High Performance GPS Disciplined Oscillator and Distribution Amplifier with Network Time Protocol Support

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***Abstract*— The world runs on time. Modern communications systems require clocks to match among all actors in a system, in many cases to better than 16 parts per billion [1].**

This project will build a global positioning system disciplined oscillator capable of 16 parts per billion accuracy. A high fanout distribution amplifier and local time server are included, both of which are driven off the high accuracy signals from the global positioning system disciplined oscillator. To achieve this high accuracy, this project requires careful design of both analog and digital systems.

I. Introduction

> "Does anybody really know what time it is?
> Does anybody really care?" —Chicago

It used to be that all the vast majority of humanity needed as a notion of time was that which could be provided by a glance at the sky. In our modern world this vague notion of time is not all that appropriate. Instead, much of our modern world depends on time comes as a surprise to many. This need is hidden from view, deep in the inner working of the things we take for granted, the Internet, the cellular phone system, or the GPS system that keeps us from getting lost on unfamiliar trips. In practice, the stringent requirements of many of these systems require the use of atomic clocks in communications installations as nothing else meets the tolerances. However, atomic clocks are not the only way of achieving these tight tolerances. A global positioning system (GPS) disciplined oscillator (GPSDO) can also meet these specifications, while providing automatic self calibration and aging compensation in the natural course of operation. That said, to fly somewhere in a plane does not require one to be able to build a 747. Nor does the use of a cell phone require the ability to understand how one works. However, to those who create these systems that do depend on time, an accurate notion of time can be critical for testing or implementing system functionality.

To provide time and frequency references, there are several different types of reference. Some are cheap, and good enough for low specification use only, while others cost several thousand dollars and up and come close to meeting the very definition of the second itself. This project revolves around a middle ground, that of the disciplined oscillator. In short, a disciplined oscillator is one whose undesirable characteristics are adjusted and suppressed with the use of a better but directly unusable source clock. Currently GPS is commonly used to provide the high accuracy reference clock. This same approach will be taken in this project. The targeted accuracy is 10 parts per billion (ppb) accuracy with 1 ppb expected.

Besides the high accuracy oscillator, other additions like the built in distribution amplifier and the network time protocol (NTP) server are provided as a number of instruments can use clock references and it can be important that all machines share an accurate time reference.

II. Background

There are several different methods of generating an accurate and tight variance clock source. Each has advantages and disadvantages with respect to price and performance.

A. Quartz Oscillator

A cheap quartz frequency reference, like those used in a watch or many computing systems may be 100 parts per million (ppm) or worse from true, but these references cost only pennies. Even at the upper end of the scale, accuracies of 10 ppm at room temperature are about as tight as is practical for basic quartz oscillators as thermal effects begin to affect the frequency significantly. Above this point, there are a number of compensation schemes that correct to a degree this drift, but none of them are as effective as placing the oscillator inside a temperature controlled chamber.

B. Oven Controlled Crystal Oscillator (OCXO)

A significant upgrade from this is to use a high tolerance frequency reference of this type, and place it in a heated oven to well above ambient to remove the effects of frequency drift. These usually cost two or three orders of magnitude more than a basic crystal. However, for that price, accuracies of 0.1 to 10 ppm are common, with a change with ambient temperature from 2 to 500 ppb and a variance better than 10 parts per trillion (ppt) [2].

C. Current Atomic Clocks

The definition of the second is 9,192,631,770 transitions of a cesium atom at 0 K. A clock that measures this transition is by definition accurate, although measurement uncertainties become the bigger problem at that point. In the United States, the holder of the clocks that define the second is the National Institute of Standards and Technology in Boulder, Colorado. Their flagship clock, NIST-F2, has a current measurement uncertainty of 1×10^{-16} [3]. Their previous clock, NIST-F1, has an uncertainty of about 3×10^{-16} [4] and is planned to be run in parallel with NIST-F2 concurrently for the near future [3].

In the commercial sector, atomic clocks are also available. Most commercial standards use rubidium instead of cesium, both for cost reasons, and because the use of rubidium allows simpler microwave cavities and is less susceptible to magnetic fields [5]. These commercial grade standards are accurate to within 50 ppt, and have short term variance near 2–10 ppt. However, long term accuracy is limited by aging effects and commercial standards may drift on the order of 100 ppt per year [6].

D. *Disciplined Oscillators*

Clock sources in this category have multiple components, consisting of a low accuracy, but tight variance oscillator like an OCXO, and a high accuracy, but large variance or less usable reference signal. In the past, many frequency standards of this type used the 60kHz carrier of WWVB (a NIST broadcast radio station) as a reference signal as NIST controls the frequency to an accuracy better than one ppt. A product like the Spectracom 8165 can lock to WWVB with an accuracy of one ppb and a stability around 100 ppt [7]. Unfortunately, since these systems were manufactured, WWVB changed their modulation to incorporate phase modulation, which causes this class of standard to fail to lock on properly.

Modern general purpose[1] disciplined oscillator systems are usually based around the GPS signal. Since GPS works by solving a system of equations with the current time as a variable, a GPS receiver knows the current time. Additionally, GPS satellites carry atomic clocks onboard and that accuracy is available to the receiver. This accurate, but jittery clock is then used to tune an inaccurate but low variance clock to match. A clock accurate to <100 ppb can be easily created, and well designed units can achieve a short term accuracy of about one ppb, with a longer term 24 hour average of <10 ppt. This is accompanied by the tight stability of the internal OCXO, which provides short term stability of <30 ppt including the effects of the control loop [8].

III. Proposed Work

The primary purpose of this project is to be a high accuracy and high stability local oscillator. As a secondary purpose, a distribution amplifier is integrated capable of driving several external loads, allowing more that one device to receive an accurate clock. As a related goal, not all devices can make use of the same frequency clock, so a phase locked loop (PLL) circuit is also integrated into the circuitry to allow variable output frequencies with high quality. Finally, a local NTP server is planned as a function of the device to make use of the accurate time information from the GPS network as a reference for networked computers and devices with regular clocks.

See Figure 1 on page 6 for a high level block diagram of the proposed system.

A. *Rationale*

While the correct time is important to many different disciplines, those who build, design, and test communications equipment are acutely aware of the role that accurate frequency measurement plays in the modern world. Systems as critical to our way of life as the cellular network require clocks accurate to between 16 ppb and 50 ppb for large area base stations [1]. Additionally, the GPS constellation that many of us depend on for getting to unfamiliar places would not work without accurate and low variance timing. For this reason, both GPS satellites and many cellular base stations carry atomic clocks onboard to prove high quality sources of time. This need for high accuracy references in modern systems prompts the focus on sub 10 ppb frequency error.

Even in laboratory settings where the absolute frequency is not important, the variance of the frequency may be important. It is also important that multiple instruments which are involved in a process all agree as to frequencies. It may be fine that a 1 MHz signal is 1% off, but if one device is reading 1% high, and the other device is reading 1% low, then the potential exists to get stuck looking for a problem that only exists in the measurement tool. In that case, having both devices agree on the frequency is much more important. The synchronization problem provides a reason to have several outputs to drive a whole lab full of equipment that needs to know what the local “Standard Time” is.

Finally, an NTP server is included to handle the other devices and probable general purpose computing devices that need to know time and a format that corresponds to the way humans view time in days, hours, minutes, and seconds.

B. *Oscillator*

To achieve both high accuracy and tight variance, the oscillator system will need to both minimize the average frequency offset, as well as the instantaneous frequency offset. One of the best ways of doing this is to take a low variance and stable clock that is inaccurate and drifts in the long term, and adjust it to remove the inaccuracy and drift. This method requires a more accurate reference signal, but is insensitive to that signal’s variance. In normal operation, a GPS receiver is required to have an accurate long term view of frequency, but in the short term, it is very jittery. This project aims to combine the excellent short term stability and variance of an OCXO, with the long term accuracy of the GPS receiver. Done properly, this transfers the accuracy of the GPS and the stability and variance of the OCXO to the output, without severely degrading either.

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[1] Excluding data stream clock recovery and similar systems.

To achieve this transfer a VCOCXO (voltage controlled OCXO) is needed to allow the runtime adjustment of the frequency under processor control. The control voltage is generated by a precision DAC under processor control. However, since these analog systems are capable of responses to very small levels, it is important that all possible sources of drift are removed. In particular, temperature changes in the environment cause significant error. Thus, it is important that the temperature of the analog control system be held nearly constant, to minimize the drift. Holding a small area at a constant temperature is easy if the exact temperature may be set to make it easy to hold that temperature. The best temperature to heat a system to is above the maximum environmental temperature excursion, plus the temperature that internal self heating would cause. This ensures that the control loop can dump energy into the system until the set-point is reached. As a part of the oscillator, a heated oven will be placed around all of the analog control circuits to adjust the oscillator to minimize the thermal drift.

C. Frequency Measurement

To discover how much to adjust the oscillator, a method of counting and comparing the frequencies from the oscillator and the GPS reference is required. As there are many ways of computing the adjustment, provisions will be made to allow several different measurement methods. Two of the most common and likely to work methods are a variant of the traditional phase locked loop architecture and a frequency counter based approach over many periods of the reference.

D. Phase Locked Loop

To provide additional output agility, some of the external outputs will be connected not to the raw oscillator output, but will instead be connected to a PLL frequency multiplier/divider chip. This allows a programmed frequency change such that an instrument that instead of a 10 MHz clock, needs a 27 MHz clock, will still be able to be used with this equipment. The control interface for these PLLs is planned to be over the on board Ethernet link, with status and outputs available on the front panel.

E. Distribution Amplifier

As an instrument, this will not be all that useful if it is only capable of driving one external piece of equipment. This is at its most useful when many to all instruments that measure time in a lab are all getting their frequency reference from a single box. Thus, a distribution amplifier stage will be present, such that several different instruments may be driven with a single clock without interference from each other. This makes a device like this project useful for a whole lab, not just a single instrument.

F. NTP Server

Common GPS modules provide both the timing information needed to adjust the oscillator as well as data as to the current time. With the information about frequency, and the information about the current time, enough information is available to both keep time at the correct rate, but also to set the clock to match human time systems.

With that in mind, many devices in a lab, from the regular computers that monitor and log results, to measurement and acquisition devices have a use for the current time. As the information is there, and the standard NTP server protocol is rather simple to implement, it makes sense to write a high quality NTP server that uses the information from the GPS to set other instruments on the network. The requirement of Ethernet connectivity that NTP demands is not an extra feature to the system as the PLLs need some form of communication to set their value and Ethernet was already planned to be in use for that purpose.

G. Power Distribution and Supply

Since this system has very tight tolerances, the power supply must be carefully designed to minimize the influence of noise of the frequency output. To that end, all of the critical power supplies will be heavily noise filtered and derived from low noise regulators separate from those used by the non-critical systems. Additionally, careful layout of the power domains will be needed to minimize coupling between critical and non-critical areas.

As a second consideration, since long term information will be monitored about the relative frequencies of the two systems, it is important that momentary power glitches or short outages do not negatively impact the control loop function. To achieve short term holdover, a battery or super-capacitor backup system is planned to keep the system running during brief interruptions. While a holdover period of an hour or more would be excellent, even a few minutes would be useful for events such as tripped breakers or power blips.

IV. Risk Assessment

Despite being a complicated system with a very high bar to reach for full success, this system has a graceful degradation path to projects that are much simpler to implement.

The first stage of the graceful degradation is the relaxation of the target specifications. Instead of the targeted 1 ppb, the target may be 2, 10, 25, or even 50 ppb. This corresponds to both systemic inaccuracies, as well as a lack of control loop convergence. Beyond this point, the system performance is better suited to the non use of the control system as it will be doing more harm than good to the performance.

The second stage is a system that is not GPS disciplined, instead using the raw OCXO for a frequency reference, but retaining the NTP server and distribution amplifier. Finally, the minimal system comes in two different variants. The first variant is only the distribution amplifier (modified to remove the output PLL circuits) and the OCXO without NTP support, while the other is the the OCXO and a NTP server, but lacks the distribution components.

Both of the minimal systems are reasonably risk free, as the components and technologies in use are similar to those I have worked with in the past. I am familiar with the NTP specification and have written multiple client programs, and the distribution amplifier circuits without a PLL are simple and unlikely to cause significant problems. Additionally, I have built Ethernet connected systems with microcontrollers and have very few problems with proper function.

The only other portion of the systems likely to cause problems are the underlying infrastructure subsystems like power supplies, microcontrollers, assembly, and mechanical or size considerations. However, not only have I worked extensively on systems utilizing these parts, I also have several outside resources that I can use to verify designs and troubleshoot potential problems. Thus, I do not consider the infrastructure components of this project to be a risk generating portion of the system.

V. Schedule

Projected Schedule:

1) Beginning of May — Begin PCB design
2) End of May to first week of June — Design Done, start fabrication process
3) End of June — Fabrication done, start assembly
4) First week of July — Assembly done, PCB bring-up
5) End of July — Individual systems functional
6) End of September — System expected to be functional as a whole
7) October and November — Slack time and testing
8) December — Finish up documentation and testing for senior project

VI. Evaluation

Evaluation of the GPS disciplined oscillator component of this is simple in concept. The primary objective is to adjust the OCXO to a tighter frequency accuracy while not harming its excellent variance specification. In practice, measuring frequency down to 1 ppb is a non trivial problem. The biggest hurdle is having a frequency reference that is even better than is targeted. In practice, this is an atomic clock. One of the commercial grade rubidium references will be more accurate and tighter variance than this project intends to be. There are three ways of measuring the offset frequency. Option one is to plot the two signals in X-Y mode on an oscilloscope and measure the rate of rotation. This directly gives the frequency difference between the two signals. The advantage of this method is it also allows for observations by eye as to the behavior of the signals. Option two is to use a frequency mixer, which for digital signals is as simple as an XOR gate, and then knock off the high frequency term. The low frequency difference term can then be provided to a frequency counter capable of long gate times. This will also give the difference in frequency. The final option is to use a frequency counter that is capable of measuring below a part per billion and that has an external reference input. The condition for success for the oscillator subsystem is an improvement in the accuracy of the source OCXO. The ideal behavior would be an accuracy of better than 10 ppb or even 1 ppb. Measuring the variance of the subsystem is more problematic and is considered out of scope for the project.

The condition for success of the NTP server component is simply that it returns NTP packets sufficient that a computer is able to sync its time to it. Notably, this excludes any accuracy or variance problems with the NTP implementation. Ideally, they would be minimal as well, but that is not a factor for success.

Similarly, the goal of the distribution amplifier is that the outputs are all replicating the input faithfully, and that the PLLs are functional and creating frequencies that they are programmed to. There is no measurement of output jitter for the PLL circuit, or similar problems from the output buffers.

VII. Required Resources

- I will need external people who have both precision measurement experience and those who can verify design and system architecture. I also need a small amount of mechanical design support, mostly with the thermal design and an enclosure. I already have arranged support from a practicing electrical engineer and some practicing mechanical engineers.
- I will need the usual electronics bench systems of digital multimeter, oscilloscope, and similar. I already own suitable equipment for this and additionally have access to this as a student.
- In the test equipment category, I will need a higher accuracy and tighter variance frequency reference than what I am building such that I will have a way of quantifying the actual performance of my system. I am currently exploring options for borrowing a rubidium atomic frequency standard unit for comparison purposes, both through the university and privately.

  Additionally, I may need other test equipment for full characterization of this device beyond the stated accuracy target. While I have yet to determine concretely what would be needed, I expect that I will be able to borrow the needed tools if necessary.
- I may need a normal allotment of bench space in the hardware lab once the fall semester starts. However, until then, I have the bench space and all of the equipment needed to develop the system.

Budget-wise, I expect this to be an expensive project. However, this is a piece of test equipment that I actually have a use for in my lab. Thus, the high price is acceptable as I have a use for even the minimal configurations of the project. The expected budget for the project is somewhere between \$500 and \$1250, depending on the variable board, parts, and mechanical costs as well as the final design decisions about accuracy and variance.

A. *High Level Bill of Materials*

While the final parts in use have not been decided, representative parts for the important subsystems have been selected.

- High precision 10 MHz VCOCXO — This oscillator is trimmed to be accurate by the control loop in the system, and transfers its variance to the output. An oven controlled oscillator is a very low variance and reasonably accurate frequency source. The voltage control input directly affects the frequency of the output, allowing an external circuit to improve the accuracy of the system.
  DOC020V-010.0M — 20 ppb stability
  OH200-51003CV-010.0M — 2 ppb stability
  OH100-50503CV-010.0M — 2 ppb stability
- High precision voltage digital to analog converter (DAC) — This high precision DAC gives the system the ability to adjust the control voltage of the VCOCXO in small steps, to provide the greatest trim resolution.
  MAX5318 — 18-bit DAC
- Control loop microcontroller — Responsible for reading the current frequency error and trimming the VCOCXO to minimize it. May be also acting as a frequency counter.
  Some form of STM32F0/2/3/4 microcontroller
- Frequency counter FPGA — Measures the frequency error between the 1Hz reference and the 10MHz oscillator.
  MachXO2-7000HE
- Clock Fanout Buffer — Buffers the single clock output from the oscillator to all of the internal devices that need a clock.
  CDCLVC1112PWR
- Low Jitter Phase Locked Loop — Provides basic frequency synthesis from the 10MHz fixed frequency output for some external outputs to allow easier testing of devices with different frequency needs.
  Unknown Part: TBD
- External Clock Buffers — Buffer the internal clocks to drive external cables to instruments.
  Unknown Part: TBD
- GPS Receiver — Sources both the current time information to the NTP subsystem, but also provides the accurate 1Hz clock to the frequency error calculation system.
  FGPMMOPA6H
- Power Supply — Specifications to be Determined
- Network Microcontroller — Runs the NTP server, status readout, and PLL control.
  STM32F407 or better
- Ethernet PHY — Connect the Ethernet hardware in the STM32 to the physical and electrical signaling layer.
  LAN8710a

VIII. Summary

The creation of an extremely high accuracy and low variance frequency standard will require the primary oscillator to be dynamically adjusted to match the atomic clocks that are a part of the GPS system. To be a useful addition to an engineering lab, components have been added around the core of the project to drive more than one external instrument and to provide more than one frequency, but the core is the oscillator itself.

While GPS disciplined oscillators may be bought readymade from a number of manufacturers, this is an educational project that not only will I learn about the challenges of system design down at the ppb level, but I will also have a useful addition to my lab bench that will give me the ability to measure frequency to a tighter degree than any current standard I own.

IX. Acknowledgements

- Dr. Peter A. Jensen — For convincing me that my enthusiasm for this project should not go unpunished.
- Dr. Ken Stevens — For providing the opportunity the learn how much time interested me and for overseeing this project.
- Aerel Design — Will be providing guidance and resources (Workplace: All three engineers will be involved as this includes both mechanical and electrical design.)

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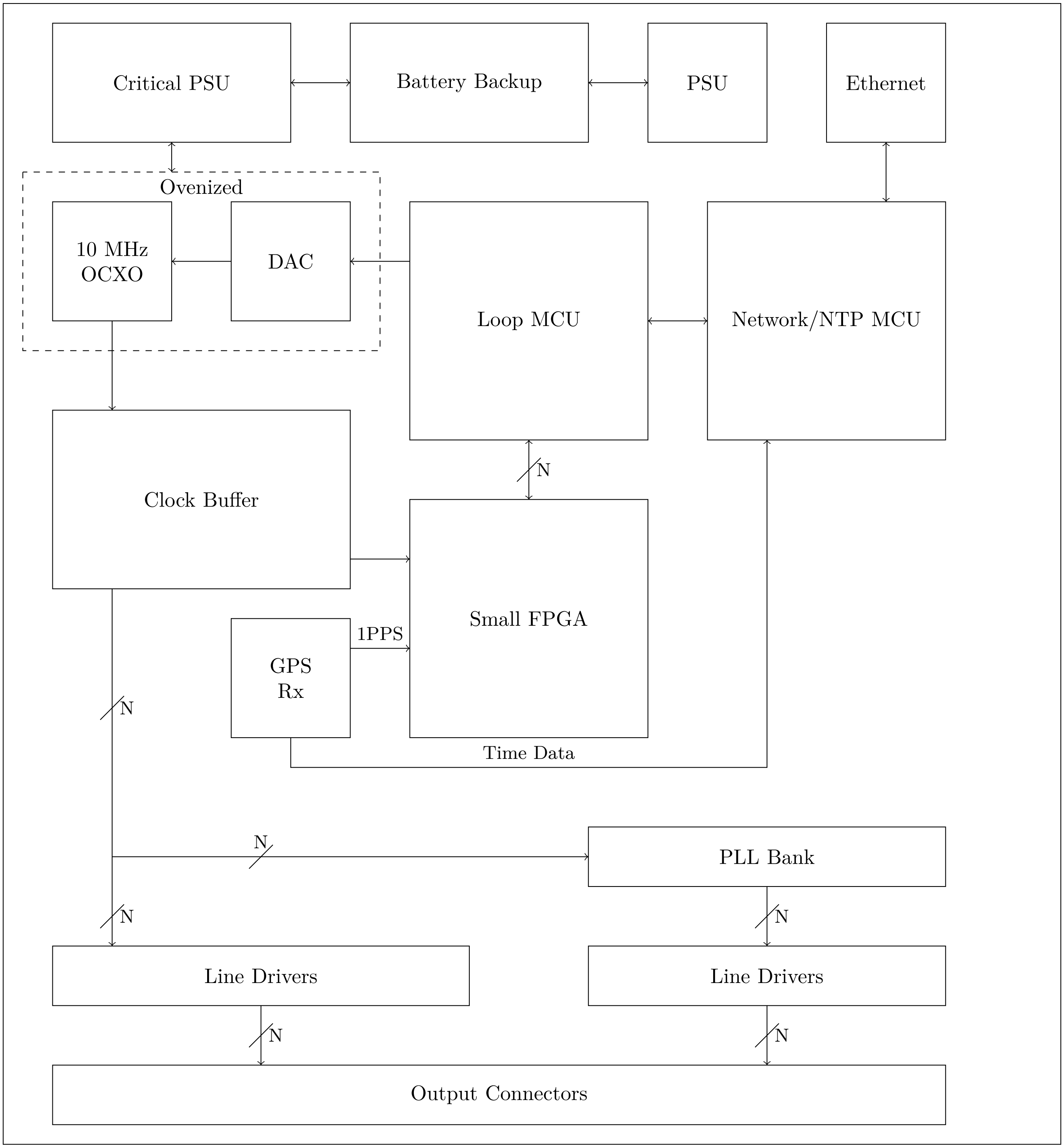

Fig. 1. High level system block diagram