Symmetricom SmartClock Technology

Improving Oscillator Long-term Stability for Synchronization Applications

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Heartbeat of the Net

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I. Introduction: The Need for Highly Accurate Timing Synchronization

Modern applications in digital telecommunications, metrology, manufacturing, calibration, wireless communications, and power transmission require highly-accurate timing. Equipment functionality and reliability and the quality of services delivered can be dramatically affected by the proper application of precise timing units. Until recently, the cost of highly-accurate timing was prohibitive. Now, excellent network and timing synchronization are available at reasonable cost.

Local and Reference Sources

Highly-accurate timing systems must compensate for the fact that no single clock can be continuously available, and that all clocks lose accuracy over time. Most systems employ a local clock and periodically calibrate this clock against a reliable reference such as an atomic clock.

Universal Coordinated Time (UTC) is the accepted representation of absolute time and is coordinated by the Bureau International des Poids et Mesures (BIPM) in France using information from cooperating timekeeping centers around the world. Designated UTC centers, such as the U.S. Naval Observatory (USNO), the National Institute of Standards and Technologies (NIST) in the United States and many others throughout the world, provide local standard time sources or synchronization references. With current technologies, a clock can be remotely located and still achieve high accuracy and traceability.

The selection of clock technology, and the method of obtaining the reference signal, directly affect the cost and accuracy of a timing solution. A variety of alternatives—typically with accuracy and/or cost trade-offs—exists for deriving and maintaining precise time.

Clock Technologies

A local clock keeps time in terms of a local epoch signal. This may range from an ac motor tied to a national power grid at either 50 or 60 Hz, or an internally generated signal similar to that of the quartz crystal oscillator in most wristwatches. The most accurate clocks use internal oscillators that produce highly reproducible pulses or epoch intervals. Typically the more expensive the oscillator, the better the clock's accuracy. Rubidium- or cesium-based clocks or oscillators, for example, can maintain accurate time for long periods after synchronization with a primary time source. Unfortunately, they are too costly for many applications. Quartz oscillators, while less expensive, require more frequent synchronization to a reference or synchronization source to maintain the same accuracy.

Reference Sources

In the past, traveling clocks were taken from places maintaining reference time scales (like NIST or the USNO in the United States, or other national timing references around the world), and physically transported to synchronize remote clocks. This method, while still used occasionally today, is expensive and inconvenient.

Today, users of time and frequency can easily receive a reference signal from a number of facilities. Time traceable to UTC is readily available worldwide via both terrestrial and satellite broadcast technologies.

Some of the more common terrestrial (ground-based technologies) are:

- VLF and LF transmissions such as Omega and Loran-C
- HF transmissions
- Television broadcasts
- Telephone and computer network distribution
- NIST's Automatic Compuoptical fibers

Some of the more common satellite technologies are:

- GOES weather satellites
- Navstar Global Positioning System (GPS)
- Former Soviet Union GLONASS

These technologies vary greatly in accuracy, expense and accessibility. Some transmissions are susceptible to daily variations, weather conditions, or propagation delays, and may not be available everywhere.

Oscillator Performance

Oscillators vary in their ability to maintain an accurate frequency over time. Cesium-beam frequency standards offer the best long-term stability—the most stable cesium standards have been designed to be insensitive to environmental perturbations. This results in a clock that is the most accurate for the longest period of time. Cesium standards are expensive (up to approximately U.S. $70,000) and are typically applied in the most critical applications or environments that require a primary standard or independent clock.

Rubidium standards have poorer long-term stability and are more environmentally sensitive, but actually have better short-term accuracy over periods ranging up to several thousand seconds. They are lower in cost (U.S. $1,200 – $5,000) than cesium, but they require periodic calibration against a reference signal or synchronization source.

The HP 5071A uses a cesium-controlled oscillator to deliver maximum accuracy and stability.

High-quality quartz oscillators are inexpensive (priced from U.S. $200 – $1,000), but they are less stable than either cesium or rubidium. Quartz oscillators are environmentally sensitive, especially to temperature. Quartz oscillators and rubidium standards exhibit a systematic change in frequency with time. This is called aging. Although appearing to be linear over short periods of time, in fact aging in either oscillator is more satisfactorily modeled by a logarithmic function over long periods of time.

All standards, cesium, rubidium, or quartz, show random fluctuations with time. This is usually expressed by the Allan Deviation (or root Allan Variance) of the oscillator. A typical Allan Deviation curve for a quartz SmartClock is shown in Figure 6. The curve can be interpreted as a plot of the uncertainty expected between successive measurements of oscillator frequency for any given measurement period.

II. Symmetricom SmartClock Technology

SmartClock technology improves the performance and accuracy of low-cost oscillators and enhances the availability and implementation of reference sources. Symmetricom SmartClock algorithms provide highly-accurate timing units at price points that meet the requirements of many contemporary applications.

Based in part on work done at National Institute of Standards and Technology (NIST), SmartClock technology also results from years of experience in the design and manufacture of precision oscillators.

Timing System Components

Symmetricom's precision timing systems have four components in common:

- An oscillator frequency source
- An external reference signal—cesium, GPS, or telecom signals (E1/T1)
- SmartClock algorithms that characterize system behavior and enhance performance
- A microprocessor that processes the SmartClock algorithms and controls the oscillator frequency, should the reference source become unavailable.

SmartClock algorithms learn an oscillator's behavior. The resulting timing system provides long-term clock accuracy dependent primarily on the reference used.

Correcting and Adjusting for Instabilities

SmartClock algorithms, used with an external reference source, compensate for both aging and temperature-induced frequency changes. In the case of aging, for example, a quartz oscillator changes frequency at an approximately predictable rate, and the resultant deviation over time can be determined.

Random noise also must be considered. SmartClock monitors the frequency control variable of the internal oscillator while it is locked to the external reference. This gives a measure of the frequency difference between the internal oscillator, if it is free-running, and the external reference over time. The resulting measurements include the effects of random noise in the oscillator, the measurement circuitry, and any noise in the external reference as well as any aging and environmental effects in the oscillator. From this information, SmartClock makes a continuous prediction of clock error over time if the external reference becomes inoperative. SmartClock actually "learns" the basic behavior of the oscillator.

SmartClock Implementation

Currently, SmartClock is implemented in two ways—steered and unsteered.

In steered implementations of SmartClock (Figure 1), the frequency of a quartz or rubidium oscillator is compared to that of the reference signal. An error signal is sent to the microprocessor which, in turn, adjusts the frequency of the oscillator. The SmartClock also learns the behavior of the oscillator over both time and temperature. This information is then used to steer (or adjust) the oscillator intelligently during holdover mode when an external reference source is not available.

In the unsteered version of SmartClock (see Figure 2), the frequency translator is implemented in the form of a synthesizer using a quartz oscillator as its timebase. A continuous measurement is made between the external reference and an appropriate signal from the oscillator. When the software knows the measured difference, an appropriate command can be sent to the Frequency Translator.

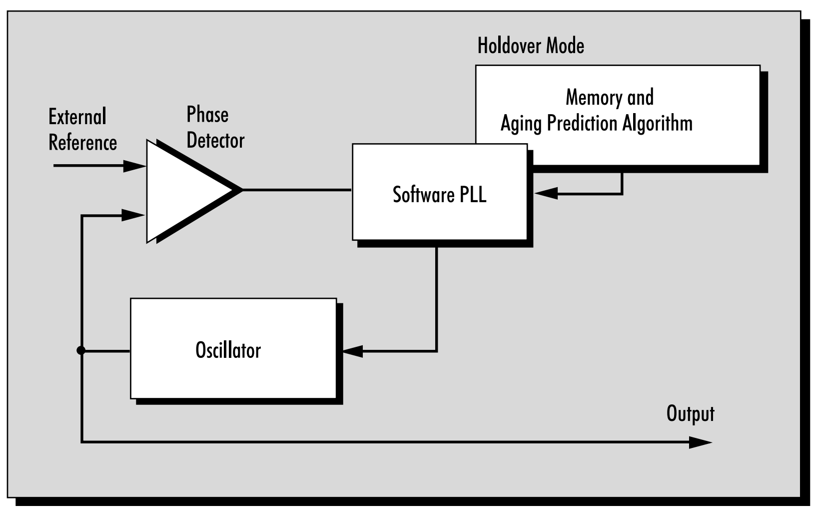


Figure 1. SmartClock Technology includes algorithms for steering the oscillator. The frequency is corrected to compensate for the effects of aging and temperature.

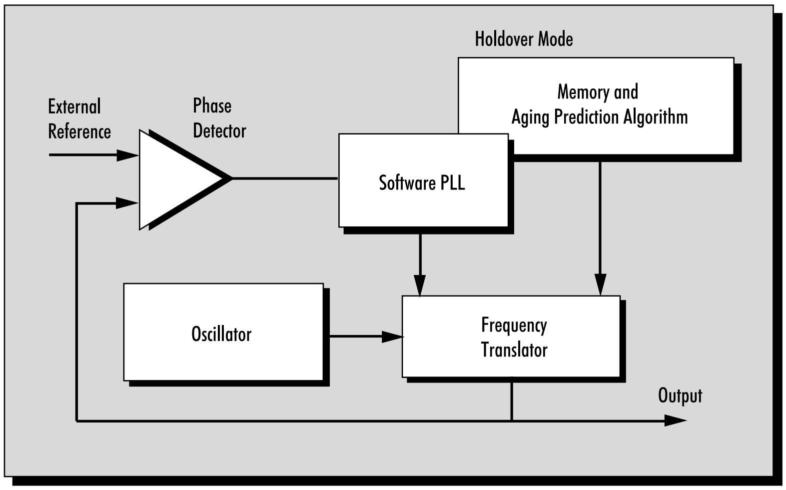


Figure 2. In this unsteered version of SmartClock, performance is improved by letting the oscillator free run and adjusting the output frequency of a high-resolution synthesizer.

Enhanced GPS

The Global Positioning System (GPS) provides a highly reliable reference source for SmartClock. With 24 satellites, each completing two earth orbits per day, the GPS worldwide satellite system provides positioning and timing capabilities for both military and civilian applications. Developed by the U.S. Department of Defense, the GPS system is subject to Selective Availability (SA). SA is the Department of Defense's deliberate degradation of the GPS broadcast signal in order to deny high accuracy position information for short times to unauthorized users.

In timing receivers however, the effects of SA can be significantly reduced. Observations of the spectral characteristics of SA show that it has a time error peak at about 400 seconds.[1] Thus, any filter that attempts to reduce SA must have time constants that are significantly longer than 400 seconds. Enhanced GPS is a SmartClock digital filtering technique that exploits the observed correlation characteristics. When properly designed and matched to an internal frequency reference source, a filter can greatly reduce the effects of SA. The standard specification for the time output of a 4-satellite GPS position solution, with SA on, is 170 nanoseconds rms (340 nanoseconds at the 95 percent level). For a multi-channel GPS timing receiver at a fixed position, this rms deviation can be reduced to about 16 nanoseconds using a high precision quartz oscillator as a flywheel and SmartClock techniques. With atomic standards such as rubidium or the HP 5071A Primary Frequency Standard as a reference, the rms deviation can be further reduced.

Experimental results with timing receivers typically show a deviation of 16 nanoseconds rms, a tenfold reduction in the effect of SA [2]. Figure 3 shows the effect of SA. The data shows the time instability of the GPS signal after averaging with a 6-channel receiver in position-hold mode. Figure 4 shows the results of using the SA filter to reduce the effect of SA. In this case, the SA filtered data shows a 13.7 nanosecond rms scatter. Mean value and slope have been removed from Figures 3 and 4. Similar filtered data as measured by the USNO is shown in Figure 7.

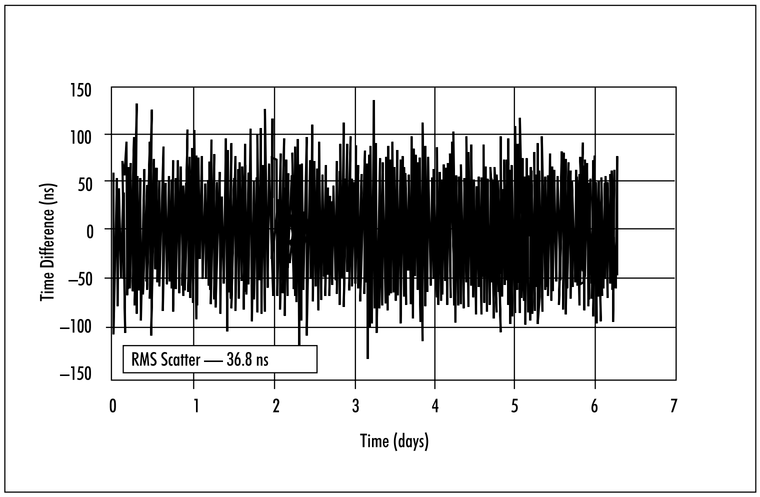


Figure 3. Raw timing data taken from a 58503B Time and Frequency Reference Receiver with the SmartClock filter disabled. The plot shows measurements of the time difference between the 1-pps output from the 6-channel GPS engine and that from an HP 5071A Primary Frequency Standard versus time. The measurements were taken over a period of six days.

The key is that the spectral characteristics of SA and the time-domain stability characteristics of the oscillator used must be matched through the types of filters and the time constants used in the various control loops. Each oscillator type requires a unique filter technique to optimize the reduction of SA effects.

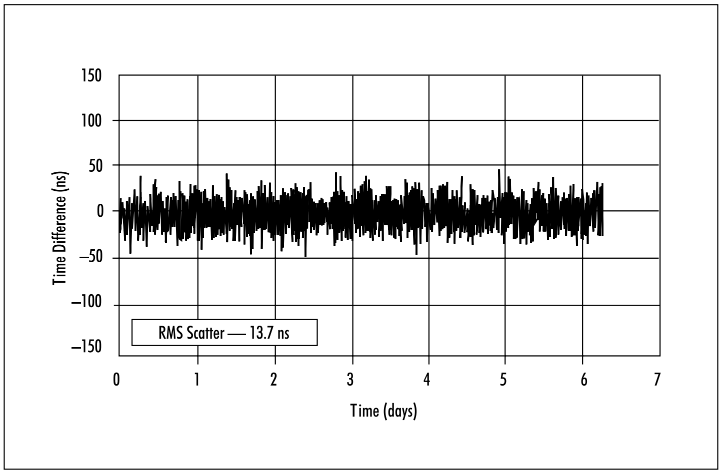


Figure 4. Time interval measurement data taken by measuring the 1-pps output of the 58530B Time and Frequency Reference Receiver against the HP 5071A Primary Frequency Standard showing the effect of the SmartClock filter reducing overall scatter to less than 16 nanoseconds rms.

Enhanced RAIM

Receiver Autonomous Integrity Monitoring (RAIM) is a series of algorithms that continuously checks each satellite against all others under observation. RAIM can take many forms. The GPS engine used in Symmetricom timing modules has its own version, T-RAIM, or Time-RAIM. In addition to T-RAIM, Symmetricom timing receivers have an extra layer of RAIM. This algorithm checks timing information received from the GPS engine against internal timing derived from the unit's own precision oscillator. Algorithms also monitor the overall health of the timing module, its timing signal, and the signals received from the GPS engine to determine when the extra layer of RAIM needs to be implemented to preserve the overall timing accuracy.

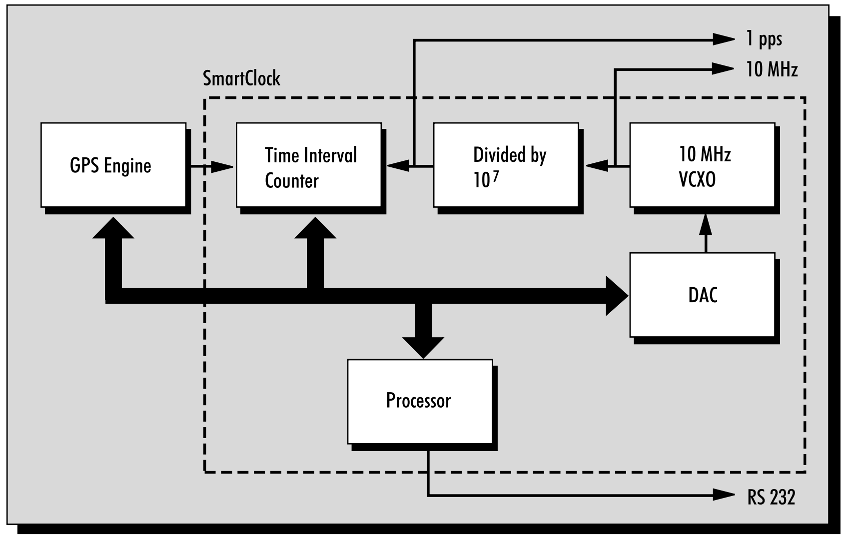


Figure 5. Block diagram for the 58503B Time and Frequency Reference Receiver.

Enhanced Learning

During normal operation, the internal precision oscillator, usually a quartz oscillator, is phase-locked to the GPS signal by comparing the time difference between the 1-pps (pulse-per-second) signal from the GPS engine to a similar signal derived from the internal oscillator. A block diagram is shown in Figure 5. While locked to the GPS system, SmartClock employs enhanced learning to measure the aging and temperature response of the internal oscillator. Over a period of time, changes in the oscillator frequency caused by aging and temperature changes are accurately measured using the reference signal from the GPS engine as filtered by the enhanced GPS algorithm. Changes caused by humidity or pressure can be minimized by using a hermetically sealed oscillator.

Long-term changes, those occurring over a period of many hours, are related to the aging of the internal oscillator. Frequency changes also occur as a function of temperature, which is measured by the hardware. These are measured and stored in internal memory. Data related to the aging of the oscillator is stored in RAM and are redetermined each time the receiver is turned on. Constants related to temperature performance are stored on EPROM, since temperature performance does not substantially change during periods when the oscillator is not powered.

Normal Operation

Normal operation of the Symmetricom timing modules begins by tracking four or more GPS satellites to determine the geographic position of the antenna accurately. Initially, the timing module uses a short time constant to control the oscillator, thus providing rapid time setting of the module. Following a series of checks of the overall operation of the module, the time constant incrementally increases to its final value. This usually takes from 2 to 18 hours. At this point, the timing module is fully functional and should meet all of its specifications, excluding holdover.

While locked to GPS, SmartClock technology in the timing module starts learning the characteristics of the internal precision oscillator. The learning algorithm requires two full days of data to ensure that an adequate determination of the aging can be made. Learning continues as long as the unit is powered and locked to GPS. Data from the most recent 48 hours is stored in RAM. Older data is discarded.

The module shares the long-term stability of GPS when locked. Short-term, the timing module stability is directly determined by the short-term stability of the oscillator used. For averaging times greater than 24 hours (86,400 seconds), the frequency accuracy is better than 1×10^{-12}. A typical stability curve is shown in Figure 6.

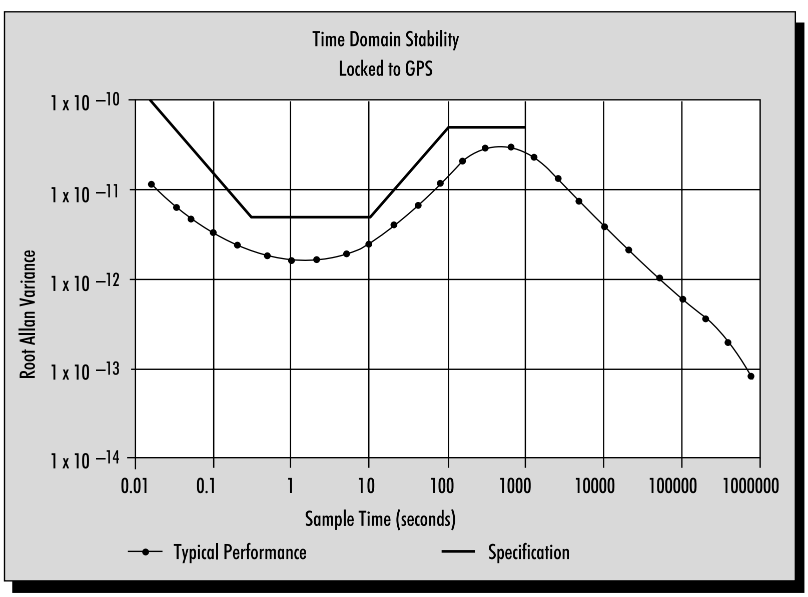


Figure 6. Root Allan Variance of the SA filtered time difference data measured by a 58503B GPS Time and Frequency Reference Receiver.

Table 1. GPS Timing Errors

Cause	Magnitude of Error
GPS System (with SA)	340 ns (at 95%)
Propagation	
Ionosphere	up to 40 ns
Troposphere	up to 20 ns
Solar Flares	40 ns to system inoperative, dependent on severity
User	
Receiver	<20 ns
Horizontal Position Errors	negligible if self-survey is used
Vertical Position Errors	3 ns per meter of altitude error
Antenna Cable	up to 3 ns per meter of antenna cable length measurement error
Multipath	up to 50 ns
Environmental	up to 15 ns

Timing accuracy is directly affected by the errors discussed previously. Assuming that all of the user-controlled errors (Table 1) are negligible, SmartClock timing modules with quartz oscillators achieve timing accuracies better than 110 nanoseconds at the 95 percent level. As an example of this, Figure 7 shows data taken from a 59551A GPS Synchronization Module by the United States Naval Observatory. This data was acquired using a direct measurement between the USNO master clock and the 1-pps output of the 59551A. The peak-to-peak deviation is 100 nanoseconds. The average offset is 20 nanoseconds. The offset is the result of a 10-ns GPS engine time bias used at the time and a known offset of GPS from the USNO master clock of another 10 nanoseconds.

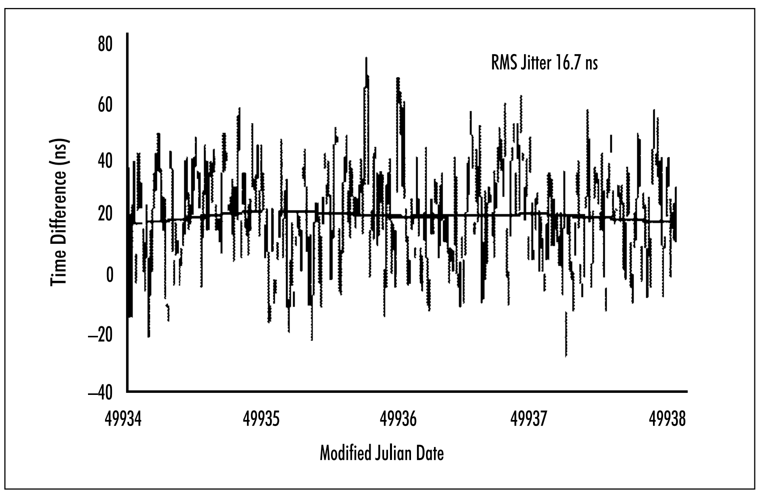


Figure 7. Direct measurement of the 1-pps output of the 59551A GPS Synchronization Module against the USNO master clock. The smooth line is a daily fit.

The timing module easily met its timing specification of ±110 nanoseconds over this period. Data shows that, compared to the USNO master clock, the timing module was less than ±70 nanoseconds, with an rms jitter of 16.7 nanoseconds. The maximum deviation of the 1-pps signal was less than 6 nanoseconds over any one-minute period. The standard deviation was less than 1.8 nanoseconds over any one-minute period.

As determined from the 1-pps data, the 24-hour average frequency offset was 4.6×10^{-13}.

Holdover Operation

Occasionally, the reference signal is not available. If the reference is a telecom signal (E1 or T1), the signal may be lost for various reasons, such as lightning, physical damage, urban canyon and local jammers. In the case where GPS is the reference, the antenna may become unusable because of weather, broken or damaged cable, or other causes, or the receiver may temporarily lose track of the satellites. The satellite system may receive a bad data upload, malfunction or otherwise be unavailable. Whatever the cause, during loss of the reference, accurate timing signals must still be generated and used to control customer equipment.

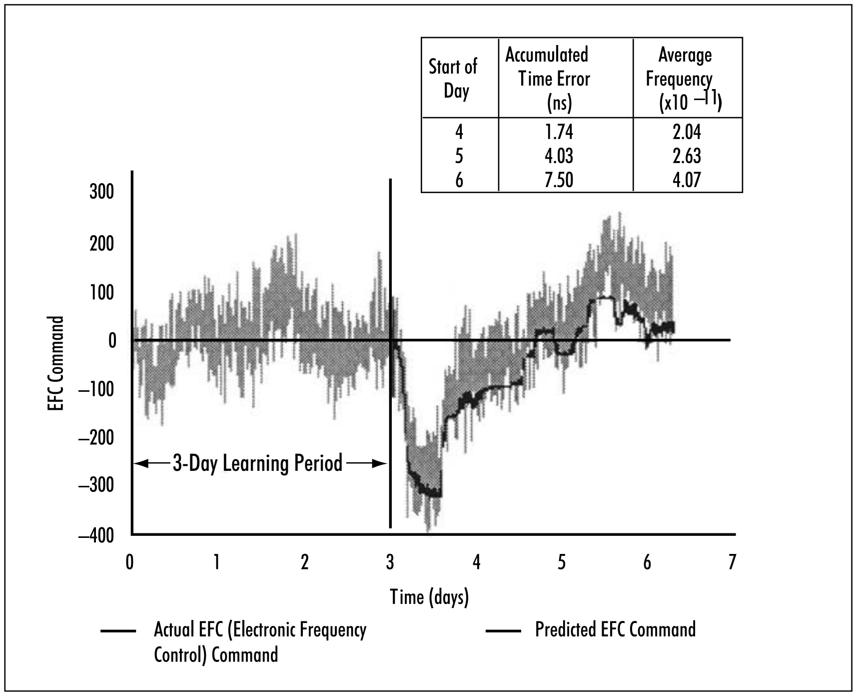
During the loss of the reference, Symmetricom SmartClock uses information learned previously about the oscillator to control the oscillator and attempts to maintain all timing outputs at essentially the same level of precision as that obtained while locked to the reference. This form of operation is called holdover.

A control loop tracks temperature changes in the module and computes the corrections for the oscillator to remove temperature effects. Another loop tracks elapsed time and compensates for any aging effects. Other loops continue to monitor the GPS engine to determine whether normal operation can be resumed.

Typical specification requires that the module maintain frequency accuracy to better than 1×10^{-10} during holdover and accumulate timing errors no greater than 8.6 microseconds for the first day of holdover, after three days of learning time. Actual performance is highly dependent on the overall length of learning time available before holdover. The longer the learning period, and the more stable the oscillator, the more accurate the prediction.

Figure 8 illustrates the effects described above. Here, the value plotted in light gray is the electronic frequency control signal that steers the oscillator.

This unit had previously been operating for several weeks. At the start of this test, the memory was cleared of previously learned data, then the oscillator relearning was started. At the end of day 3, all of the learned data, including the predicted future performance of the unit, was retrieved.



Start of Day	Accumulated Time Error (ns)	Average Frequency ($x10^{-11}$)
4	1.74	2.04
5	4.03	2.63
6	7.50	4.07

Figure 8. Example of holdover showing environmental effects.

During the next three days, actual operation (the light gray curve) was compared to the predicted operation (the dark curve). This is the most accurate way of determining the quality of the prediction in all circumstances. Another way would have been to disconnect the antenna and observe the results. However, it becomes difficult to determine the cause of any unexpected time or frequency error. The data shown in Figure 8 is a more accurate second-to-second picture of overall performance.

Comparing actual to predicted performance allows an easy determination of both the expected frequency offset and accumulated timing errors. The assumption is that both were perfect at the start of the comparison.

The data shows a diurnal variation caused by changing temperature. The unit was operated in a normal room environment. During the night, the room's climate control was turned off, causing a decrease in room temperature. The large dip in the curve at the start of the experiment marks the start of a weekend, when a much larger temperature change was seen.

Computed values show that at the end of day 4, the first day in simulated holdover, the frequency error was 2.04×10^{-11} and the accumulated time error was 1.74 microseconds. At the end of day 6, the third day in simulated holdover, the frequency change was 4.07×10^{-11} and the time error was 7.5 microseconds.

Symmetricom SmartClock System Benefits

SmartClock allows selection of the oscillator and reference source most appropriate for the application. During normal operation, system accuracy is determined by the accuracy of the external reference. A SmartClock-based system, using a rubidium or high-quality quartz oscillator combined with an external GPS reference, achieves near-cesium performance over the long term.

Symmetricom SmartClock eliminates the need for frequent calibrations. Its learning capabilities and the GPS reference source automatically ensure ongoing accuracy. This accuracy complements the field-proven reliability of the Symmetricom quartz-based oscillators that can claim a Mean Time Between Failures (MTBF) of more than 500,000 hours. Rubidium and cesium standards offer moderate reliability with 50K-150K hours, and 120K-150K hours MTBF, respectively.

The extremely high performance and low cost of Symmetricom SmartClock units facilitates implementation of advanced synchronization systems. It can provide the precise frequency reference needed for wireless communications systems. For new digital communications systems like CDMA and Flex Pagers, it also can provide time synchronization. Applications in digital telecommunications include providing accurate synchronization signals for equipment and networks at international gateways as well as tandem, long distance, and local offices. It provides the precise timing required for power system applications that include traveling wave fault location, sequence of events reconstruction, adaptive relaying, phasor measurement, and stability control, and it can be used as a reference in a standards lab.

As technology advances and competition increases in each of these areas, a cost-effective timing solution is critical to an installation’s success.

III. Appendix A: Basic Clock Equation

What will be covered is the basic theory of the causes of time errors by an uncorrected oscillator. First the effects of aging or drift rate will be examined, then the environmental effects. This will give the basic clock equation for time errors.

Derivation of the Clock Equation

In a simplified form, the frequency of an oscillator at any time t can be expressed as:

$$f_t = f_0 + f_r \int_0^t a(t')\,dt' \qquad \text{Equation 1}$$

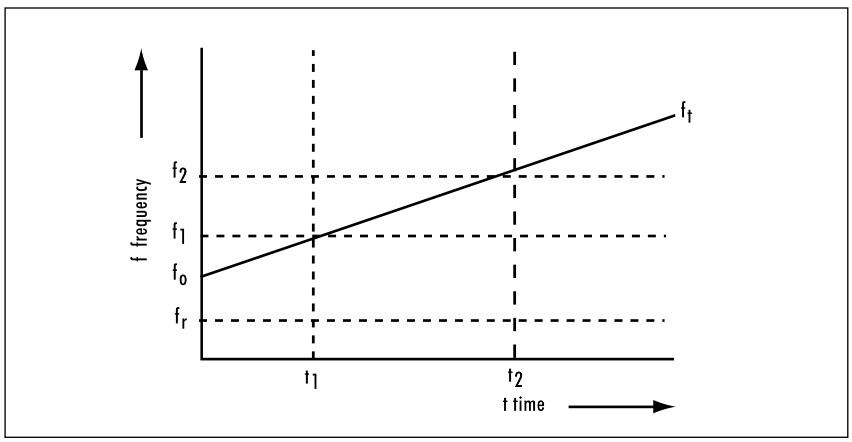


Figure A1. Oscillator Frequency vs. Time.

where: f_t = frequency at time t
f_0 = initial frequency at time t=0
f_r = reference frequency
(f_t and f_0 are assumed to be about the same as f_r)

and a(t) is the aging rate of the oscillator expressed as a function of time.

Aging rate or drift rate is the fractional rate of change of frequency per unit of time. Conventionally, we express the frequency of an oscillator in terms of its fractional frequency. Fractional frequency is defined as:

$$\frac{\Delta f}{f_r} = \frac{f_2 - f_1}{f_r}$$

where: $f_t = f_1$ at time = t_2
$f_t = f_2$ at time t_2

Customarily we define the fractional frequency by the letter y. By subtracting the reference frequency from each side of Equation 1 and rearranging, we have:

$$y = y_0 + \int_0^t a(t')dt' \quad \text{Equation 2}$$

The term y_0 is called the syntonization (or initial frequency) error. For quartz oscillators, the aging rate is normally stated in terms of a daily fractional frequency deviation. As a well-aged quartz oscillator has a nearly constant aging rate per day, we usually express the daily aging rate as if it were constant; e.g., $\pm 5 \times 10^{-10}$ per day.

Any oscillator over a period of time will exhibit a change in its frequency, y. A clock based on this oscillator will gain or lose time because each oscillator cycle is a little short or long. We can determine the change in time, or the time error by integrating frequency.

$$x = \int_0^t y(t)dt + x_0 \quad \text{Equation 3}$$

or:

$$x = x_0 + y_0 t + \int_0^t dt' \int_0^{t'} a(t'')dt'' \quad \text{Equation 4}$$

where: x is the time error in seconds

and x_0 is the initial time error, also known as the synchronization error

In the case where the oscillator aging rate is constant, Equation 4 becomes:

$$x = x_0 + y_0 t + \frac{1}{2}at^2 \quad \text{Equation 5}$$

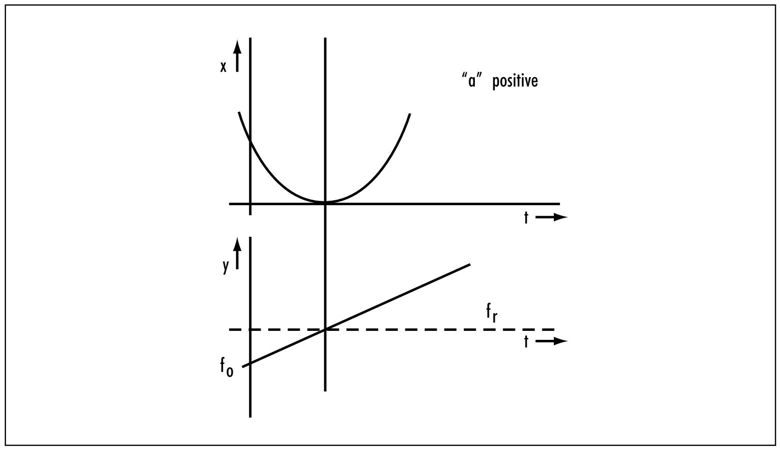


Figure A2. Positive Frequency Drift

Time Error versus Frequency

Equation 5 indicates that the accumulated time error over any time t depends upon the values of four quantities; (1) initial time error x_0, (2) initial frequency error y_0, (3) aging rate usually assumed to be constant, and (4) elapsed time.

A plot of Equation 5 as a function of time is a parabola for which the vertical displacement depends on the value of x_0, Figure A2. The corresponding frequency plot is shown beneath the time error plot. Note that the oscillator frequency is precisely equal to the reference frequency at the point corresponding to the vertex of the error curve.

If the frequency drift or aging were negative, the parabola would be inverted (Figure A3).

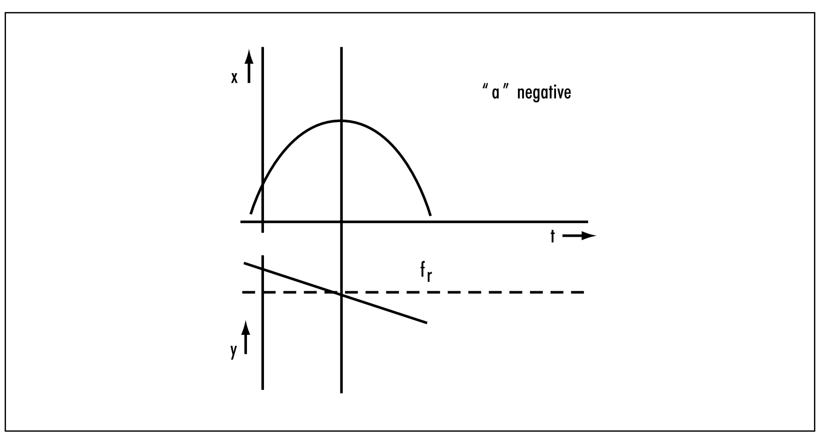


Figure A3. Negative Frequency Drift

Figure A4 shows corresponding plots of frequency and time errors to clarify their relationship.

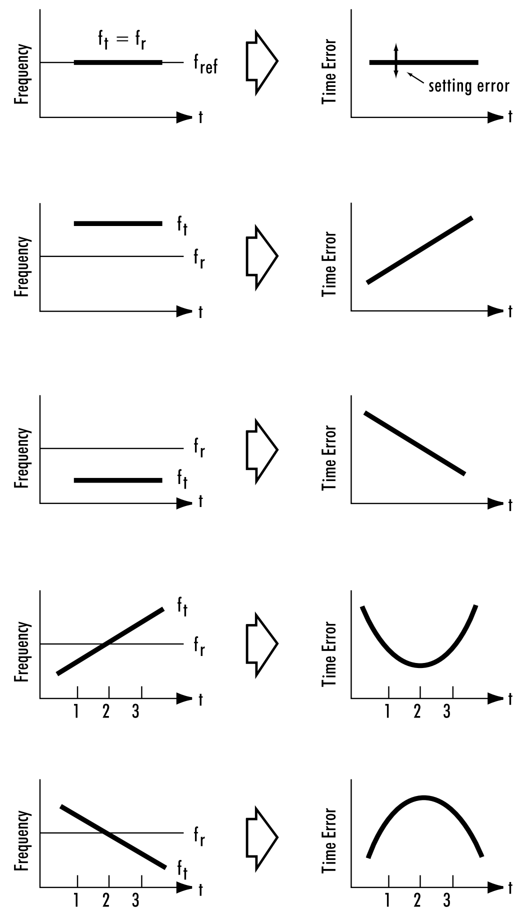


Figure A4. Frequency offsets and resulting time errors.

Example

As a specific problem, consider a GPS-based time system that needs to maintain ±10 μs for 24 hours in the absence of the GPS reference signal (usually called the holdover or flywheel mode). Although the GPS satellite system itself is very robust, the GPS antenna could be damaged or disconnected. This would cause the loss of the GPS signal. Assume that this occurred at time t = 0.

Assume the quartz reference oscillator in the time system has an uncorrected, constant aging rate of $+1 \times 10^{-10}$ per day. Since the time system was locked to GPS immediately before t = 0, we will assume that the following are true:

1. $y_0 = 0$
2. $x_0 = 0$

The accumulated time error Equation 5 becomes:

$$x_a = 0 + 0 + \frac{1}{2}\left(\frac{1 \times 10^{-10}}{\text{day}}\right) \times (1\text{day})^2 \times \left(\frac{86,400s}{\text{day}}\right)$$

or

$$x_a = 4.32\ \mu\text{s, well within the 10 }\mu\text{s specified.}$$

Time Error Resulting from Environmental Effects and Noise

So far the clock equation has been based upon perfect conditions. However, environmental conditions are usually a major cause of timing error in precise timekeeping applications. In addition, there is a statistical uncertainty associated with the time domain stability of the oscillator and with system and measurement noise.

For environmental conditions, we need to consider:

- Effects of temperature changes on frequency (T)
- Effects of pressure changes on frequency (P)
- Effects of humidity (H)
- Effects of magnetic fields (M)
- Effects of gravity (G)
- Cross-coupled interdependent effects.

With all of these conditions, we can write Equation 4 as:

$$x = x_0 + y_0 t + \int_0^t dt' \int_0^{t'} a(t'')dt'' + \int_0^t \mathrm{E}(\mathrm{T, P, M, H, G})dt' + \varepsilon(t)$$

Equation 6

where ε(t) is the time uncertainty in the reference signal and the measurement process, and E (T, P,...) is the fractional frequency change caused by the time-dependent environmental effects.

When locked to GPS, the time uncertainty component of ε(t) over one day amounts to about 50 ns. Over the same period, the noise component of ε(t) can be assumed to be stochastic and therefore average out over the period.

Many of the environmental effects can be minimized by the design of the oscillator and its careful placement in the operating environment. Pressure and humidity effects can be virtually eliminated by sealing the oscillator. Most of the remaining effects can be minimized by oscillator placement. The one component not so easily controlled is temperature.

Example

Looking again at our GPS-based time system in holdover, assume it now experiences a temperature ramp to a new fixed temperature over a 24-hour period. The temperature profile is shown below (Figure A5). For simplicity, we will assume to first order that the coefficient of frequency versus temperature is independent of time and ambient temperature (i.e., the temperature coefficient is linear). We will also assume that aging is negligible.

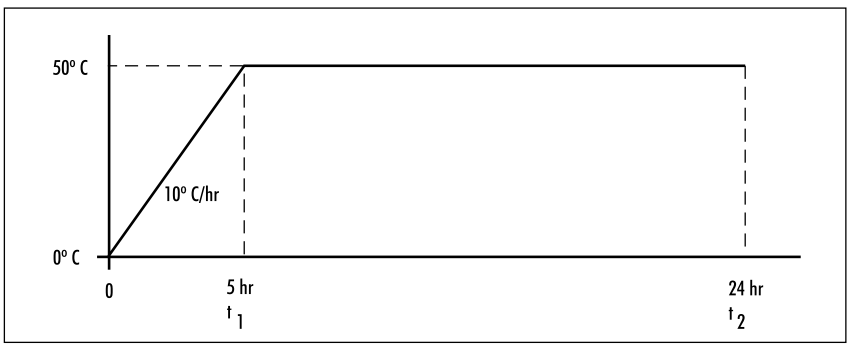


Figure A5. Temperature Profile

Let t_1 = 5 hours (18,000 seconds)
t_2 = 24 hours (86,400 seconds)
R_t = temperature ramp of 10°C per hour
T_0 = start temperature of 0°C
T_2 = final temperature of 50°C
$T_f^{(1)}$ = first order frequency-temperature coefficient of 1×10^{-12}/°C.

Again, assume that immediately prior to the start of holdover, the system was locked to GPS so that any initial time errors are zero.

The problem will be broken down into two parts, the temperature ramp and the fixed temperature offset.

For the temperature ramp:

$$x_t = \int_0^{t_1} T_f^{(1)} R_t t dt$$

$$x_t = T_f^{(1)} R_t \frac{t^2}{2}\bigg|_0^{t_1}$$

or:

$$x_t = \frac{(x10^{-12}/°\mathrm{C})(10°\mathrm{C/hr})(5\mathrm{hrs})^2(3{,}600\mathrm{s/hr})}{2}$$

$$x_t = 0.45\ \mu\mathrm{s}$$

For the constant temperature region from t_1 through t_2:

$$x_t = \int_{t_1}^{t_2} T_f^{(1)} T_2 t dt$$

$$x_t = T_f^{(1)} T_2 \times (t_2 - t_1)$$

$$x_t = (1 \times 10^{-12}/°\mathrm{C})(50°\mathrm{C})(19\mathrm{hrs})(3{,}600\mathrm{s/hr})$$

$$x_t = 3.42\ \mu\mathrm{s}$$

After 24 hours, the total time error due to temperature changes is 3.87 µs.

Now including aging from the first example, the total time error (worst case) is:

$$x = x_a + x_t$$

$$x = 4.32\ \mu\mathrm{s} + 3.87\ \mu\mathrm{s}$$

$$x = 8.19\ \mu\mathrm{s}$$

Therefore, this timing system would have maintained the ±10 µs requirement for 24 hours with loss of lock to GPS and with the given temperature profile.

IV. Appendix B: Applications and Products

Digital transport networks are being pushed to the limits with new technology such as SONET/SDH. Service providers, anticipating increased performance, new standards, and a vastly expanding user base, realize that network synchronization will be vital for competitiveness. The traditional timing synchronization approach—applying piecemeal solutions to problems—is being replaced with well-planned network-wide synchronization strategies.

With increased accuracy requirements, better synchronization solutions are required at more and more locations in each network. Networks are "flattening" their synchronization hierarchies by using higher performance clocks at regional and even local sites.

The arenas of power generation, transmission, and distribution are also becoming increasingly competitive. Deregulation, expanding consumer requirements, and environmental restrictions are placing unprecedented demands on supplying companies and utilities. Complete and synchronized data analysis is critical for suppliers to increase power capacity, quality, and services reliably. Synchronization products provide a foundation for real-time monitoring and control applications, and detailed network disturbance analysis.

All of the Symmetricom timing products offer a common set of benefits, including:

- Compliance to industry standards
- Shelf modularity
- High reliability and redundancy
- Excellent short-term stability
- GPS compatibility

Symmetricom's Timing and Synchronization Products

Symmetricom provides a range of timing and synchronization products based on our advanced GPS technology and SmartClock. These products include:

- *Primary reference sources.* A primary reference is often referred to as the master clock. Top level synchronization solutions demand the highest accuracy and best long-term stability since they are used to drive multiple lower level synchronization units.

- *Specialized products and full custom solutions.* Symmetricom offers customization services and specialized products such as the 59551A GPS Synchronization Module for synchronizing measurements for power transmission systems.

The compact 58503B Time Frequency Reference Receiver delivers excellent accuracy, easy operation (no periodic adjustments are required), and extremely low cost of ownership.

- *Synchronization units.* These products deliver synchronization signals at specific points within a network or site, or distribute a reference source to multiple points. Since many organizations require large numbers of these units, they must be affordable while maintaining accuracy and stability throughout the synchronization infrastructure.

Metrology and Manufacturing

The 58503B GPS Time and Frequency Reference Receiver, a lightweight compact module, fits comfortably into not only controlled lab environments, but also a variety of general-purpose calibration and manufacturing applications that require precision time or synchronization.

The 58503B source maintains frequency accuracy of better than 1×10^{-12} (measured as a 24-hour average), even in the presence of Selective Availability. This performance, combined with the unit's low cost, makes it an attractive lab alternative compared with more expensive cesium and rubidium solutions. Manufacturing companies are taking advantage of the 58503B. Because of its low cost, it can be located anywhere precision time and frequency are needed, eliminating or simplifying distribution systems and expensive cable runs.

In operation, the 58503B requires no periodic adjustment or calibration. This, along with its greater than 100,000-hour MTBF, provides an extremely low cost of ownership. If the GPS signal is lost, the 58503B automatically goes into its intelligent holdover mode. An RS-232 port and a TTL alarm output (BNC) allow easy performance monitoring. Either of these outputs will enable you to monitor the status of the 58503B automatically.

Synchronizing Wireless Networks

Accurate timing is essential for the evolving digital cellular personal communications systems (PCS) and paging applications. Soft handoffs—passing a CDMA user from one base station to another—require accurate synchronization. The 58503B general purpose reference source can deliver accurate and stable synchronization signals for both analog and digital base stations.

Today, many wireless networks also require customized designs for timing and frequency synchronization and distribution. For network equipment manufacturers building volume quantities of wireless communications base stations or other equipment, Symmetricom's customization services can shorten implementation cycles and lower in-house development costs without sacrificing quality and affordability. Other features Symmetricom can bring to the wireless market include:

- Shortened time to market
- Lowered costs
- Improved system and service quality
- Reduced project risk

Custom designs use many of the same technologies incorporated in the 58503B and are tailored to client specifications. A custom design can accommodate the needs of any analog or digital cellular, specialized mobile radio, or personal communication system manufacturer. Clients specify the exact form, fit, and function of the equipment needed for synchronizing base station operation. Custom products are manufactured to Symmetricom's quality standards and are supported worldwide.

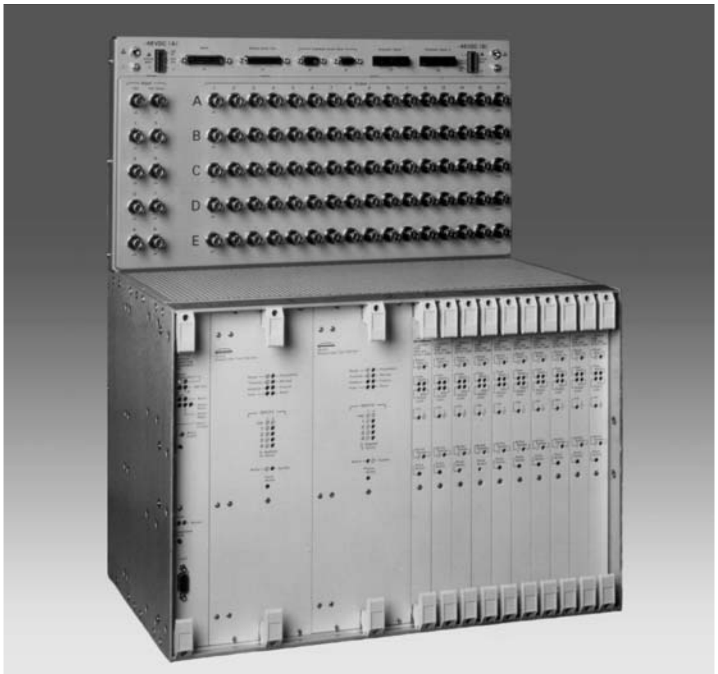
Wide Area Measurement Synchronization

The 59551A GPS Synchronization Module is the first product to provide cost-effective, wide-area synchronization of measurements. It overcomes the limitations of traditional measurement tools and greatly extends applications directed at monitoring and controlling power transmission systems.

The 59551A can be placed at any of the critical points in the power system or any other distributed system. The low unit price ensures that synchronization networks can provide complete field data for analysis.

The resolution and time-tagging features of the 59551A make it ideally suited to applications such as frequency and magnitude measurement, state estimation, stability protection and adaptive relaying. The 59551A also provides key data for newly evolving monitoring applications such as fault recording, disturbance recording, and verification of computer modeling of transmission and generation systems. With the 59551A, planners have access to real-time field data to predict more accurately and control safely the behavior of power systems.

The 59551A GPS Synchronization Module is affordable, can be placed at many points throughout a wide-area power system, and provides essential real-time field data for predicting and controlling power system operation.



The 55400A Network Synchronization Unit lets users configure efficient and cost-effective synchronization distribution solutions for large sites.

Network Synchronization

The quartz-based 55400A Network Synchronization Unit distributes clock signals for telecommunications networks. The rack-mountable unit filters incoming timing references from external clocks or GPS reference modules and outputs timing signals throughout a building or office.

The 55400A incorporates quartz and SmartClock technology to provide features that ensure reliable distribution solutions:

- Online switchable reference sources
- Holdover mode during loss of reference signal
- Hot-pluggable input and output signal cards
- Distribution of multiple output signals

A master subrack and expansion subrack can each accommodate five pairs of output cards. Each card pair provides 16 outputs for a subrack total of 80 protected outputs. This functionality supports the economical distribution of multiple output signals throughout a large facility.

The 55300A GPS Telecom Primary Reference Source is a highly accurate, low-cost source of precision frequencies for telecom networks.

GPS Telecom Primary Reference Source

The 55300A GPS Telecom Primary Reference Source provides highly-reliable, low-cost sources of precision frequencies for telecom digital networks. The 55300A is lightweight, compact, and fits comfortably into controlled lab environments, wireless base stations, and remote or unattended applications.

The 55300A maintains frequency stability of better than 1×10^{-12} (measured as a 24-hour average), even in the presence of Selective Availability. The unit is an excellent solution for flattening existing digital networks and delivering performance that exceeds industry standard requirements for lower-level points on the synchronization hierarchy. The 55300A provides a low-cost reference source that improves network services and provides scalability to synchronization solutions.

V. References

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[2.] J.A. Kusters, et al, “A Globally Efficient Means of Distributing UTC Time and Frequency Through GPS,” *Proceedings of the 26th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, December 1994, pp. 235-254.

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VI. Glossary

Aging Rate — The frequency aging of an oscillator refers to the change in the frequency of oscillation caused by changes in the components of the oscillator, either in the resonant unit or in the accompanying electronics. Aging differs from drift in that it does not include frequency changes due to changes in the environment.

BIPM — Bureau International des Poids et Mesures. The maintenance of International Atomic time (TAI) and of Coordinated Universal Time (UTC) has been the responsibility of BIPM since January 1, 1988. Located in Sevres, France, BIPM provides the coordination and computation of timing and stability data from about 230 atomic clocks kept by 65 laboratories worldwide.

Cesium clock — A primary time reference which uses a fundamental property of the element cesium as a reference to produce a highly accurate and stable time reference.

Epoch — Usually denotes the interval elapsed from an arbitrary origin; this origin is customarily stated in terms of a natural phenomenon common to all observers. Epoch also may denote a particular instant of time.

GPS — The United States Department of Transportation’s Global Positioning System. It features 24 satellites in semipolar orbits using six orbital planes. The satellites broadcast their precise time and position to users whose receivers use this information to determine both accurate time and location.

HF — High Frequency, usually assumed to range from 3 to 30 MHz.

LF — Low Frequency, usually assumed to range from 30 to 300 kHz.

Loran-C — A series of 29 transmitting stations comprising 12 Loran-C chains operating in the 90-100 kHz frequency band. Provides local and long range navigation capabilities and a timing signal. Major user is the Maritime community, with extensive use also in aviation.

NIST — National Institute of Standards and Technology. NIST provides the metrology standards for the United States. NIST is the primary source of frequency accuracy and contributes to atomic time stability as maintained by BIPM.

NRL — Naval Research Laboratories.

Omega — Developed and implemented by the United States Department of the Navy with assistance of the Coast Guard and 6 partner nations. It provides worldwide, all-weather radio navigation capability, operating in the 9-14 kHz band.

Rubidium clock — A time reference which uses a fundamental property of the element rubidium as a reference to stabilize a quartz oscillator. Rubidium clocks are much less stable than cesium clocks as they exhibit a slow frequency drift as well as greater sensitivity to the environment. Because of these instabilities, rubidium clocks must be periodically calibrated.

Synchronize — To set the time or phase of two or more clocks to each other or the same reference value.

Syntonize — To set the frequency of two or more sources to precisely the same value.

USNO — United States Naval Observatory. Both the official time for the U.S. and the time reference for the GPS navigation system are maintained by the USNO. The USNO contributes to the UTC time scale.

USNO MC — This is the designation of the master clock at the USNO. The master clock is an ensemble consisting of 42 Primary Frequency Standards.

UTC — Coordinated Universal Time (Temps Universel Coordonné). The world time scale maintained by the BIPM. UTC is maintained by averaging time data from major timekeeping centers located around the world. The BIPM is also responsible for other basic standards for international commerce.

VLF — Very Low Frequency, usually defined to be less than 30 kHz.

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