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Precise Satellite Timing Modules

Microsemi Space Forum 2015

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Microsemi SPACE FORUM

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

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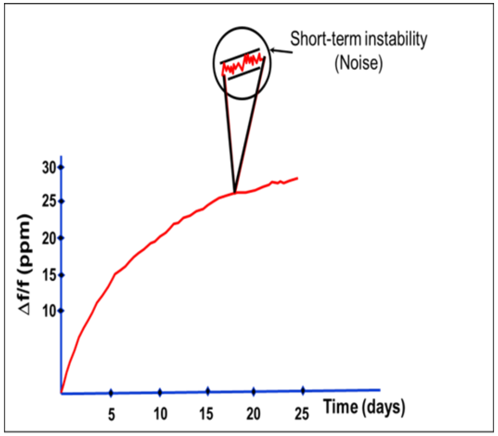
Satellite Timing Module (STM) - Overview

- Precision frequency sources are required for time keeping and metrology in communication, navigation, reconnaissance and scientific satellites
- Source 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

Satellite Timing Module

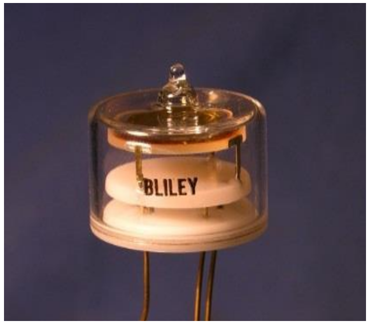
Crystal Oscillator Drift and Noise



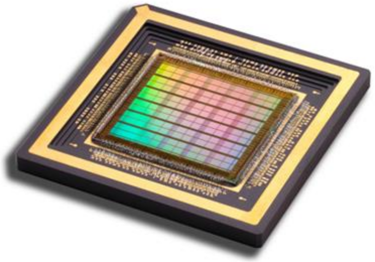
Ovenized Crystal Controlled Oscillators and Digital Frequency Control

- 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 1×10^{-13} are very challenging to steer

Bliley 5 MHz Crystal



Microsemi FPGA



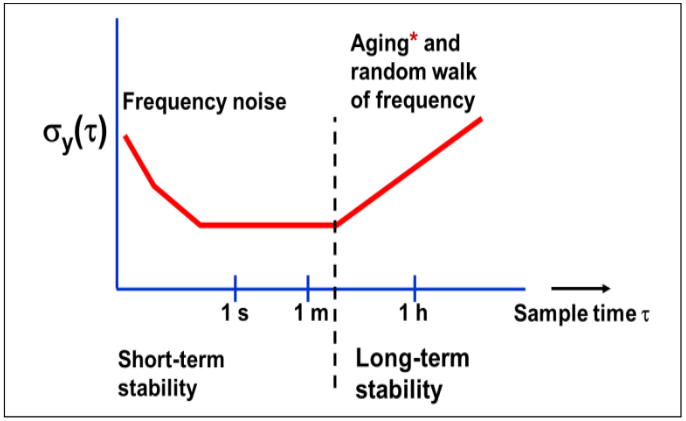
Allan Deviation (aka Frequency Stability)

- 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

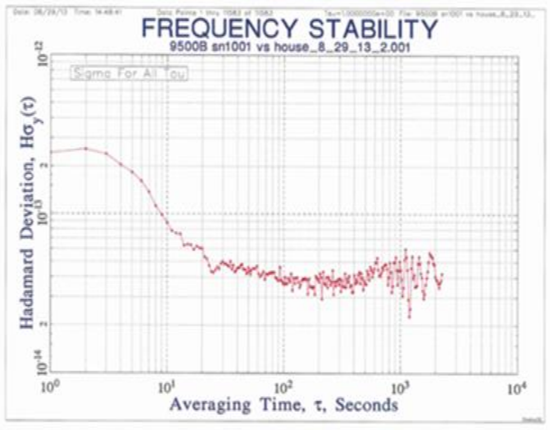
$$\sigma_y^2(\tau) = \sigma_y^2(\tau, m) = \frac{1}{m} \sum_{j=1}^{m} \frac{1}{2}\left(y_{k+1} - y_k\right)_j^2$$

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 τ's.

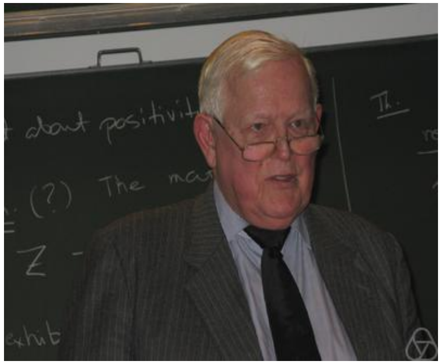
Measured Allan Deviation



Kalman Filtering for Optimized Performance

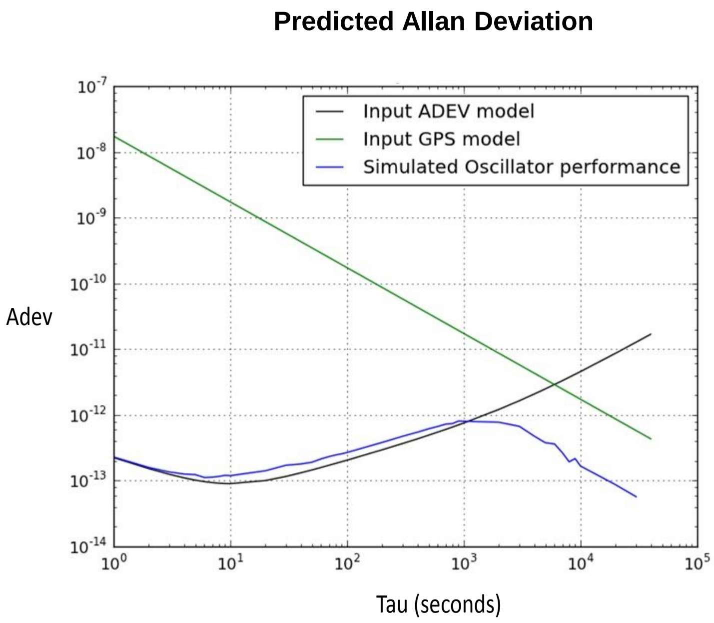
- Dr. Rudolph Kalman pioneered the filter bearing his name which is a form of a Bayesian estimator used in many applications including navigation and timing
- Method is used along with knowledge of the statistics and dynamics of system to predict future performance
- Widely used in many application including 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

Doctor Kalman



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



STM Implementation

- 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

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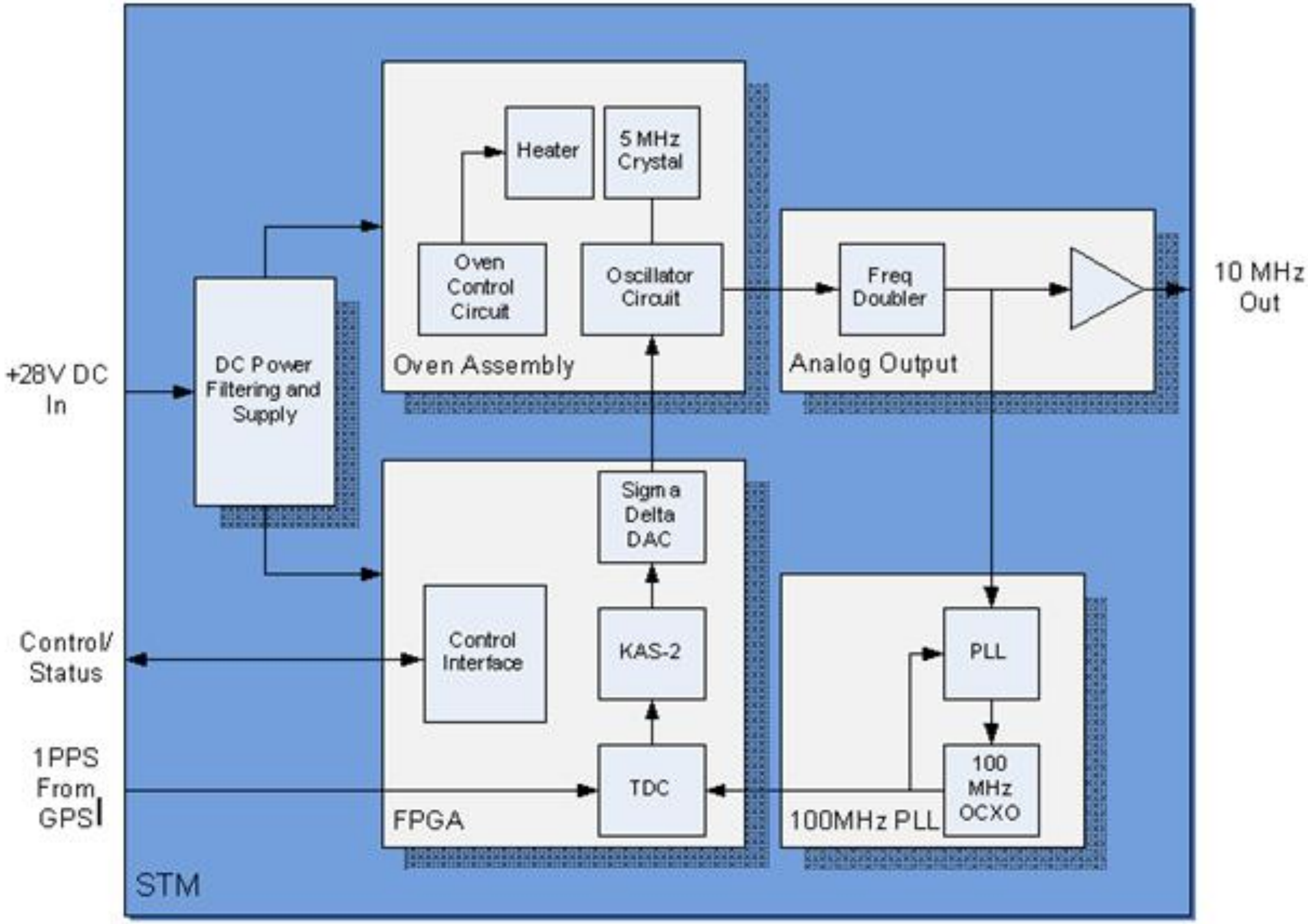
STM Design – Block Diagram



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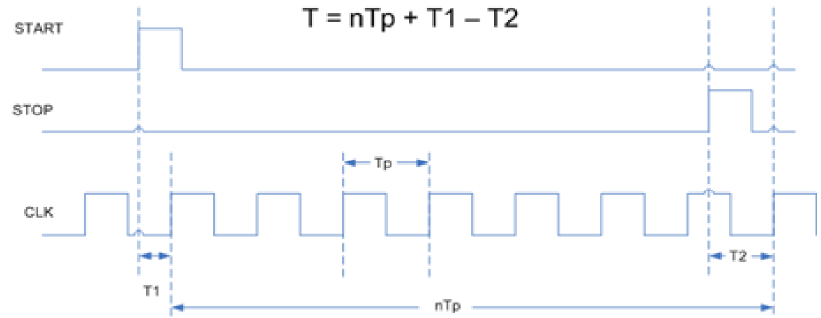
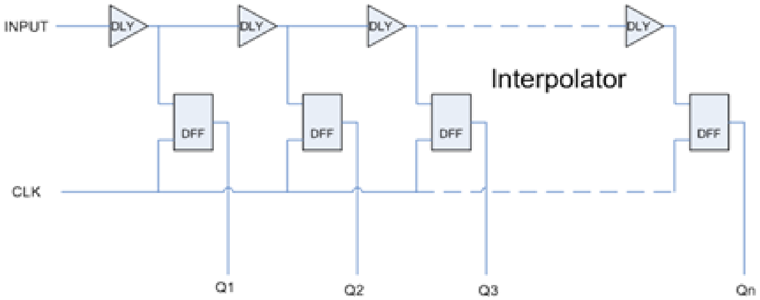
Time Interval Measurement – Time to Digital Conversion

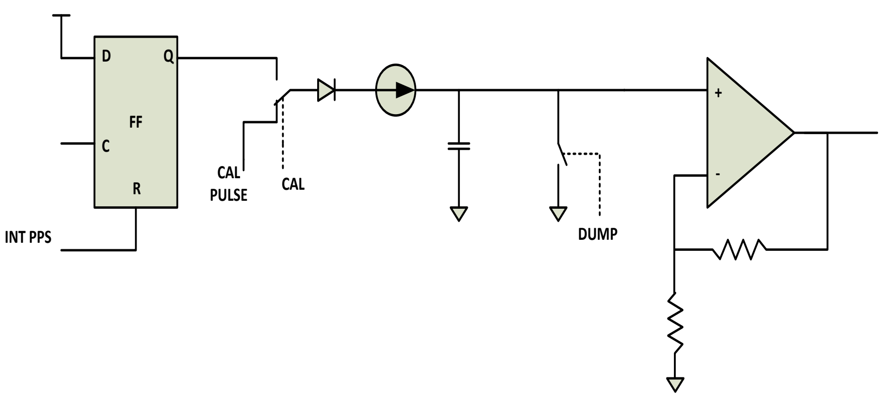
- Principal Advantage is the implementation in a single FPGA
- Technique uses a carry chain with circuit elements that validate the rising edge of the start pulse and compares the delay to the stop pulse.
- As an example a carry chain with a 30 ps resolution would require 167 elements for a 200 MHz clock
- 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.

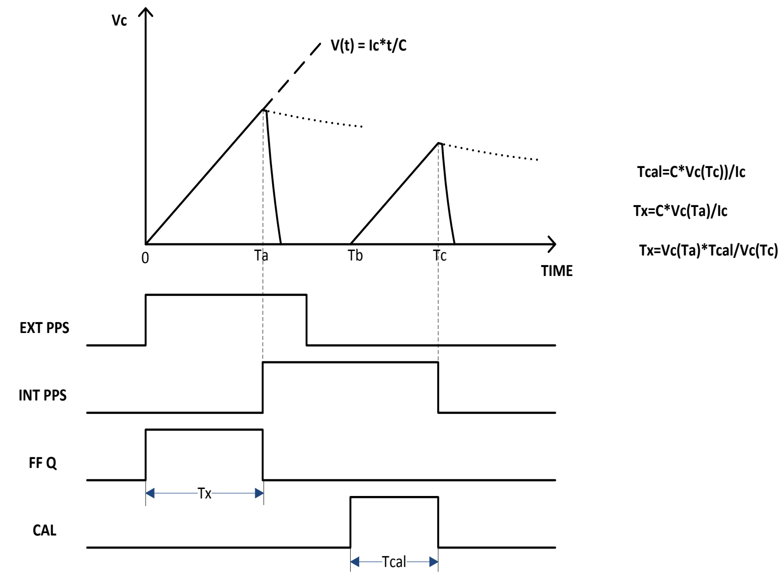




Time-Voltage Conversion

- 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 than 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

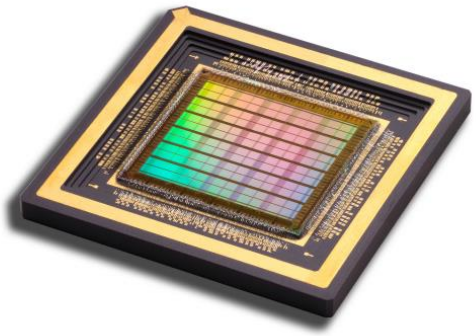




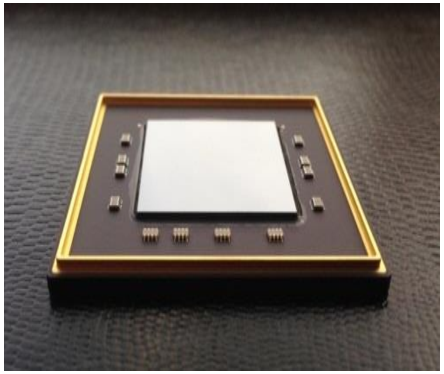
STM Design Description

- 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

Microsemi RTAX-D

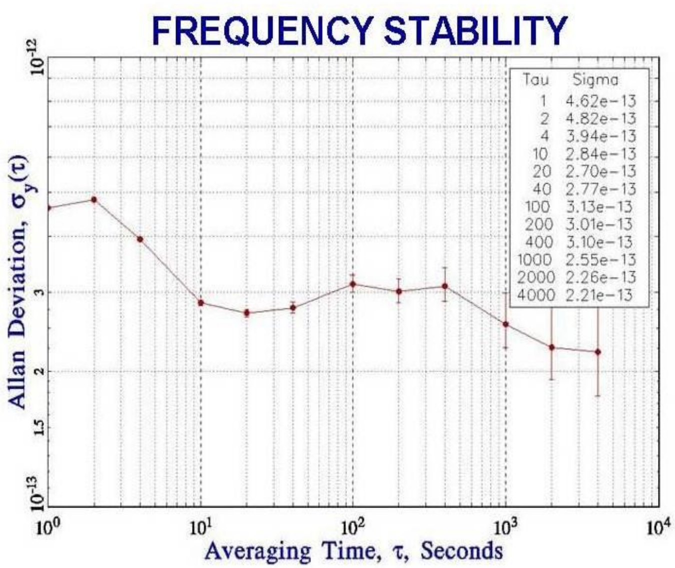


Microsemi RTG4

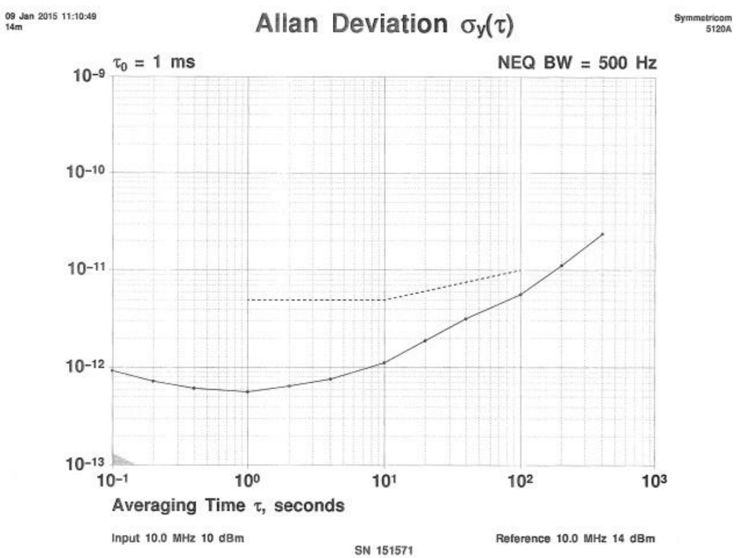


STM Measured Data

9500B STM Data



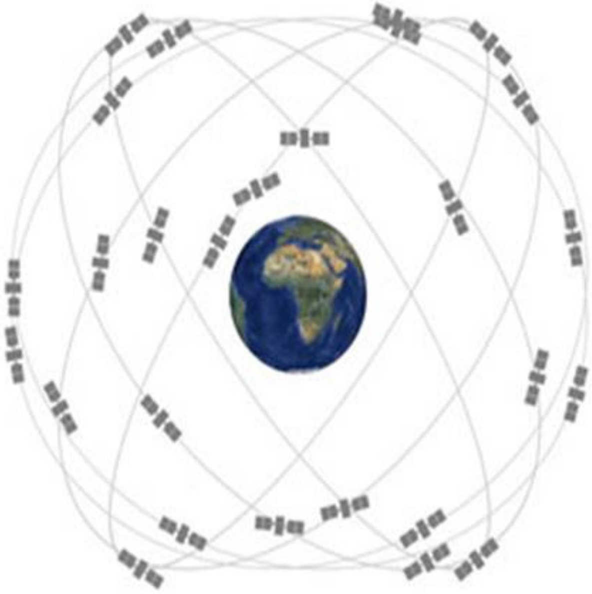
9735 OCXO



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

GPS Constellation



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 uses 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

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