Abstract: This paper investigates a method for achieving timing accuracy of approximately 3ns using low-cost, low-power components suitable for use in embedded systems. After developing an error model and a prototype costing $440 and consisting of an Oncore M12+ GPS receiver, an uncompensated 33MHz oscillator, and an Altera Cyclone Programmable Logic Device, testing indicated short-term frequency stability on the order of $1.5\times10^{-15}$ seconds with the full system only consuming 1.7W from a 5V supply. Further testing is required to fully characterize this approach.

I. INTRODUCTION

The need for accurate time measurements has existed since explorers began to sail the vast oceans. For the ancient mariner, longitude calculations were directly dependent on the presence of a time source that kept its accuracy in spite of the constant motion, temperature changes, and turbulent weather. Today, time is the most precisely defined measurement available, frequently used to define other units of measure including length and voltage [1]. However, these time references and standards are typically provided by equipment suitable only for the laboratory as they are heavy, expensive, and are operated from relatively high-power sources.

For example, a Hydrogen Maser, an accurate atomic clock that makes use of changing energy states of pure Hydrogen to provide a 1.420 GHz internal frequency reference, weighs 227kg (including batteries,) occupies nearly 0.4m$^2$, and consumes up to 150W of power. Clearly, this time reference is not suitable for low-power applications nor is this time reference readily mobile. Coupling these issues with a price tag in the range of $500,000 US prohibits its use in many small, low-cost, in-field applications.

Such applications include the New Mexico Institute of Mining and Technology’s (NMT) Lightning Mapping Array (LMA) [2]. This collection of self-contained stations spread over thousands of square kilometers records the time of lightning events as they occur overhead by acquiring their radio-frequency emissions. Afterwards, this data is passed through reconstruction algorithms to create three-dimensional maps of the lightning data. Because of the nature of these algorithms, errors in the time measurements on the order of 40ns correspond to relatively large spatial errors on the order of tens of meters. The system requires low weight, small size, and low power consumption to be deployed quickly by pickup truck or other light automobile, to operate for days on battery and solar power, and additionally to provide the time accuracy required to produce usable data. The paper covers a brief background in Section II that documents pertinent information about time standards and a summary of the previous LMA solutions, Section III discusses how the prototype system and error model were developed, Section IV covers the composition of the prototype system, Section V presents the results of testing completed at the time of this paper’s submission, and Section VI provides conclusions and outlines the potential for future work.

II. BACKGROUND

A clock, quite simply, is the combination of an oscillator and a counter [1]. The source of the frequency can be anything from a simple quartz crystal to one of the emission spectra of Hydrogen. Quartz crystals, although exhibiting high frequency stability over short periods, are susceptible to variations in temperature, physical shocks, and aging effects. To limit the effect of temperature, the quartz crystal can be placed in a temperature-controlled oven in a device known as a Oven-Controlled Crystal Oscillator (OCXO). Because the temperature variations are linear, compensation circuitry can correct for these deviations in a Temperature Compensated Crystal Oscillator (TCXO) without the need for a power-consuming constant temperature environment. Unfortunately, both of these techniques still have difficulty maintaining long-term stability; both are affected by physical shock, vibration, as well as age. Low-cost, short-term stable Crystal Oscillators (XOs), however, are not without application in precision time systems. When coupled with an external time reference such as the Global Positioning System (GPS), absolute time accuracy of 3ns has been demonstrated [3].

The GPS is based on a cluster of 24 satellites in circular orbits above the earth. As its name suggests, the signals from the satellites are commonly used to accurately determine position. However, because the satellites carry accurate time sources synchronized to the best time standards available, the same signals used in navigation can also be used to provide low cost, low power, global access to accurate time sources. For the application at hand, the LMA, using satellite-based radio transmissions
is also desirable. In the event that a land-based radio transmission were used, such as a WWV, WWVB, or WWVH radio broadcast, each time system would need to be appropriately delayed to compensate for the signal’s propagation across the array, a distance of up to 100km. Although this is possible, one needs to know the exact positions of each element in the array, a task well suited for GPS. Thus, GPS provides not only the exact location of each element of the array but it also provides accurate time.

The previous LMA design makes use of a 25MHz XO that is disciplined to match the GPS time. By averaging many measurements together, an on-board microcontroller makes minor changes to the oscillator to keep it exactly at 25MHz and additionally phase-locks the local time to match the GPS time. Unfortunately, this approach creates discontinuities every second—a byproduct of updating and synchronizing the local XO. The system has been demonstrated and proven, showing a complete system-wide relative time-accuracy of around 40ns.

III. DISCUSSION

Although the previous system has proven reliable, the designers of the LMA hypothesized that there is more detail in the observed lightning events than can be captured with its current time-accuracy. To improve upon the previous system, this design addresses not only time accuracy but also size, cost, power, and manufacturing complexity. Manufacturing complexity concerns prohibited the use of Ball-Grid Array (BGA) devices as the resulting design would be assembled at standard soldering stations. The other constraints—size, cost, power—generally forced the design to have as few physical parts as possible. After pursuing several different options, the development of the new system began with the choice of the local oscillator. The results of this decision provided direction for the development of a prototype system.

The oscillator decision was critical because of time accuracy requirements. The need for nanosecond accuracy (parts-per-billion) could only be met by any oscillator having greater stability and accuracy than typical “high precision” (accurate to several parts-per-million) crystal oscillators. Because of power and cost concerns, an OCXO was not an option. A TCXO was also not an option because it could not be readily determined when and how the compensation would be affected. This type of concern was demonstrated by the compensation system in the previous LMA, introducing noise in the process of synchronizing the local XO.

The fundamental concept of the design was to use a frequency-stable uncompensated XO and the GPS reference continuously to measure its frequency. This approach provides resistance against temperature changes, aging issues and still can provide the necessary, accurate time measurement.

In the event that a stable, high-frequency PCB could be created for this application, the arrival of the GPS signal could be directly sampled with a gigahertz counter: the local time would be directly locked to the signal presented from the GPS receiver to within 1ns. Unfortunately, this is not practical because of not only the careful board design required for gigahertz circuitry but also of the requirement for additional, expensive components. Because of the Analog to Digital Converters (ADCs) available elsewhere in the LMA system, a 20-40MHz system-wide clock is desirable. This decision tends toward performance similar to the previous LMA, employing a 25MHz clock; without some enhancement to the system, time accuracies similar to the previous LMA system can be expected.

To decrease the PCB requirements and still make use of higher-frequency circuitry, a Programmable Logic Devices (PLD) became the choice for the main processing element of the system. Several PLDs provide internal Phase-Locked Loops (PLLs) to synthesize other clock frequencies from a single incoming clock. Thus, while the system can make use of a 33MHz clock, a 200MHz or faster clock can be synthesized inside the

![Figure 1 Measurements required to provide an accurate time standard for the revised LMA system.](image)

Note that the sampling clock is typically 33MHz, the multiplied sampling clock is generated by a PLL on the PLD, and the Pulse Per Second (PPS) signal is provided by the GPS receiver. The PPS is measured by taking rising-edge counts.
PLD to make more accurate measurements of the reported GPS signal. The PLD now contains all of the high-frequency logic, allowing for a lower part count and short circuit-path lengths inside the PLD. Figure 1 shows the measurements taken and Equation (1) shows the computation necessary to determine the time of each sample. In this equation, $t_{PPS}$ is the time associated with the precision GPS-reported Pulse Per Second (PPS) signal, $t_{RAIM}$ is an error-reducing adjustment provided by the Oncore M12+ GPS receiver, $m$ is the number of rising edges of the multiplied sampling clock after the last sample was taken, $M$ is the multiplier for the sample clock, $n$ is the number of samples taken in the last second, and $N$ is the computed XO frequency.

$$t_{sample} = t_{PPS} + t_{RAIM} + \frac{m+n}{M+N}$$  \hspace{1cm} (1)

From Equation (1) come three sources of error. The combination of the $t_{PPS}$ and $t_{RAIM}$ is reported to be close to nanosecond-accurate ($+/−0.5\text{ns}$) [4]. The other source of error comes from a truncation in measuring the phase offset of the PPS in $m$. The addition of a half-sample does not decrease the variance of this error but does serve to center the mean error on zero. The third source of error is in the computation of the sampling frequency, $N$. To control this error, consider Equation (2) which bounds the time error of the $N^{th}$ sample, the last sample in the second, to the tolerable error. By manipulating this inequality into Equation (3) and knowing that the tolerance is significantly smaller than $N$, Equation (4) approximately bounds the maximum deviation in frequency $\delta N$ based on the tolerable error and sampling frequency.

$$N \cdot \frac{1}{N} - \frac{1}{N + \delta N} \leq \varepsilon_{tol}$$  \hspace{1cm} (2)

$$\frac{-\varepsilon_{tol}N^2}{N + \varepsilon_{tol}N} \leq \delta N \leq \frac{\varepsilon_{tol}N^2}{N - \varepsilon_{tol}}$$  \hspace{1cm} (3)

$$|\delta N| < \varepsilon_{tol}N$$  \hspace{1cm} (4)

By combining the approximation in Equation (4) with the requirements for nanosecond accuracy ($\varepsilon_{tol} = 0.5 \times 10^{-9}$) and a sampling frequency of 33MHz, the sampling frequency must be computed so that $\delta N$ is within 0.0165 counts.

It is important to note that this computation model does not cover many additional sources of noise. Because the actual sampling mechanism in the A/D converter is distant from the physical implementation of the counter on the PLD, an additional delay will be introduced. Furthermore, logic delays, jitter, and additional metastable conditions will be present and may introduce substantial phase-noise to the time produced in this method. However, the LMA system is not concerned with absolute time but rather with the relative time among the various array stations. The nature of the reconstruction algorithms mentioned in the introduction is concerned with the relative arrival times; if the above sources of noise are uniform among each of the stations, they pose little impact to the reconstruction algorithms and can be ignored for this application. Clearly, testing of the device is necessary to validate these assumptions.

---

**Table 1** A budget summary of the cost to manufacture the prototype, excluding final assembly costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altera Cyclone EPC16QC100C7</td>
<td>$59</td>
</tr>
<tr>
<td>33.3333MHz Uncompensated Crystal Oscillator</td>
<td>$4</td>
</tr>
<tr>
<td>Misc. support hardware and connectors</td>
<td>$50</td>
</tr>
<tr>
<td>PCB manufacture</td>
<td>$75</td>
</tr>
<tr>
<td>Oncore M12+ GPS receiver</td>
<td>$252</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$440</strong></td>
</tr>
</tbody>
</table>
IV. PROTOTYPE SYSTEM

To verify the assumptions made in the previous section, a simple, low-cost PCB was made as in Figure 2 with a cost summary as in Table 1. This prototype contains all of the basic components needed for the outlined time standard: a GPS receiver, an Altera Cyclone Chip, and a readily available oscillator. Because this time standard was part of a larger project, the prototype also included support hardware that was not a part of the time standard.

The entire unit—completely assembled, powered, programmed, and running—consumed only 1.7W from a 5V power supply. This low power consumption coupled with a total cost of $440 met the performance constraints for the time standard section of the LMA. However, meeting any power and budget constraints is meaningless if the design can not meet the time accuracy requirements.

V. RESULTS

As there were no instruments available to test directly the prototype’s time accuracy, two indirect tests were performed: a test on the short-term stability of the crystal oscillator and a test on the frequency-stability of the system. The first test, that to determine the short-term stability of the crystal oscillator, is relatively simple and involves no external components. The prototype system was programmed to collect the information needed for Equation (1) and additionally record the ambient temperature reported by the Oncore GPS unit. This data was then passed from the PLD to a computer over a standard serial connection. With this information, standard mathematical techniques were used to characterize the short-term frequency-stability of the crystal oscillator.

Results of such a test are presented in Figure 3, the test conducted in an environment with a constant temperature (25.7±.3 degrees Celsius.) Over the course of the fifty minutes in this test, the measured oscillator period varied from its mean by no more than 1.5x10^{-15} seconds and had a standard deviation of 5.6x10^{-16} seconds. This indicated an extremely high stability in the short-term crystal oscillations. Furthermore, these measurements only made use of a two-second averaging to provide the necessary oscillator frequency measurement. The use of such a small averaging window makes the overall system much more responsive to changes in oscillation frequency dominantly introduced by changes in temperature. Because the LMA system is primarily interested in thunderstorm activity, rapid temperature changes are likely to exist.

The second test was designed to determine the frequency-stability of the system. Unfortunately, on careful evaluation of the data and procedure, the test ultimately could not be used to characterize the standard. The concept of the second test was to use a known frequency standard to provide a local reference. The equipment that was available for the test was a FTS4080 Cesium Frequency Standard and, when calibrated, would...
serve this purpose well. Since the units’ last calibration in 1996, the frequency of the oscillator had drifted, as is indicated in Figure 4. A counter driven by the 10MHz output was used to synthesize a reference PPS. By measuring its rising edge with the prototype, calculating its time via Equation (1), and then computing a linear least-squares fit to the data, the prototype system measured the Cesium Standard oscillations to have accelerated approximately 0.0149166Hz.

Because the test procedure used the time standard outlined in this paper to determine the reference time standard, all measurements made indicated that the errors were smaller than the error in the measurements. Although this strong correlation seems to indicate the system model is valid, it does not provide any characterization. The large spike in Figure 4 is the manifestation of an unknown problem with the serial receiver programmed in the PLD. Periodically, the serial receiver fails to capture the incoming GPS data stream. At the writing of this paper, it is unclear if this failure is the result of environmental noise captured by the simple, unshielded PCB design without any ground planes, noise introduced by the PLL, or noise from a number of other sources. However, three failures in 3500 samples seems to be a tolerable failure rate for this application. It is expected that this rate will decrease once the design is improved with a more noise-considerate PCB layout.

VI. CONCLUSIONS

Initial testing of the prototype indicates great promise in this technique. The prototype runs on 1.7W of power from a 5V source, has part costing around $440, and requires less than an hour of a skilled technician’s time to assemble. Testing should continue, making use of two reference time standards to characterize the prototype standard [1].

The development of this system is not limited to its application within the LMA; the techniques used can be deployed to any remote, low-power data logging systems that require accurate time acquisition over large distances (100km.)

ACKNOWLEDGEMENTS

The authors wish to thank Dr. William Rison and the Langmuir Research Laboratory for providing the funding for this project. The time standard outlined in this paper was conducted in partial fulfillment of the Senior Design course at the New Mexico Institute of Mining and Technology (NMT) under the direction of Dr. Scott Teare. Senior Design Team-6 was mentored by Dr. Aly El-Osery and worked in labs at NMT and in the nearby National Radio Astronomy Observatory (NRAO) Array Operations Center. Without the after-hours efforts donated by Betty Scott, Leon Abeyta, Jim Muehlberg and the LO/IF group, the project could not be assembled nor tested. The authors additionally wish to thank Rebecca Evans and Mark Janney for their help in the revision process.

REFERENCES


Scott A. Miller is recent graduate of the New Mexico Institute of Mining and Technology with a B.S. in Electrical Engineering, a B.S. in Computer Science, and a minor in math. He has worked internships for General Dynamic Decision Systems, Los Alamos National Laboratories, and Hytec, Inc. His current research interests are in reconfigurable computing and embedded systems and he is pursuing a Masters’ degree in Computer Science at NMT.