

Precision Commercial of the Shelf (COTS) Oscillators for Space Applications

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ABSTRACT

Space missions are evolving and now span a wide range of orbits and mission lifetimes that require different methods of mitigation for radiation. Some missions now leverage commercial electronics that allow for state of the art performance at costs appropriate for the programs. Microsemi continues to provide timing for applications such as GPS and SBIRS that require stringent performance, reliability and radiation performance. In addition, Microsemi has adapted several products from either military heritage or commercial designs that have adequate radiation tolerances for short duration, CubeSat and low earth orbit (LEO) or experimental missions.

The presentation will describe Microsemi's COTS quartz oscillators and atomic clocks, and the results of radiation testing to 100 krads (Si.) In addition, background information regarding single event effect (SEE) radiation susceptibility of quartz oscillators to more severe environments that contain neutrons and heavy ions will be reviewed. Context for the decision to use of COTS products in comparison to radiation hardening by design will be provided.

Introduction

In the past, frequency sources for space such as crystal oscillators or atomic clocks were developed along the lines of radiation hard by design and testing of components and the clock in its entirety. Such approaches were needed because of long mission durations, beyond 15 years, and complex natural and man-made environments. In order to maximize the radiation hardness of clocks, common parts were leveraged with definitive radiation responsiveness. Frequently, retesting was performed as a greater understanding of the mission conditions was defined. Radiation analysis was then utilized to determine the changes in components parameters by the use of statistics, and these results used in Worst Case Circuit Analysis to validate that the clock would operate over the mission. Finally, radiation testing is performed on hardware as appropriate. Testing included 100% screening and/or radiation qualification testing.

Developing lower cost clocks have two distinct paths. The first path is to substitute commercial parts into an established radiation hardened design. The second path is to characterize commercial clocks under specific radiation conditions. This is similar to an up-screen approach. Microsemi is in the process of characterizing three different devices for applications in space. The first device is an ovenized crystal controlled oscillator, designated the model 9635QT. The second and third devices are commercial atomic clocks the SA45, referred to as the CSAC - Chip Scale Atomic Clock, and the SA33, referred to as the MAC – Miniature Atomic Clock.

9635QT

The 9635QT is based on the heritage designs of the Microsemi 9600 and 9700 ovenized crystal control oscillators. The design was developed in 1995 and updated approximately ten years later. Over 500 oscillators for this family have been launched into Commercial, Military and Scientific applications. The baseline design is

radiation hardened above 100 krad (Si), along with neutron insensitivity, SEL immunity and SEU acceptable behavior. As is the case with Microsemi's space qualified crystal oscillators, an adapted Colpitts configuration is employed for oscillation and the crystal of choice is a 3rd overtone SC (Stress Compensated Device.) The oscillator represents a good trade-off of high performance and SWaP (Size Weight and Power).



The 9600/9700 family of oscillators has been analyzed and tested numerous occasions with perform demonstrated in radiation testing laboratories and on missions. The space version of the oscillator includes established reliability and class S equivalent or higher reliability components. The crystal itself is manufactured using swept quartz and often radiation preconditioned to further reduce sensitivity. The 9635QT is a 10 MHz version of the oscillator; however COTs components are used for cost reduction. The crystal is not manufactured using swept quartz. Testing was performed to understand the total dose sensitivity of the oscillator. The testing was performed on two oscillators at the University of Massachusetts Lowell to a total accumulated dose of 100 krad (Si.) The results were very satisfactory with a typical change of less than 35 ppb, equivalent to a per rad of 3.5e-12, very similar to fully space qualified versions of the same oscillator.

Figure 1 – 9600/9700 Family of Oscillators

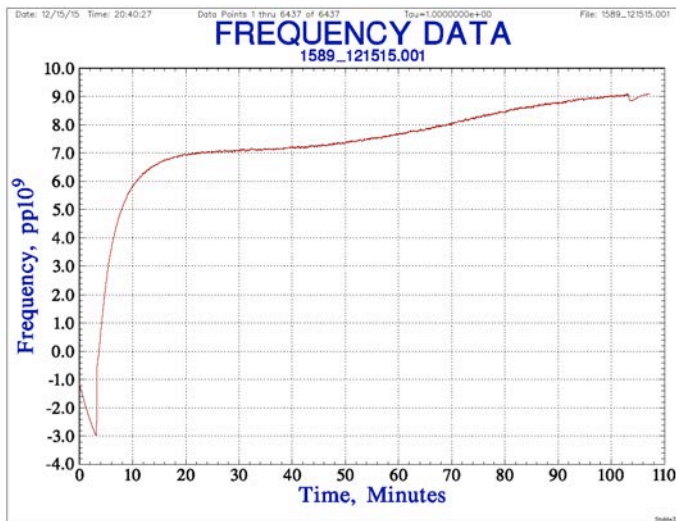


Figure 2 – 9635QT Frequency vs. Total Dose

After exposing the oscillators to the radiation, the proper operation was verified by characterization testing at the Microsemi facility in Beverly, Massachusetts. Although further testing for additional radiation environments, may be required, the 9635QT is an excellent candidate for CubeSat or LEO missions that require excellent performance at a moderate price. This is a result of the direct heritage to the space qualified design.

Chip Scale Atomic Clock

Microsemi's Chip Scale Atomic Clock or CSAC was developed for ultra-low power applications requiring an atomic clock. The key features are excellent SWaP with performance exceeding that of conventional ovenized crystal controlled oscillators. The power consumption of CSAC is less than 120 mW. This is significantly less than atomic clocks that have typical power of greater than 10 Watts. The CSAC provides a 10 MHz output as well as 1 Pulse per Second (PPS) and has the ability to be steered to a 1 PPS input. Another interesting capability is the CSACs time of day functionality. Microsemi has performed radiation testing on the clock in the 2013 to 2014 time

period and realized that performance in environments of up to 50 krad (Si) was reasonable by replacement of a radiation susceptible TCXO with a radiation tolerant device and increasing the shielding thickness . The paper presented on the Space CSAC is referenced at the end of this paper and provides a comprehensive summary of the oscillator.



Figure 3 – Space CSAC

SA33 – MAC Miniature Atomic Clock

Although the CSAC provides significantly improved accuracy and stability compared to crystal oscillators, design aspects required to achieve the very low power consumption have reduced performance compared to conventional Rubidium atomic clocks. Conventional Rubidium atomic clocks have been typically large and consumed significant power, and as a result have only been used in rare exceptions on Satellites such as the GNSS systems like GPS and Galileo. The same technology that allowed for the creation of the CSAC, Coherent Population Trapping, resulted in the development of a low power Rubidium oscillator. In this case, the SA33 provides high performance consistent with conventional clocks and requiring only 5 Watts of power at 25 degrees Centigrade. In addition, the size of the oscillator is 2" x 2" x 0.7". The end of this paper references a complete paper on the design and performance attributes of the SA33.

Total dose radiation testing was performed on two SA33 oscillators and operation was demonstrated to 10 krads (Si.) The oscillators lost lock at approximately 12 krads (Si). Analysis of the failure mode indicated the commercial TCXO inside of the clock. This was the same failure mode for similar testing of the CSAC. This TCXO could be replaced with a radiation tolerant version and the possibility of radiation shielding evaluated.

Another advantage of Microsemi's CSAC and MAC atomic clocks are the ability to survive high level of shock and vibration relative to typical commercial devices. The CSAC can withstand 2000 g's of shock and the MAC operating levels of vibration of 8 grms and survival above 30 grms.

The following page shows a photograph of the SA33 and a plot of the performance under radiation.



Figure 4 - SA33 Rubidium Oscillator

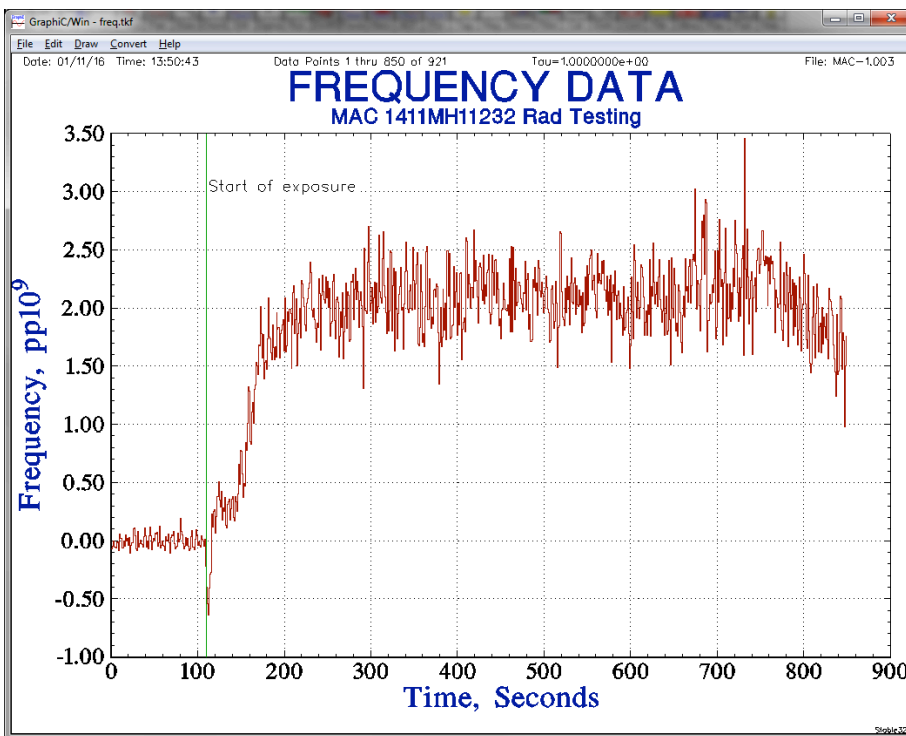


Figure 5 - Radiation Testing of SA33

Radiation Environments

Particular environments are highly dependent on the specific orbits and in turn the mission requirements. Beyond the effects of total dose, there are neutron response, SEE and heavy ion impacts. In general, these are less stringent than higher orbit applications. The fundamental design of the 9635QT, its similarity to the fully space qualified oscillators and simpler design makes it amenable to more challenging environments. The CSAC has been tested under more rigorous environments and shown stable performance. In principal, both the CSAC and MAC contain significant commercial components and are likely to be susceptible to SEE effects. A reasonable user case would be to use redundant devices. Specific testing would be required for these commercial oscillators that matched the mission conditions.

Comparison of Oscillators

Selection of the oscillator for an application depends on the specific performance requirements and system limitations. The following table shows the key performance parameters and options.

	9635QT	CSAC	MAC	Comment
Output	10 MHz sine wave	10 MHz CMOS 1 PPS	10 MHz CMOS	
Power Consumption	1.3 W	120 mW	5 W	Steady state 25 degrees C, vacuum
Frequency Accuracy	2×10^{-8}	5×10^{-10}	5×10^{-11}	At shipment
Temperature Stability	$\pm 2 \times 10^{-8}$	$\pm 5 \times 10^{-10}$	$\pm 2 \times 10^{-10}$	-10 to 70 °C
Phase Noise	≤ -95 dBc/Hz ≤ -125 dBc/Hz ≤ -145 dBc/Hz ≤ -150 dBc/Hz ≤ -155 dBc/Hz	≤ -50 dBc/Hz ≤ -70 dBc/Hz ≤ -113 dBc/Hz ≤ -128 dBc/Hz ≤ -135 dBc/Hz	≤ -70 dBc/Hz ≤ -87 dBc/Hz ≤ -114 dBc/Hz ≤ -130 dBc/Hz ≤ -140 dBc/Hz	@ 1 Hz @ 10 Hz @ 100 Hz @ 1 kHz @ 10 kHz
Aging (Drift)	9×10^{-9}	9×10^{-10} , typical	1×10^{-10}	Per month
Options		1 PPS Steering, Time of Day		

Conclusions

Satellite Missions have evolved over the past decade in which trade-offs have been made for duration, reliability, the ability to leverage high performance commercial electronics to achieve performance, price targets and reduced deployment times. High performance clocks can be adapted to support these objectives with minimal compromise for reliability. Microsemi's precision clocks the 9635QT, CSAC and MAC are unique products that are capable of meeting these missions.

References:

1. "Space CSAC: Chip-Scale Atomic Clock for Low Earth Orbit Applications", M. Stanczyk, P. Cash and Mike Silveira, 2014 PTTI Meeting
2. "SA.3Xm Rubidium Oscillator: Performance and Applications ", W. Krzewick, P. Gerry and J. Malcolmson, Microsemi, 2016 PTTI Meeting