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SATELLITE TIMING MODULES

Peter Cash
Microsemi, peter.cash@microsemi.com

Dan Boschen, Igor Kosvin, Sam Stein
Microsemi, dan.boschen@microsemi.com, igor.kosvin@microsemi.com, sam.stein@microsemi.com

ABSTRACT

Precision frequency sources are required for time keeping and metrology in communication and navigation satellites. The frequency sources for the satellites are typically quartz oscillators and in rare instances when absolute accuracy is required, atomic clocks. Frequency sources can then be used to establish a time base for each satellite or groups of satellites, typically with ground station support. All frequency sources are subject to change over time, usually referred to as drift or aging. As a result, the frequency and time must be adjusted remotely, a process that consumes effort and often impacts the accuracy of the local time. Autonomous and accurate local frequency and time for individual or constellations of satellites provide a significant improvement in current system's capabilities.

The availability of time by means of GNSS allows for adjustment of the local time of a system by means of one pulse per second (1 PPS) and delivered time of day information provided in the constellations. The use of Kalman filtering to steer high performance crystal oscillators provides high accuracy and stability while maintaining the long term performance of the GNSS on-board atomic clocks. Microsemi has developed a space-borne product that leverages heritage space ovenized oscillators and advanced Kalman filter algorithms that has demonstrated exceptional performance for 1 PPS steered and un-steered conditions. This paper will describe the module design, the basic methodology and steering architecture, and results of the simulations and measurements of hardware.

Ovenized Crystal Oscillators

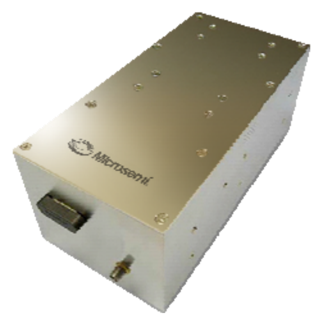
Ovenized crystal controlled oscillators (OCXOs) are the most frequency stable type of crystal oscillators. The quartz crystal is typically a stress compensated ("SC") cut 3rd or 5th overtone device. SC cut crystals are manufactured from made-made quartz that is grown in a high temperature and high pressure environment. This material is refined by applying a high electric field across the material and then subsequently cut into bars. This process, called sweeping, removes ionic impurities. The bar is then cut into individual wafers along an axis defined by two rotations that result in a specific temperature vs frequency curve and several performance advantages in comparison to singly rotated crystals. These advantages include high static and dynamic temperature stability, lower activity dip probability and drive level sensitivity, higher intrinsic Q, and lower radiation sensitivity.

Figure 1: Bliley 3rd Overtone Quartz Crystal

The crystal is used in an oscillator circuit which excites the crystal at the proper frequency and filters out undesired modes and overtones. Microsemi utilizes a modified Colpitts style circuit which includes an automatic gain control circuit and a varactor diode that electronically adjust the frequency of the oscillator. The voltage that biases the varactor circuit is controlled by means of high stability digital to analog (DAC) circuit. Sigma-Delta DAC architecture is used for very high precision and linearity. The high stability of these oscillators require that the voltage provided to adjust the frequency be extremely low noise and high resolution to allow for the external control within a control loop such as a Kalman filter or other similar application. In order to produces the best frequency stability; a high gain thermal control loop is utilized. The control loop maximizes the gain in thermal vacuum internal to a mechanical assembly optimized to minimize thermal gradients. The oven construction is dependent on the size, weight and power (SWaP) requirements for the application. Microsemi has two specific designs. The first is designed for minimal SWaP, the model 9700, uses thermal vacuum as an insulator and yields performance for Allan deviation on the order of 1×10^{-12}. The model 9500 includes a more complex electronic and mechanical design yields Allan deviation of 1×10^{-13}. This oscillator is usually classified an Ultra-Stable Oscillator (USO).

Figure 2: 9700 OCXO

Figure 3: 9500 Ultra Stable Oscillator

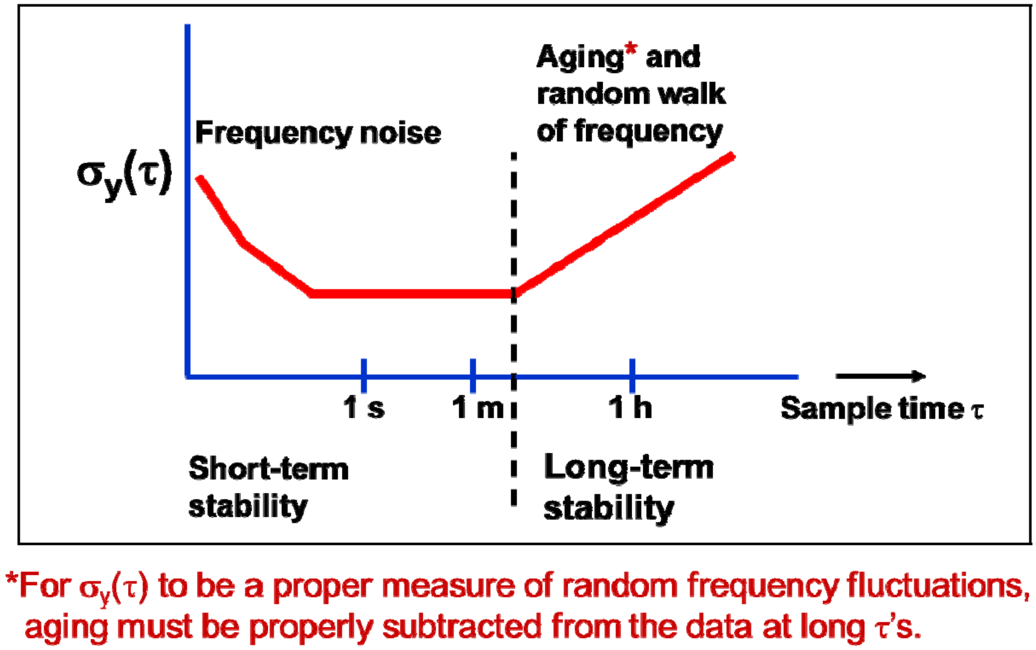


Allan deviation, or two sample variation, is an industry standard means of defining oscillator and atomic clock performance. Allan deviation is a statistical method for determining the frequency stability (or time stability) of precision sources that is optimized for the noise processes of quartz and atomic oscillators. An equation for the Allan variance is shown on the following page. The measurement is characterized over various time intervals from a fraction of a second to many thousands of seconds. In general, precision ovenized oscillators have good Allan deviations for time intervals of 0.1 to 100 seconds. Atomic clocks, depending on the specific type, have superior stability at 100 seconds and beyond because a relative lack of frequency drift compared to quartz oscillators.

Equation One

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

Figure 4: Allan Deviation of Typical Clock



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Kalman Filtering for Optimized Tracking Performance

Kalman filtering, first introduced by Dr. R. E. Kalman in 1960 in his famous paper "A New Approach to Linear Filtering and Prediction Problems," has been used in a wide range of tracking and prediction applications from navigation for the Apollo spacecraft to estimating user location in today's GPS receivers. The Kalman filter, a form of Bayesian estimation based on the squared error minimization and utilizing the knowledge of both the statistics and dynamics of a system, is an ideal choice for disciplining an oscillator to a long term reference signal such as GPS due to its performance improvements and ease of use. The Kalman filter is more computationally intensive compared to other traditional tracking loop methods. For today's low-cost processing resources for terrestrial applications this is no longer an issue for implementation, however for space application the selection of the necessary electronics capable of operation in a specific radiation environment is challenging.

The loop for tracking the oscillator's long term stability to GPS utilizes a proprietary Kalman filter algorithm (KAS-2) together with state variable feedback for optimized stability performance. A plot is shown in Figure 4 of the typical Allan Deviation (Adev) that can be achieved with the KAS-2 algorithm (blue) compared to the undisciplined oscillator Adev (black) and GPS PPS reference Adev (Green). The loop bandwidth for this particular system is approximately 1000 seconds, below which is achieved the superior short term stability of the oscillator and above the long term stability of the GPS signal. The output phase tracks the smoothed GPS phase so that the overall result outperforms the long term Adev input from the GPS receiver, and this effect is pronounced for lower

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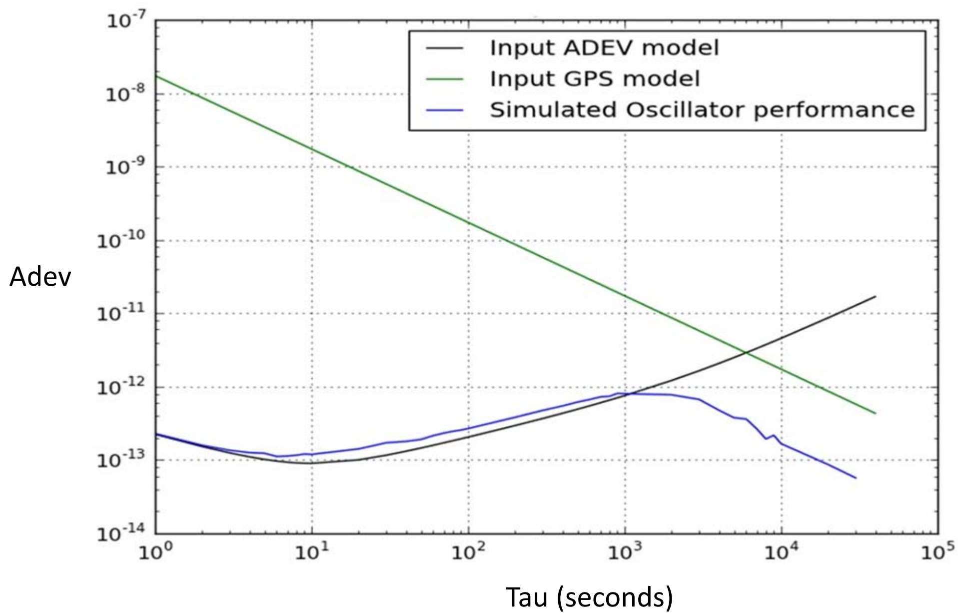
* "Quartz Crystal Resonators and Oscillators, A Tutorial", Dr. John Vig, US Army Communications-Electronics Command

flicker noise oscillators as they get to average the GPS signal longer and state variable feedback takes advantage of this configuration.

Figure 4: Simulated oscillator performance with Kalman filter showing achieved Allan Deviation



The Kalman filter functions optimally when the noise characteristics of the oscillator and reference signal are clearly understood. A very simplified explanation of the Kalman filter is that of a weighted exponential average, a recursive algorithm making use of noise statistics and current and past samples, to come up with the optimum prediction of what the next sample should be. In the context of the control voltage to a voltage controlled oscillator, the control voltage applied will be the best estimate of what it should be based on the past history of the error between the phase of the oscillator output and the reference epochs from the GPS receiver pulse-per-second (PPS) signal. The filter is represented as state-space model, and combines the statistics of the system with the dynamics of the system to come to the best estimate of the state of the system. The state can represent any number of unknowns; for a disciplined oscillator this is usually the frequency and phase of the system.

Functionally, the oscillator output is divided down to create a local PPS signal, which is compared to the reference (and noisier in the short term) PPS signal from a GPS receiver. The error signals, called innovations, when non-zero indicate errors in the time reference of the disciplined oscillator. Due to process and system noise the innovations will always be non-zero, but the goal is to minimize the squared error and thus optimize oscillator performance. The Kalman filter adjusts its state estimates to minimize the squared error between the state estimate and the true state. The adjusted state estimates are used for the control voltage to the oscillator and also fed back recursively for the estimation process.

Two advantages that the Kalman filter offers are that it adjusts its weighting optimally based on measurement noise, and that it can operate with only a partial set of measurements. As measurement noise decreases, the filter relies less on the state information (estimates) and more on the current measurements. During periods of absence of the GPS signal (holdover conditions), the Kalman offers superior tracking capability continuing to provide estimates of the future control voltage signal based on past estimates, including the frequency aging, while the GPS signal was available. Additionally the Kalman filter is dynamic and produces optimal estimates during the startup phase of measuring and feedback.

State variable feedback was chosen because it provides optimal control loop performance while taking the outputs of the Kalman filter as its inputs. Optimization of the feedback loop is subjective and application dependent. For example, a phase lock loop such as the one described above has a tradeoff between frequency smoothness and long-term wander; the lower the wander the greater the short-term frequency variations. Linear Quadratic Gaussian control may be used in order to compute gains that minimize a selected cost function and remove the subjectivity from the design process. The cost function should be derived from the application requirements.

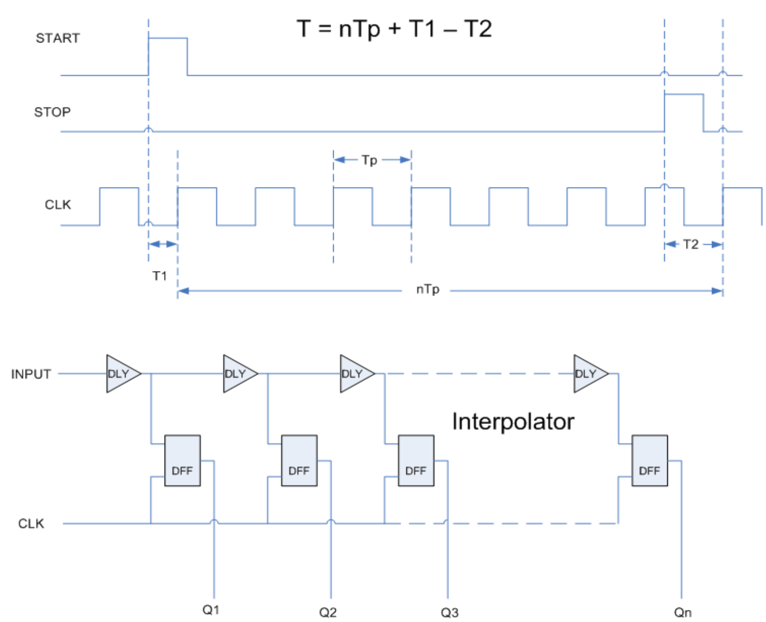
Time-Interval Measurement Techniques implemented in the STM

The accuracy and stability of the time difference measurements between local 1PPS signal and external 1PPS input signal are important parameters defining the overall system performance. The STM requires sub-nanosecond resolution and accuracy to achieve the target performance. Given limited component availability for Space applications we narrowed our approach to two methods: Direct FPGA TDC implementation and Time-Voltage Converter implementation.

Direct FPGA TDC Implementation

The main advantage of this method is that the implementation requires only one component – an FPGA. Over the years Microsemi has successfully used this method in COTS High Reliability applications. Most of the modern commercial FPGAs allow for a straight-forward implementation, the clock should be fast enough to give sufficient coarse resolution. The Interpolator is responsible for capturing the "fractional" part of the time difference and consists of number of sequentially connected delay elements. Each of the delay elements is paired with DFF element to capture the state of the delay chain at the end of the measurement. For the method to work, the number of individual delay elements should be sufficient so the overall time delay of these elements will be longer than one clock period of the CLK.

Figure 5: Time to Digital Conversion



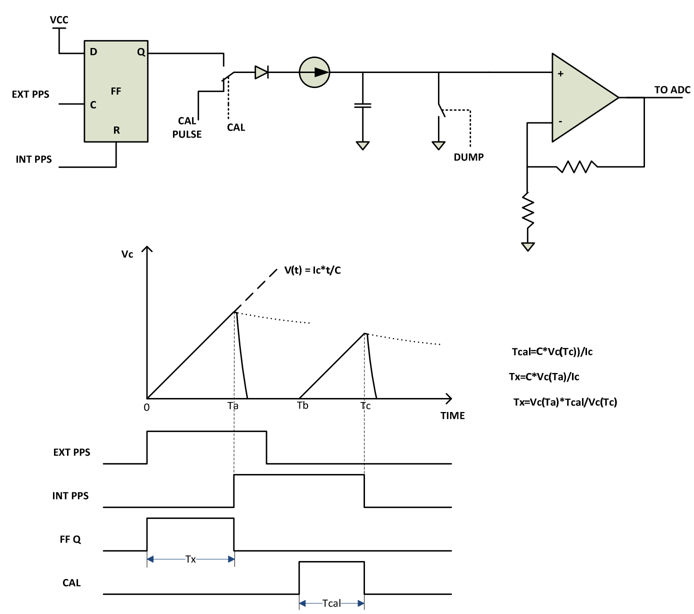
For example, if the clock frequency is 200 MHz and the propagation delay of each individual delay element is 30ps the delay chain should have more than 167 elements sequentially connected. Constructing such a long delay chains in FPGA is a challenge. It requires intimate knowledge of given FPGA architecture and ability to place the elements in a way to minimize routing delays between the elements and make them as uniform as possible.

Another challenge is the fact that the delay time of the individual elements is not calibrated. It changes over temperature and between different devices. We had to implement a calibration provision where we measure the number of elements in the delay chain that equal to one period of the clock. In addition, not many space FPGA devices can handle relatively high frequency clocks and allow design developer access to individual delay elements. So far we were able to implement this method in a Xilinx Virtex-5QV FPGA. Unfortunately, the radiation limitations of this FPGA make it unsuitable for many applications. Efforts are underway to move this approach to the next generation Microsemi RTG4, which is expected to have greater radiation hardness.

Time-Voltage Converter Implementation

While Direct FPGA TDC implementation allows to greatly reducing the number of required components, it requires use of high performance FPGA. Currently, most high performance FPGAs are SRAM based and has limited radiation hardness. For the most demanding radiation applications SRAM based technology is not suitable. The alternative way to achieve necessary accuracy and resolution of the Time Interval Measurements is to use Time-to-Voltage converter. The method itself is not new and has been used extensively in commercial applications before high performance FPGAs became affordable for mass-produced products.

Figure 6: Time to Voltage Converter Approach



The External PPS pulse rising edge activates current source that linearly charges the capacitor (see Figure 6 above). The Internal PPS pulse rising edge stops the current source and at this moment the capacitor voltage Vc is measured with ADC. By implementing calibration pulse that immediately follows the main measurement the variations of capacitance and current source over temperature or long term changes can be eliminated from the equations.

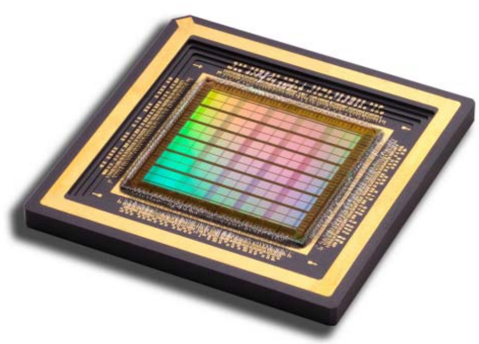
This method requires more components and still requires some Finite State Machine (FSM) implemented to control the CAL and DUMP signal timing, etc. Bit, since for the most applications the Time Interval Measurement circuit is part of the Phase Lock Loop (PLL), an FPGA or Microprocessor are already present in the system and can be used to implement the necessary state machine and routines necessary for retrieval of the measurements from the ADC. We found that use of medium performance Rad Hard FPGAs, like Microsemi RTAX series, is particularly attractive due to their ability to withstand high TID and SEU rates. Implementation of the PLL using this method does not require very high clock performance, as the time between the measurements (approx. 1 second) gives plenty of time margin for low clock frequency systems.

Satellite Timing Module Description

The Satellite Timing Module (STM) design uses a model 9500 or 9700 OCXO and a controller assembly to steer the oscillator using Kalman filtering described earlier in this paper. . The block diagram in Figure 9 shows the module design. The initial design of the product has been delivered with a Xlinix Vertex 5 FPFA approach for a benign radiation environment. The design included a 28 V power supply and specific output and input requirements for the Program. The power supply is designed within the requirements of a standard 100 krad radiation environment and established EMI/EMC requirements. The STM includes a high performance model Microsemi 9800 OCXO to maximize performance of the module. The 100 MHz OCXO is phase locked to the precision low frequency oscillator. The locked signal then provides the input to the Time to Digital Converter. Data is shown on the following page from the development hardware.

The production version of the STM will utilize a Microsemi RTAX-D for the moderate performance model 9700 based solution. The RTAX is a space qualified designed currently being used on several National Defense contracts with severe radiation environments. Experience on a current program has shown the Xlinix device to be unsuitable for more challenging requirements. The lower performance goals, < 1 x 10-12 Allan Deviation, allow for the use of 100 MHz TCXO. This oscillator offers reasonable performance while reducing size weight and power (SWAP.)

Figure 7 - Microsemi RTAX-D FPGA



The higher performance 9500 series based (Ultra stable Oscillator) STM solution will leverage the Microsemi RTG4. This FPGA is in the process of being released, tested for radiation hardness and qualified. The higher frequency capabilities will allow for higher levels of performance with a goal of Alan Deviation of 3×10^{-13} or better.

Figure 8 - Microsemi RTG4

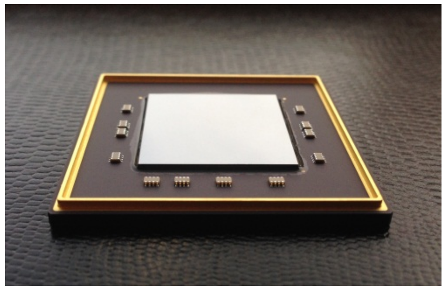


Figure 9: Satellite Timing Module functional diagram

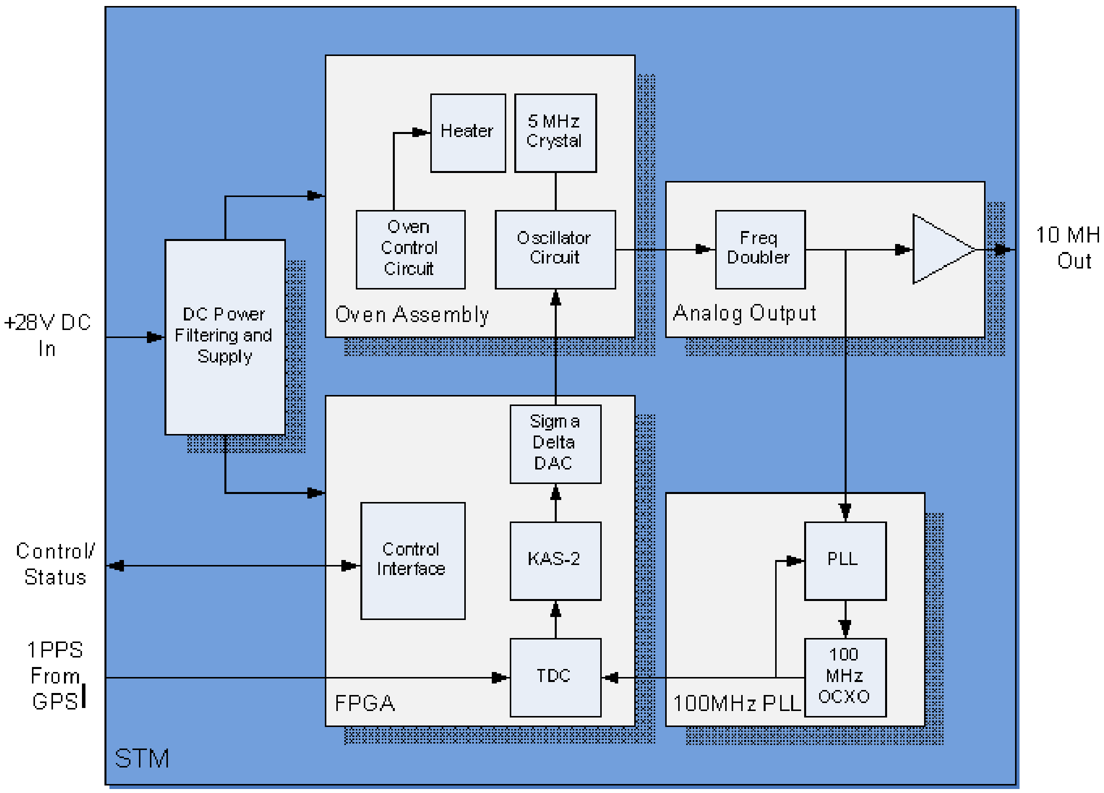
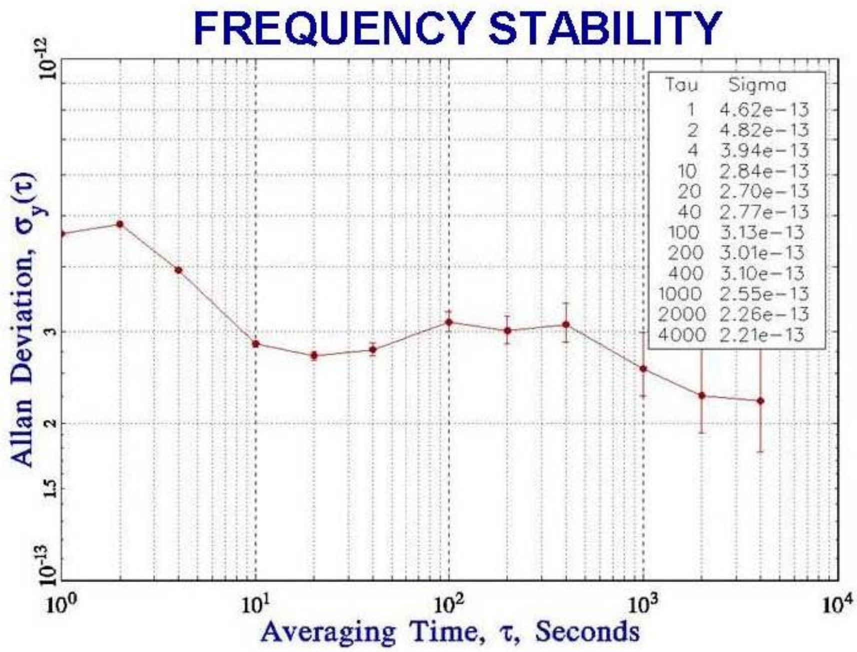


Figure 10 – Measured Allan Deviation



Conclusions

Microsemi has developed a new class of space qualified ovenized crystal oscillators that use GNSS derived 1 PPS data to optimize the performance of the clock. This Satellite Timing Module provides frequency and time to the payload that is traceable to the atomic clocks and can operate independently for limited time periods.

With one of the industry's most comprehensive portfolios of space products, Microsemi provides radiation-tolerant FPGAs, rad-hard mixed-signal ICs, rad-hard DC-to-DC converters, time and frequency solutions, linear and POL hybrids, custom hybrid solutions, and rad-hard discretes including the broadest portfolio of JANS Class diodes and bipolar products, Microsemi is committed to supporting our products throughout the lifetime of our customer programs

Acknowledgements:

1. "PTTI Systems Tutorial", Joe White, 2013 PTTI Meeting
2. "Time Recovery in the Field", Samuel Stein, 2010 PTTI Tutorials
3. "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications", John Vig, May 2013 PTTI Tutorials
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