner, allowing performance benchmarks to be established for a variety of practical conditions that can help manufacturers tune their software algorithms to improve robustness. For strong signals (>36 dB-Hz), the receiver tested was immune to most ramp rates but not to higher MJ magnitudes. For weaker signals (25–32 dB-Hz), the receiver showed a definite sensitivity to ramps, square waves,



▲ **FIGURE 6** GPS receiver acquisition failure rate in response to varying accelerations of up to 32 parts per billion per second or approximately 1 g (as simulated with a ramp function with a varying rate) for low (less than 25 dB-Hz), medium (25–32 dB-Hz), and high (greater than 32 dB-Hz) C/N_0 values.



▲ **FIGURE 7** As in Figure 6 but for square waves of varying magnitide and a fixed 60-second period.



▲ **FIGURE 8** As in Figure 6 but for square waves with periods of 40 and 60 seconds overlaid on a one-third g acceleration profile and for a medium-strength signal.

and combinations of the two. The results indicate that the concerns spurring this study about the negative effect of oscillator anomalies on receiver acquisition performance were justified and definitely deserve further study. However, it is reasonable to expect results to vary widely between manufacturers.

Cost Trade: Silicon or Quartz?

The question then is, where to spend precious resources to obtain maximum efficiency and reliability? Is the marginal added cost of a superior frequency standard a better trade than added SP complexity and more memory? Consider the current approximate costs for 180-nanometer complementary metal oxide semiconductors: gates cost US$0.08–0.10 per square millimeter, and static RAM costs US$0.12 per 16 kilobytes. Contrast this to approximately US$0.15–0.50 for either improved screening or newer technology compensation methods, and the trade is clearer. Of course, silicon costs continue to improve, but this improves the cost basis for improved oscillator technology as well.

Accommodating oscillator drift and drift rate is directly proportional to the required integrated circuit (IC) die area and power dissipation. Expanding the maximum code and Doppler search windows requires more correlator taps and/or Doppler frequency bins as well as more microprocessor throughput and memory. These improved capabilities translate into higher IC die area and thus cost, not to mention dissipating more power. More-sophisticated software is usually required as well, increasing both time to market and development costs.

Choices

To address the challenges highlighted in this article, it is instructive to review the low-cost oscillator technology options available to designers as well as what lies ahead. Table 3 provides a summary of the most popular options.

What's Next? Some exciting new technologies are currently in development that can help address the desire for improved performance in mass-produced products that are cost competitive with current technology. Higher-performance IC designs will reduce overall frequency error and reduce drift rates toward the 1 ppb/s level. This, along with expected improvements in manufacturing and screening processes, promises to further minimize anomalous behaviors.

Summary

The small added cost for a superior oscillator will conserve engineering resources during the development process and reduce LCC. Furthermore, reduced receiver architecture complexity will make it easier on system developers, helping to maintain healthier performance margins. In the end, future growth options will be less constrained because system architects will have more freedom to innovate, improving the efficiency of engineering resource allocation.

Acknowledgments

Janaka Ranasinghe, Tim Rae, and Sinan Altug of Rakon and Phil Ward and Jack Murphy assisted with this article. The article is based, in part, on the paper, "Frequency Standards: Key Enabler to Optimizing Indoor GPS Performance," presented at The Institute of Navigation GPS/GNSS 2003 meeting in Portland, Oregon, September 9–12, 2003. ⊕

"Further Readings" can be found at *www.gpsworld.com*.

Larry Vittorini runs a consulting business, Genesio Systems Engineering, in Irvine, California, and currently serves as a consultant to Rakon. Contact him at ldvittor@yahoo.com.

Brent Robinson is managing director at Rakon, Inc., in Auckland, New Zealand, and has more than 25 years of experience in the design and manufacture of crystals and oscillators.

The "Innovation" column is coordinated by **Richard Langley**, who appreciates your comments and topic suggestions. To contact him, see the "Columnists" section on page 2.