Precise Satellite Timing Modules

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Introduction

- Precision timing on orbit is a critical requirement for many applications including navigation, communication and data collection
- Historically the timing has been provided by using ground stations or on board atomic clocks
- Microsemi Satellite timing modules generate precision time on orbit with a significantly reduced ground station support (or atomic clocks)
- Presentation will describe the basic technology, the approach to optimal steering of quartz oscillators and the design of the Microsemi STM
Satellite Timing Module (STM) - Overview

- Precision frequency sources are required for time keeping and metrology in communication, navigation, reconnaissance and scientific satellites
- Sources are typically quartz oscillators and in some cases atomic clocks
- Drift associated with these clocks require frequency and time to be adjusted by ground stations
  - Undesired Dependency and Costly Process
- The STM uses the output of a space craft GPS receiver, in the form of a 1 Pulse per Second (PPS) to steer a ovenized crystal controlled oscillator (OCXO) using proprietary Kalman filtering called KAS-2
Ovenized Crystal Controlled Oscillators and Digital Frequency Control

- Ovenized crystal controlled oscillators (OCXOs) are the most frequency stable type of crystal oscillators.
- Quartz crystals are 3rd or 5th overtone stress compensated cut which are swept for highest performance for space radiation environment that yield "Q"'s greater than 2.5 M.
- Microsemi uses a modified Colpitts oscillator circuit including automatic gain control with varactor tuning for the lowest possible noise.
- Precision isothermal ovens are utilized with high gain circuitry for thermal stability.
  - Ultra-stable oscillators control the temperature to milli-degrees over an 100°C operating temperature range.
- Digital frequency control is accomplished using Digital to Analog Converters (overlapped) and Sigma Delta Converters.
  - The challenge is to not introduce noise from the process that distorts the crystal oscillators signal.
  - DACs are most commonly used, however the cost, complexity and radiation hardening requirements are significant.
  - Sigma delta converters, generated from within FPGAs, offer key advantages.
  - Ultrastable oscillators that have Allan Deviations of $1 \times 10^{-13}$ are very challenging to steer.
Allan Deviation (aka Frequency Stability)

- Allan Deviation (or two sample variation) is a standard measure of performance used to compare the performance of clocks.
- Fractional frequency differences are calculated at specific time intervals, Allan Deviation is used because of drift component of clocks.
- Statistical method for determining frequency stability (or time stability) that is optimized for noise processes of crystal oscillators and atomic clocks.

Mathematical Allan Deviation Formula

$$\sigma_y^2(\tau) = \sigma_y^2(\tau,m) = \frac{1}{m} \sum_{j=1}^{m} \frac{1}{2} (y_{k+1} - y_k)^2$$

Allan Deviation Characteristics

*For $\sigma_y(\tau)$ to be a proper measure of random frequency fluctuations, aging must be properly subtracted from the data at long $\tau$'s.*
Kalman Filtering for Optimized Performance

- Dr. Rudolph Kalman pioneered the filter bearing his name which is a form of a Bayesian estimator used in many applications including navigation and timing.
- Method is used along with knowledge of the statistics and dynamics of system to predict future performance.
- Widely used in many application including navigation, signal processing and economic predictions.
- Ideal choice for disciplining a crystal oscillator to a long term reference such as GPS.
- Kalman Filter calculations are computationally intensive and a challenge to implement in space applications.
- Microsemi has developed a proprietary Kalman filtering algorithm with state variable feedback called KAS-2.
- Implementation is dependent on the accurate characterization of the clocks being utilized.
- Higher performance clocks yield better results.
Kalman Filtering for Optimized Tracking Performance

- Plot below shows the performance that has been achieved by the KAS-2 Algorithm
- Loop Bandwidth for system is approximately 1000 seconds
- Output phase tracks the smoothed GPS signal so that the results out perform the long term performance of the GPS receiver
- Improvement is most pronounced for high stability oscillators
- The long term stability is consistent with atomic frequency standards
Functionally, the oscillator output is divided down to 1 PPS and compared to the reference 1 PPS.

The error signals, called innovations, are always less than zero, however the goal is to minimize the squared error.

Kalman filter adjusts the state estimates to minimize the error and uses the estimates to change the frequency control tuning voltage of the OCXO.

KAS-2 has two advantages:
- Adjustment of the weighting based on measurement noise
- Operation is possible with a partial set of measurements

Key result is that performance of the system is better than the individual performance of the clocks.

During periods of the absence of the reference signal, the filter continues to steer the OCXO based on past performance. Including the aging of the crystal oscillator.

Additionally, the Kalman filter is dynamic and produces optimal estimates during startup of the module.
STM Design – Block Diagram
Time Interval Measurement – Time to Digital Conversion

- Principal Advantage is the implementation in a single FPGA
- Technique uses a carry chain with circuit elements that validate the rising edge of the start pulse and compares the delay to the stop pulse.
- As an example a carry chain with a 30 ps resolution would require 167 elements for a 200 MHz clock
- Careful routing of the FPGA is required to achieve the maximum performance.
- Technique was implemented in a Xilinx V5 FPGA for mission with relatively benign radiation environment. V5 had sufficiently high operating frequency for the application.

\[ T = nT_p + T_1 - T_2 \]
Time-Voltage Conversion

- Limitations of current SRAM based FPGAs for high radiation environment
- External Pulse rising edge activates a current source and the internal pulse edge stops the source. The voltage is then digitized using an Analog to Digital converter.
- Calibration pulse then optimizes the measurement to account for non-ideal effect.
- Methodology is more complex, requiring a microprocessor (FPGA implementation), ADC etc., however medium performance radiation hardened device such as the Microsemi RTAX series is sufficient
STM Design Description

- STM is a flexible design that allows for a miniaturized OCXO or Ultra-stable Oscillator to trade off performance vs power/weight.
- Design includes a power supply, the voltage controlled OCXO, 100 MHz PLL circuit and controller assembly which contains the FPGA.
- 100 MHz PLL contains a OCXO that is required for high performance applications.
- Module provides SPI status and telemetry interface:
  - PPS present/absent, Internal PLL status and mode of operation.
- Time interval measurement data is provided, which allows the user to analyze performance data.
- Experience gained on a current space program will result of changing the FPGA to a Microsemi RTAX device based on radiation, power requirements and design simplifications.
- Follow-on efforts will implement the Microsemi RTG4 for higher performance/speed operation.
STM Measured Data

9500B STM Data

FREQUENCY STABILITY

Allan Deviation $\sigma_y(\tau)$

<table>
<thead>
<tr>
<th>$\tau$, Seconds</th>
<th>$\sigma_y(\tau)$</th>
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<tr>
<td>$10^0$</td>
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<td>2.26e-13</td>
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<tr>
<td>$10^{11}$</td>
<td>2.21e-13</td>
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</table>

9735 OCXO

Allan Deviation $\sigma_y(\tau)$

Averaging Time $\tau$, seconds

Input 10.0 MHz 10 dBm

Reference 10.0 MHz 14 dBm

NEQ BW = 500 Hz

Application: Reduction or elimination of Dependency of Atomic Clocks

- Global Navigation Satellite Systems utilize on-board atomic clocks such as Rubidium, Cesium and Passive Hydrogen Masers.
- All atomic clocks have some uncertainty that require periodic adjustment from the ground in order for the dissemination of time to the ground user.
- Satellite timing modules would reduce the number required atomic clocks and potentially automate the optimization process.
- Satellite constellations that have less rigorous requirements can rely solely on STM modules.
Applications: Cross-linking of Satellites

- On board timing that is independent from ground stations has significant advantages in terms of autonomy and necessary support
- The ability to eliminate interference due to communication to/from orbit
- Cross-linked satellites are independent from the ground stations and less prone to interference (jamming)
- Multiple satellites on the same time scale, with enhanced performance, allows for increased capabilities in metrology, communication, navigation and monitoring
- Satellite Timing Modules would establish a network in orbit
Conclusions

- Microsemi has developed a new class of space qualified oscillators that use a GNSS derived 1 PPS data to optimize the long term performance of ovenized crystal controlled oscillators.

- The oscillators are steered using a proprietary algorithm, KAS-2, a variant form of a Kalman filter.

- The modules use space qualified FPGAs such as the Microsemi RTAX and the next generation RTG4 to implement the steering.

- The design allows for the reduced dependency of ground station support/or on-board atomic clocks and enables the possibility of crosslinking among satellites.

- These modules are capable of creating a timing network in orbit which enables a paradigm of distribution that reduces cost and complexity, and increases autonomy and performance.

- The modules are scalable in terms of complexity and can be correctly designed for the required performance of the space-borne application.
References

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- “Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications”, John Vig, May 2013 PTTI Tutorials

- “ULTRASTABLE OSCILLATORS FOR SPACE APPLICATIONS”, Peter Cash, Donald Emmons, Johan Welgemoed Symmetricom (now Microsemi), PTTI, 2008

Thank You

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