"A No-drift and less than 10^{-13} Long-term Stability Quartz Oscillator Using a GPS SA Filter"

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A No-drift and less than 1 x 10^{-13} Long-term Stability Quartz Oscillator Using a GPS SA Filter

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Introduction

Recently the time-domain spectrum of the Global Positioning Satellite (GPS) Selective Availability (SA) modulation has been characterized[1]. The continued growth of GPS, its utility, and the technology to receive and utilize the GPS signals have resulted in stable, multi-channel GPS timing receivers. These are now available from several vendors. Further, the GPS satellite constellation is essentially complete and has been declared operational, at least in its initial phase.

Coupled with the growth in hardware technology and understanding of GPS has been the development of algorithms which provide suitable enhancement to GPS timing signals, increasing their stability and accuracy. Using the above, we have constructed a near optimum SA filter which essentially removes the effects of SA on timing signals. The filter was designed with three aspects in mind:

1. Good performance and reliability obtained even in the presence of occasionally bad data and with restrictions on the GPS satellite viewing angles.
2. Improved performance for both time and frequency outputs by optimally filtering the SA Modulation to best match the stability performance of the internal oscillator.
3. Maximum performance results from minimum design and product cost.

The second and third aspects imply that oscillators other than cesium and/or rubidium should be considered.

The HP10811D/E SC-cut oscillator has been in continuous production for over 15 years, with a total production considerably over 100,000 to date. As we build only one crystal and one oscillator, continued value engineering[2] has resulted in exceptionally high yields and excellent performance, especially in aging and response to environmental conditions. As a result, the oscillator exhibits time-domain stability better than 1 x 10^{-11} well beyond 1000 seconds. This infers that the HP10811 is fully suitable for integration with GPS given that the decorrelation time of GPS has been determined to be about 400 seconds[1].

SA Filters

The SA Filter consists of algorithms implemented in a microprocessor to form a series of digital loops that have the overall effect of minimizing the effect of SA on the timing signals currently available from the GPS system.

To illustrate the effect of the SA Filter, Figure 1 shows typical data obtained by measuring the 1 pulse per second (pps) output of a six-channel GPS timing receiver against a similar pulse from an active ensemble of cesium standards. Actual data were taken each second and 100 consecutive measurements were averaged to produce the data shown. The pulse-to-pulse jitter of the ensemble is less than 100 ps and cannot be a source of the jitter seen in this figure. The slope of the data in Figure 1 represents a frequency difference of 9.4 x 10^{-14}

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between UTC(USNO) via GPS and the cesium ensemble.

Figure 2 shows two plots, the gray plot replicates the data shown in Figure 1 with mean slope removed. The rms deviation of this data is 31 ns, corresponding to the SA noise observed using 100 second averages of the receiver output. Six satellites were almost always available for tracking. The solid line shows the result of applying a filtering algorithm that is optimized for comparing GPS with a high quality cesium standard. The rms of the filter output is 1.7 ns, demonstrating the resolution that can be obtained with this technique for time transfer between cesium standards. The filter design is such that the output can be obtained in real time. This filter provides no improvement for dynamic positioning and assumes the coordinates are fixed and known. The coordinate solution obtained through the SA noise is adequate.

The effect of the filtering algorithm can be seen in Figure 3. The upper line shows the modified Allan Deviation (MDEV) of the time difference data before filtering. For times short compared with 10^5 seconds the noise is dominated by SA, and the slope is about -3/2, indicating a white phase-noise process. The lower line is the MDEV of the filtered data. The amplitude of the noise has been reduced approximately to the noise level expected from a cesium standard. At 2×10^5 seconds, outside the stop-band of the SA filter, the value of MDEV observed is of the same order as the noise typical of the steered GPS clock[3], and slightly larger than the expected noise of the ensemble, 1×10^{-14}.

The SA Filter has another attribute that makes the overall system response far more robust than a single receiver by itself. Because of the reduction in SA noise, coupled with the excellent long-term stability of the 10811 oscillator, the process is able to provide a calibration of the oscillator characteristics. Over a period of time, by tracking the oscillator's time and frequency offsets as well as its frequency drift, the effects of temperature can be discerned if they are repeatable as they are averaged over time. These model elements can be used if the system has to go into holdover mode. This procedure maintains the system with a given degree of synchronization and/or syntonization for a significantly longer period than could be predicted if the oscillator's performance were not so calibrated.

Overall, the combination of good GPS timing receivers, excellent oscillator performance, and the SA Filter algorithms permit performance while locked to GPS approaching that of low-end cesium standards and, while in holdover, to approach that of rubidium standards at a cost comparable to quartz standards.

Experimental Results

During the investigations of the SA Filter concepts, several equipment configurations were used. The difference between all of these was the manner in which the quartz oscillator was controlled. In the experiments, the oscillator was either steered and became the primary source of output, or was unsteered and was used as an internal time-base for a synthesizer.

Unsteered oscillators are more stable. Steered oscillators permit operation with simpler electronics.

Holdover Measurements

A goal of the experiment was to determine how much improvement in the aging of the oscillator was obtained by characterizing its model elements. To standardize on the method, and to continue collecting data during 'holdover,' we chose to post-process the data and predict holdover performance and compare to actual performance. As a follow-on to the data shown here, actual holdover performance is now being measured and validates our analytic method.

Unsteered Oscillators

Figure 4 is the generic block diagram of an unsteered oscillator system. The Frequency Translator may be implemented in many ways, most commonly some form of synthesizer using the quartz oscillator as its timebase. An essentially continuous measurement is made between the external reference and an appropriate signal from the oscillator. As the software knows what difference was measured, an appropriately compensated command can be sent to the Frequency Translator. Over a period of time, in comparison with the external reference, the SA filter provides the opportunity to characterize the oscillator's instability characteristics.

Figure 5 shows the results of the oscillator offset measured as described above. The oscillator had been in storage for several months before the start, and was used as we received it, with no pre-aging or syntonization. The slope seen in Figure 5 is mostly due to a frequency error of about 1.1 Hz. Frequency as computed from the phase data is shown in Figure 6. Immediately apparent is a large aging rate for the first few days. The gray plot in Figure 6 is the computed frequency showing the effects of SA noise. The solid line was obtained by processing the original data through an SA Filter

When the filtered data is examined to determine aging rates, the curve shown in Figure 7 results. A 12 hour moving window was used on the filtered data to produce this curve. The 12 hour window has the effect of enhancing any diurnal effects. A rather strong temperature dependent effect is seen.

To examine holdover response, filtered data from days 4 and 5 were used to characterize the oscillator aging. The filtered phase data was fit to a nearly parsimonious model (a linear term plus a log term). The data string used consisted of 10 points essentially uniformly distributed over the 24 hours. The holdover results are shown in Figure 8. In spite of strong temperature effects, the overall apparent aging was reduced by a factor of 20 or more when the data was taken during day 4. When the data was taken during day 5, the improvement was greater than 30. As the oscillator aged into specification, the performance continued to improve.

Steered Oscillators

Figure 9 shows the generic block diagram of a system employing a steered oscillator. The steering method and hardware were adapted directly from the HP5071A Cesium Standard. The actual steering command is a digital word passed through D/A converters and appropriate filters before steering the oscillator. The resolution of the numerical equivalent of the steering command is about 1×10^{-11} per steering unit. A plot of the steering commands is shown in Figure 10. A new steering command is computed by the system every 10 seconds. This plot also shows a non-optimal, non-parsimonious, prediction of future performance. This was obtained by doing a 2nd order regression to the data in the 24 hour period shown on the Figure as the "Characterization Period."

Again, holdover performance was determined from the difference between actual and predicted. The expected synchronization and syntonization errors are shown in the table in Figure 10. Of note is that this oscillator performed better than the oscillator used in the unsteered experiment above, and the temperature effects were dynamically compensated through a temperature sensor, with time lag and temperature coefficient factors learned in a prior experiment.

Unsteered oscillators are more stable and predictable than continuously steered oscillators. During the several experiments, we noted that while the very-long-term aging of steered and unsteered oscillators are essentially identical, the day-to-day results are considerably different. Usually unsteered oscillators show continuous monotonic aging without any unexpected results. Steered oscillators were anything but monotonic, tending to change sign of the aging every few days.

Although unsteered oscillators are more predictable, and hence have improved holdover, predictions made on the basis of steering commands produce acceptable performance, showing deviations in frequency less than 1×10^{-10} and time deviations on the order of 1-2 microseconds for periods up to 3 days after the oscillator has been characterized.

Figure 11 is a plot of the MDEV of a GPS Steered oscillator determined under two conditions. The first used the 1 pps from the system measured against the cesium ensemble with a time-interval counter. The system used is the HP5071A cesium long-term stability production measurement system. The second measured the 10 MHz output against an offset 10811 oscillator in a conventional heterodyne short-term stability system. The two measurement systems were set up to take data concurrently. A key point on the 1 pps measurement is the measurement noise seen from 1 second through 100 seconds. This is a consequence of the 1 pps circuitry that has a pulse-to-pulse jitter of about 30-40 ps, and a time-interval counter with a minimum resolution of the same order of magnitude. Hence the actual stability is represented by the bottom curve through sampling times of 10 seconds, and the upper curve for times beyond 200 seconds.

The overall curve illustrates several points. Even though steering commands are issued every 10 seconds, the digital noise is well below the output time-domain stability. The long-term stability at time samples greater than 10,000 seconds approaches that of cesium. The intermediate stability, although always below 1×10^{-11}, shows the effects of oscillator characteristics, and of the various control loops and their time constants.

Given the usually unknown condition of the oscillator, GPS receiver, and the various time delays in the SA Filter and control loops, the start-up time to full lock and tracking to GPS with GPS steered oscillators takes about 8 hours. This is shown in Figure 12. After 8 hours, the system is synchronized to within 100 ns, and the average frequency offset magnitude over the next 16 hours was less than 5×10^{-13}.

Summary

The data presented above indicate that it is possible to obtain near cesium performance in the long-term from an appropriate quartz oscillator when combined with current GPS timing receivers and a near optimal SA Filter algorithm. Further, the data shown verify that both steered and unsteered quartz oscillators give adequate performance.

References

[1] Allan, D.W. & Dewey, W.P., *Time-Domain Spectrum of GPS SA,* presented at the 1993 ION GPS-93 Conference.

[2] Kusters, J.A. & Adams, C.A., *Applications of Total Process Control Techniques in the Production of High Precision Quartz Resonators*, Proc. 39th Annual Symposium on Frequency Control, pg. 475 ff, 1985.

[3] Buisson J.A., private communication

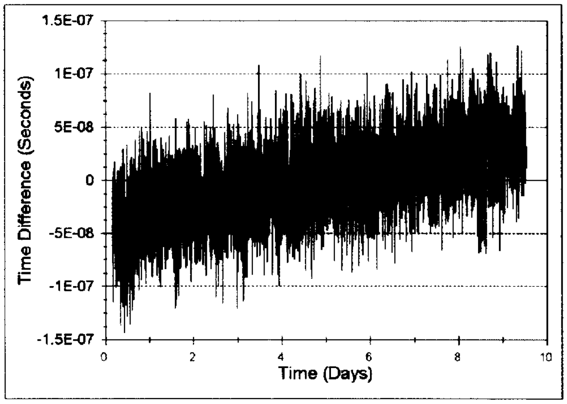

Figure 1 -- GPS Receiver vs. 5071A Cesium Ensemble 100 second averages of 1 pps data

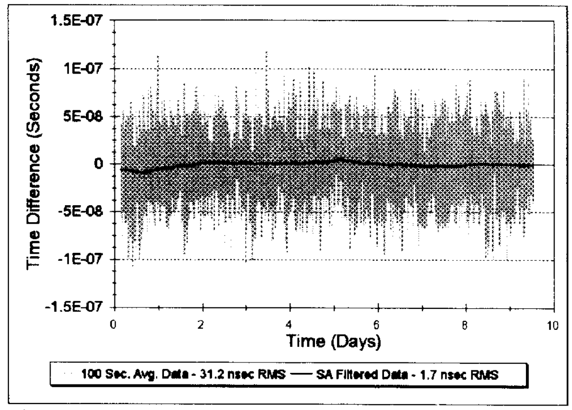

Figure 2 -- Shadow plot - raw data of Figure 1 with 9.4 x 10^{-14} offset removed. Solid line, results of applying SA filter to raw data

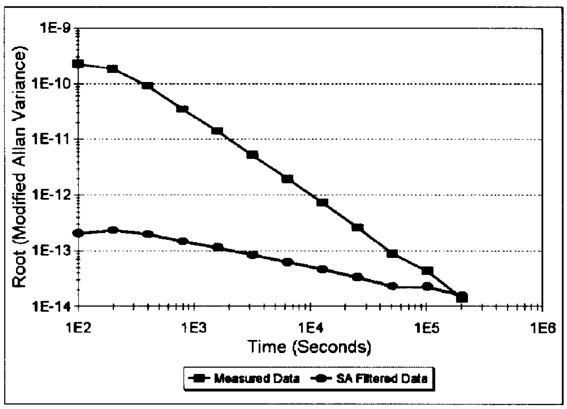

Figure 3 -- Allan Variance analysis of data presented in Figure 2.

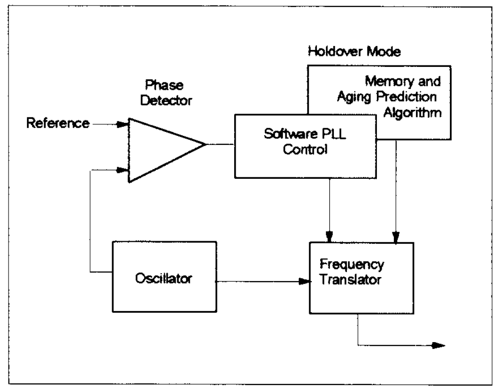

Figure 4 -- Block diagram, unsteered oscillator system

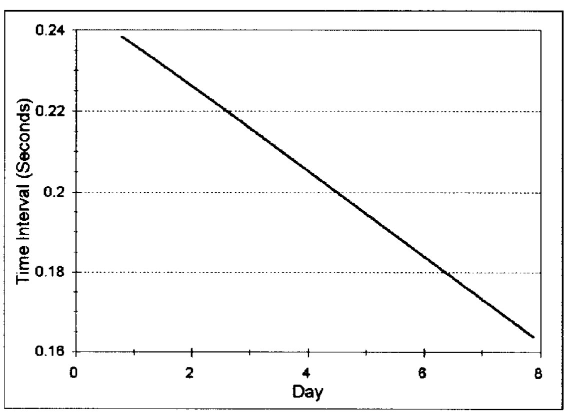

Figure 5 -- Phase measurement of unsteered oscillator vs. GPS receiver - 100 sec averages of 1 pps data.

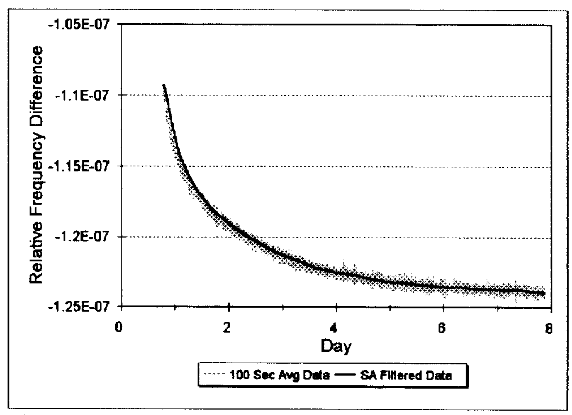

Figure 6 -- Frequency data - Figure 5. Shadowed data shows effects of SA. Solid line - results of applying SA filter to original data

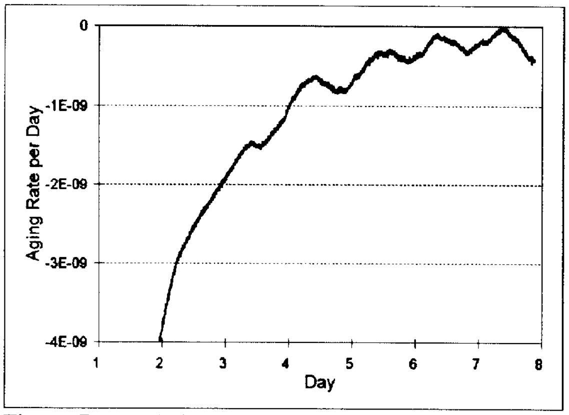

Figure 7 -- Aging curve - Oscillator from Figure 5. Curve derived from SA Filtered data with a 12 hour moving window to emphasize diurnal effects.

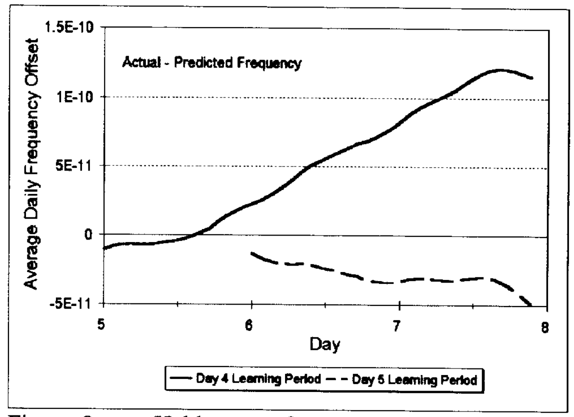

Figure 8 -- Holdover performance - Curve computed from SA Filtered data fit. Characterization period was 24 hours to reduce diurnal effects.

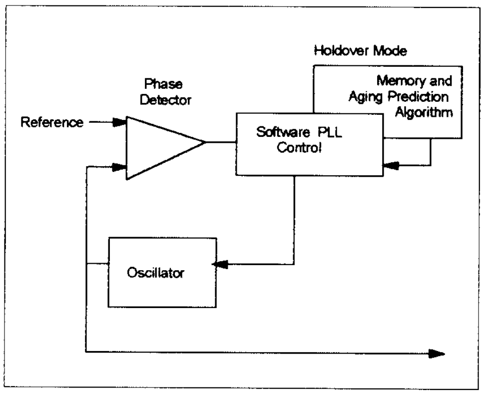

Figure 9 -- Block diagram, steered oscillator system

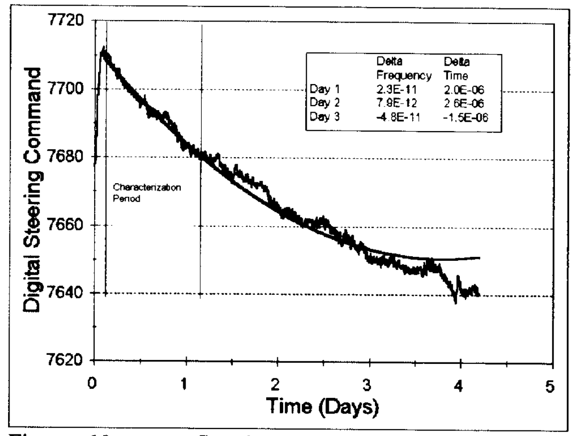

Figure 10 -- Steering commands of GPS-steered oscillator. Table gives frequency and time errors accumulated after end of characterization period.

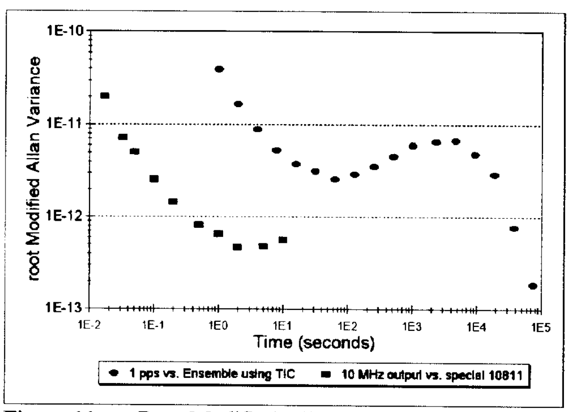

Figure 11 -- Root Modified Allan Variance, 10 MHz and 1 pps output of GPS Steered oscillator

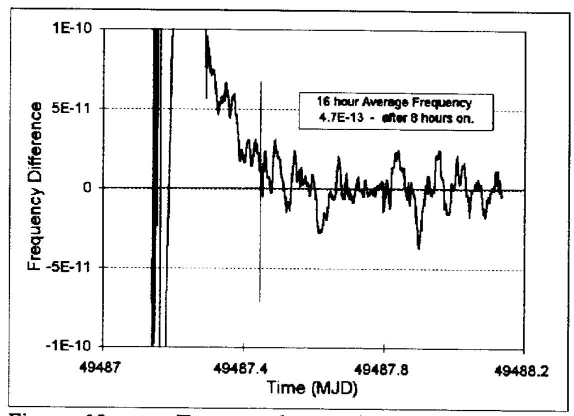

Figure 12 -- Turn-on characteristics - GPS Steered Oscillator. Frequency offset computed after 8 hours on.