Keeping Precision Time When GPS Signals Stop

Most military GPS-based timekeeping systems are vulnerable to signal outages caused by unintended malfunctions or interference from enemy threats, because they rely on a single quartz oscillator for holdover timekeeping. A reliable, robust time and frequency source is needed to sustain operation for mission-critical navigation and communication systems.

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The U.S. military requires accurate timekeeping to navigate, communicate and distribute information. All branches of the service operate systems that rely on precise timekeeping to support communications, sensors, targeting and information distribution. In some military applications, an atomic clock is used as a precision clock. More commonly, a precision oscillator disciplined by the Global Positioning Satellite (GPS) system is used.

The military has become increasingly dependent on GPS satellites to provide a common time reference for all branches of the service. The advantages of this system are its precise, sub-microsecond timing accuracy, as well as its widespread availability. The disadvantage is that GPS signals are vulnerable to outages caused by unintended interference or malfunctions in user equipment, as well as enemy threats such as jamming.

This vulnerability creates the need for a reliable, robust time and frequency source that sustains accurate timekeeping even during satellite signal outages. Without continual satellite signals, mission-critical navigation and communication systems become unsynchronized and cease to operate properly. To prevent this, accurate "holdover" timekeeping is required to flywheel through satellite signal interruptions.

The Problem with Current Clocks

The piezoelectric properties of quartz crystals make them uniquely useful for timekeeping. Wristwatches, for example, use a battery to excite a quartz crystal, which vibrates at a precise frequency to keep time. Most atomic clocks use a quartz oscillator to provide their output signals. Systems designed to receive accurate time from satellites also employ a quartz oscillator to generate their timekeeping output signals.

The problem lies in the fact that these systems use only one quartz oscillator for this important purpose. A single quartz oscillator provides the holdover frequency and timekeeping capability in most military (and civilian) GPS-based timekeeping systems. If the GPS signal is interrupted for any reason the accuracy of timekeeping must suddenly rely on that single oscillator. But for systems that require nanosecond- or microsecond-level accuracy, that's not good enough for reasons of both accuracy and reliability.

Although quartz crystals are sufficient to make wristwatches capable of keeping time within a few seconds a week, they cannot maintain higher accuracy levels for very long. All quartz oscillators experience small frequency errors, which are continually corrected in a GPS-disciplined system. Over time, they drift and their frequency changes. In addition, oscillators are sensitive to temperature, pressure and vibration. Although their reliability is pretty good, it is not perfect.

Therefore, a system that keeps holdover time with only one quartz oscillator is a system that drifts noticeably when the satellite signal is lost. For example, one military user reports that if the GPS signal is unavailable, its shipboard clocks can drift milliseconds in a few hours even though the user needs microsecond-level accuracy. Also, since most clock systems cannot directly sense an oscillator malfunction, a partial failure that degrades timekeeping can go unobserved.

Keeping Accurate, Reliable Time

Historically, when highly accurate, reliable holdover timekeeping has been required, an atomic clock has been added to the system. Since 1972, the world has kept “Coordinated Universal Time” (UTC). The UTC time scale is the consensus of hundreds of atomic clocks in national laboratories around the world. Each laboratory reports its clocks’ times to the International Bureau of Weights and Measures in Sevres, France. UTC is calculated as the weighted average of those clocks—the more stable the clock, the heavier its weighting—and published as differences between UTC and the contributing clocks.

This clock-averaging scheme is also tied to astronomical observations. When the difference between UTC and the year—defined by the Earth’s rotation about the sun—approaches one second, a “leap second” is added or subtracted to UTC. The GPS system uses a variant of UTC managed by the U.S. Naval Observatory. This time scale runs at the rate of UTC but does not observe leap seconds.

Atomic clocks are sufficiently stable to keep microsecond levels of timekeeping accuracy for weeks, and nanosecond levels of accuracy for hours and days. However, because they are relatively expensive and not well suited to rugged field equipment, only the most critical applications use atomic clocks for holdover timekeeping. Since even these clocks constitute single-point failures, some applications include two atomic clocks and continually compare them. But, if both of these clocks disagree and GPS is not available, it is difficult to determine which clock is wrong.

A Different Approach

One approach to inexpensive, accurate, reliable holdover timekeeping is the Precise Intermediate-term Computer-controlled Oscillator (PICO) Advanced Clock. It uses an ensemble of several oscillators to keep precise time when GPS signals are not available (Figure 1).

Existing Single-Oscillator Methods vs. PICO Advanced Clock

Characteristic	Single Oscillator	PICO Oscillator Ensemble
Precision	Maintains precise time only when an external precise time reference is present	Maintains precise time for hours after an external precise time reference is removed
Time/ frequency drift	Cannot compensate for oscillator drift	Compensates for oscillator drift in all connected local references, include customer-supplied clocks
Robustness	Partial or complete oscillator failure causes complete loss of time and frequency capability	Partial or complete oscillator failure, including in a customer-supplied clock signal, results in minimal loss of time/ frequency capability
Reliability	No self-monitoring or reporting capability	Sophisticated self-monitoring and reporting capability
Flexibility	Single-purpose device	Can use clock signals from existing atomic clocks, if available, protecting current investments in time/frequency references

Figure 1

The Precise Intermediate-term Computer-controlled Oscillator (PICO) Advanced Clock architecture is based on an ensemble of oscillators. This ensemble has several advantages over the single-oscillator systems used in most precision timekeeping systems, including atomic clocks and GPS-based systems.

PICO constructs and maintains a stable time scale using an averaging concept, but it performs real-time clock averaging with an adaptive Kalman filter. Each oscillator in the clock's ensemble is characterized by comparing it to the GPS timing signal, when available. The Kalman filter learns to correct each oscillator for its current deterministic errors—e.g., frequency error, frequency drift rate and drift rate change—and statistically weights and combines each oscillator's output to form a best-estimate stable frequency output. Additionally, the weights assigned by the Kalman process are proportional to the stochastic (i.e., random) error, or noise, in that oscillator's output signal, with a noisier oscillator receiving less weight. Over time, the Kalman filter also adapts both its deterministic and stochastic coefficients to reflect changes in the oscillators. If an oscillator has failed, it can be excluded from the calculations, which makes this approach a good monitor for atomic clock health.

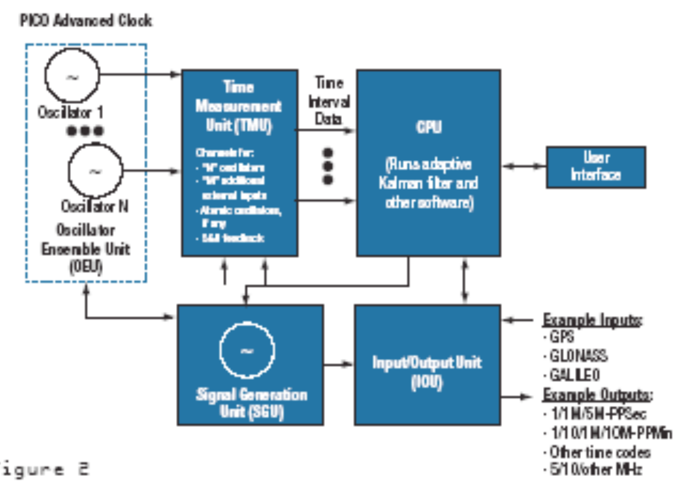

Figure 2

The PICO clock maintains a stable time scale using an averaging concept so that precise time can be maintained when the external time reference is lost.

The architecture has five subsystems (Figure 2). The Oscillator Ensemble Unit (OEU) packages the ensemble's "N" oscillators and isolates them from vibration and rapid thermal changes. The Time Measurement Unit (TMU) ingests signals from "N" oscillators in the OEU, from "M" optional atomic clocks that may be participating in the ensemble, from the Signal Generation Unit (SGU), and from the external time reference, such as GPS. Each of these N+M+2 signals is reduced to a one pulse-per-second (1 PPS) signal and differenced with the external time reference signal, which is usually the 1 PPS from a GPS timing receiver. These interval measurements are reported as numeric data to the CPU.

The CPU ingests the incoming time difference data, processes the data with the adaptive Kalman filter, and outputs an appropriate control signal to the SGU. The CPU also runs software to interface with the Input/Output Unit (IOU) and to set up and monitor the CPU via the user interface. The SGU comprises a voltage-controlled oscillator (VCO) steered by a control signal from the CPU. It is this oscillator that provides the stable time output of the clock, whether or not a GPS signal is available. The IOU handles the various input and output timing signals.

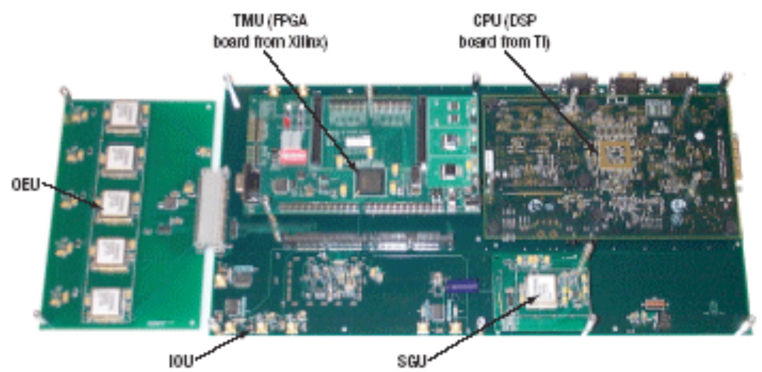

Figure 3

The prototype PICO clock was implemented for the U.S. Navy's Navigation Sensor System Interface (NAVSSI) and Link-16 terminal applications using two commercial development boards, in addition to new circuitry.

Advantages of the PICO Advanced Clock Architecture

This approach has three significant advantages. First, the performance of each oscillator can be corrected by comparison with GPS signals when they are available, thereby compensating for deterministic errors. This leaves only stochastic errors to degrade that specific oscillator's timekeeping performance when GPS signals are not available.

Next, by combining the timekeeping results of several oscillators, timekeeping statistics can be improved, suppressing the stochastic error in the system's performance by an amount that is inversely proportional to the square root of the number of oscillators. That is, an ensemble of four oscillators gives $1 \div \sqrt{4} = 1/2$ the error of a single oscillator, an ensemble of nine oscillators give $1 \div \sqrt{9} = 1/3$ the error of a single oscillator, and so on. Since this is a rapidly decreasing benefit, the prototype clock was built with five oscillators: four to reduce statistical errors by 1/2 and an extra oscillator so that four will remain working even if one fails.

Finally, the ensemble can self-identify failures. The PICO Advanced Clock provides precise, low-drift, robust, reliable and flexible holdover timekeeping, as well as a stable precision frequency reference. Its ability to synchronize within a few nanoseconds to an external time source, such as GPS or a network time reference, delivers precision results.

After synchronizing to an external reference such as GPS, PICO compensates mathematically for any drift in its clock ensemble, including customer-supplied clocks, sustaining precision timekeeping for extended periods if the external reference is interrupted. The Advanced Clock's architecture—where any oscillator's partial or complete failure, including a failure in any customer-supplied clocks, only slightly degrades the performance of the unit—is the basis of its robustness. Its self-monitoring and self-reporting functions provide reliability, and its ability to include existing customer devices, such as atomic clocks, as participants in ensemble timekeeping make it especially flexible.

Under a Phase I SBIR contract with the U.S. Navy, the Space and Naval Warfare Systems Command (SPAWAR) selected Syntonics to demonstrate the feasibility of the PICO Advanced Clock concept. After successfully completing Phase I, Syntonics was chosen to develop a prototype—adaptable to both the Navy's Navigation Sensor System Interface (NAVSSI) and Link-16 terminal applications—under a Phase II SBIR contract.

The PICO Advanced Clock approach can be used in military applications that depend on GPS for precise timekeeping and/or that require highly accurate and coordinated timekeeping information. These include precision-guided munitions, Airborne Warning and Control System (AWACS) platforms, Joint Surveillance Target Attack Radar System (Joint STARS), and submarine atomic clock performance monitoring.

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