THE SA.45S CHIP-SCALE ATOMIC CLOCK – EARLY PRODUCTION STATISTICS

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Abstract

Since the announcement of general availability of the SA.45s Chip-Scale Atomic Clock (CSAC) on January 18, 2011, Symmetricom has been ramping up production in order to meet customer demand for this new and disruptive technology. The SA.45s is the first commercially-available CSAC, with power consumption of <125 mW and short-term stability of $\sigma_y(\tau)$ < $2 \times 10^{-10}/\tau^{1/2}$. This paper will report early production statistics of SA.45s performance including power consumption, short-term stability, and temperature sensitivity. Environmental susceptibility measurements of production devices will also be presented, including mechanical shock, vibration, and total-ionizing dose radiation exposure.

INTRODUCTION

Symmetricom has been developing Chip-Scale Atomic Clock (CSAC) technology since 2001. Under sponsorship of the Defense Advanced Research Projects Agency (DARPA), Symmetricom, along with collaborators at the Charles Stark Draper Laboratory and Sandia National Laboratories, initially performed fundamental research into the optimum physics package architecture and interrogation strategy which led, ultimately, to the first demonstration of a fully integrated physics package, consuming < 10 mW of heater power and demonstrating performance (Allan deviation) of $\sigma_y(\tau) < 6 \times 10^{-10}/\tau^{1/2}$ **[1,2]**. In 2005, Symmetricom demonstrated the first fully autonomous CSAC and in 2007, presented at this conference the results of an initial prototype build of ten CSACs, capable of deployment in real-world applications and operating over a temperature range of 0 – 50°C **[3,4]**. These initial prototypes were distributed amongst a number of promising integration applications and strong positive feedback was received for the application of CSAC to wide range of emerging applications in secure communications, navigation, and remote sensing and data logging.

In 2009, based on encouraging feedback from the user community, Symmetricom initiated a program to develop a CSAC product, targeted at addressing a wide range of application scenarios in DoD and commercial systems. The result of this effort is the Symmetricom model SA.45s CSAC, initially released in January 2011, and now in full production at Symmetricom's Beverly, MA, manufacturing facility. The SA.45s is available in several configurations, corresponding to different output frequencies and operating temperature ranges, but the fundamental architecture and implementation are similar. The key specifications of the (option -002) SA.45s are:

Instability (Allan Deviation):	$\sigma_y(\tau) < 2 \times 10^{-10} / \tau^{1/2}$
Long-term Frequency Drift:	$d\bar{y}/dt < 3 \times 10^{-10}$/month
Operating Temperature Range:	-40°C to +85°C

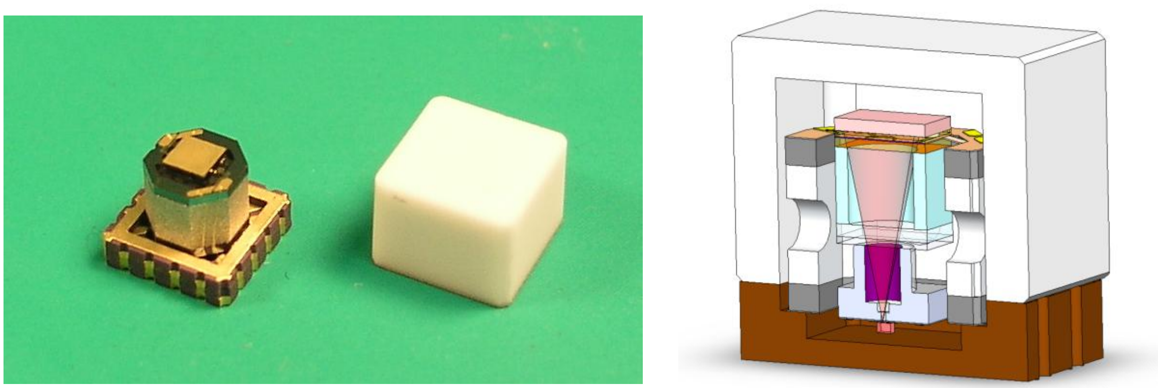
At this time, a statistically significant number of SA.45s CSACs have been produced and tested. This paper provides a brief overview of the SA.45s architecture, assuming that the reader is already familiar with the design from previous PTTI presentations. The majority of the paper presents production statistics of the key performance parameters based on the devices shipped to date. In the final section we present preliminary results of extreme environmental testing of the SA.45s, including mechanical shock and vibration and exposure to ionizing radiation.

SA.45S ARCHITECTURE OVERVIEW

This section provides a brief review of Symmetricom CSAC technology, which has been described extensively in previous PTTI Proceedings and elsewhere **[1-6]**.

PHYSICS PACKAGE

The SA.45s has package has evolved only slightly from the original CSAC design, principally to accommodate improved fabrication processes as the device has been transitioned from prototype laboratories to high-volume manufacturing. Other minor improvements have been implemented to improve performance and/or manufacturing yield.



(a) (b)

Figure 1. SA.45s physics package (a) photo and (b) cross-section.

Figure 1(b) shows a cross-section of the SA.45s physics package. The heart of the physics package is the cesium vapor cell, shown in light blue, which contains a small quantity of cesium metal, along with a temperature-compensated mixture of buffer gases. The cell is heated to >85°C to generate a dense cesium atomic vapor. The light from a Vertical-Cavity Surface Emitting laser (VCSEL, at bottom) passes through the vapor cell and is measured by a photodiode (at top). This assembly is held on a high thermal-resistance polyimide suspension and sealed inside an evacuated ceramic package to eliminate gaseous convection and conduction. The overall thermal resistance of the package is ≈5000°C/W, such that the vapor cell assembly can be heated to 90°C in a 25°C ambient with only 13 mW of heater power.

In operation, the SA.45s servos the frequency of its 10 MHz local oscillator to the frequency of the ground state hyperfine resonance of the cesium atoms contained in the physics package. Conceptually, the physics package implements a high "Q" filter at the cesium frequency, roughly 9192 MHz. The current of the VCSEL is modulated at one-half of the cesium frequency, 4596 MHz, to produce a pair of coherent first-order sidebands separated by 9192 MHz. These two sidebands generate a coherence between the two ground states, mediated by the laser-coupled excited state, which can be observed, when on resonance, by a measurable increase in the optical transmission of the vapor cell. A typical resonance spectrum is shown in Figure 2, below.

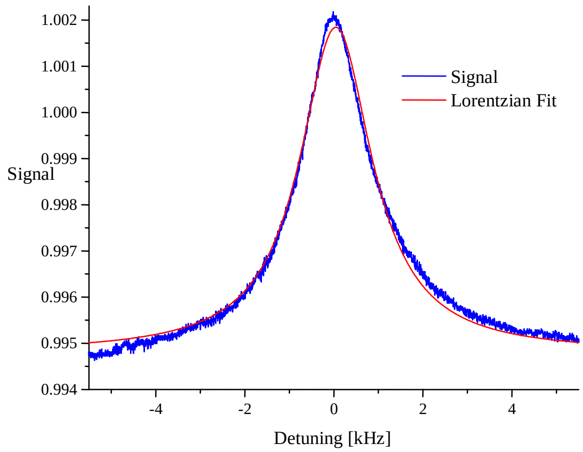


Figure 2. SA.45s CPT Resonance raw data (blue) and Lorentzian fit (red).

Figure 2 shows the CPT resonance spectrum from typical SA.45s production physics package. As shown in the figure, a Lorentzian fit to the resonance line exhibits a line width of $\gamma = 1.98$ kHz, with a fit quality of $R^2 = 0.993$. Using the formalism of **[1]**, this device exhibits contrast of $\eta = 0.7\%$, leading to figure-of-merit, $\xi = 3.5$ ppm. This is fairly typical of the production SA.45s CSACs, most of which exhibit contrast of $\xi = 3\text{-}4$ ppm.

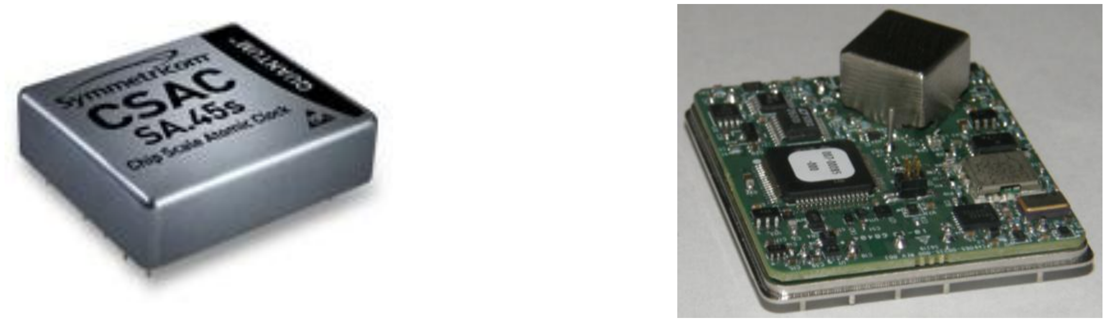
The dimensions of the sealed physics package are 7 x 7 x 7 mm (350 mm^3). Electrical connections are made to the host PCB via the feedthroughs of the ceramic leadless chip carrier (LCC) which serves as the base of the vacuum package.

ELECTRONICS AND PACKAGING

The SA.45s electronics architecture is similarly derived from the prototype designs, which have been extensively described at previous PTTIs **[3,4]**. In addition to the physics package, the principal components of the CSAC are the 10 MHz local oscillator (LO), the 4596 MHz microwave synthesizer, and the control electronics which servo the LO frequency, translated by the synthesizer, to the atomic resonance signal from the physics package.

The SA.45s LO is a low-power temperature compensated crystal oscillator (TCXO), whose 10 MHz CMOS output provides the reference input to the microwave synthesizer as well for the CSAC 10 MHz and 1 pulse-per-second outputs. The microwave synthesizer consists of a 4596 MHz LC VCO, which is phase-locked to the 10 MHz LO with an integrated circuit fractional-N phase-lock loop. The microwave synthesizer provides a tuning resolution of 3 mHz at 4596 MHz, i.e. 7 parts in 10^{13}.

The microwave synthesizer, as well as the tuning of the LO and other key parameters are under the control of a low-power digital signal processor (DSP). In addition to implementing the main clock frequency servo, the DSP maintains independent servos to optimize the physics package operating temperature, laser bias current, and microwave power level **[3]**. A serial communications interface on the DSP allows external control of the SA.45s operating state and tuning as well as monitoring of internal parameters and alarms.



(a) (b)

Figure 3. SA.45s (a) sealed and (b) with lid removed.

Figure 3 shows photos of the SA.45s (a) fully packaged and (b) with the hermetic lid removed. All SA.45s electronics are implemented on a single side of a single printed circuit board (PCB), as shown in Figure 3(b). The physics package is mounted on the PCB and contained within a high-permeability mu-metal shield. The DSP and analog signal processing electronics are located in the upper right of the PCB, as oriented in Figure 3(b) and the microwave synthesizer is in the lower right. Electrical signals from the SA.45s are provided on hermetic feedthroughs through the baseplate, so that the SA.45s can be mounted on a host PCB similar to other through-hole components. After the top cover is welded, as shown in Figure 3(b), the SA.45s is fully hermetic, providing immunity from humidity and other atmospheric contaminants. The outer package of the SA.45s is fabricated from mu-metal, thus providing a double-shielded configuration to reduce the magnetic susceptibility of the physics package.

IMPLEMENTATION AND APPLICATION

The overall dimensions of the SA.45s are 1.39” x 1.6” x 0.45” (1.0 in^3) and it weighs 35 g. It is powered at 3.3 VDC and typically consumes < 38 mA (125 mW) in a 25°C ambient environment. Two outputs are provided as 3.3 V CMOS levels, 10 MHz and 1 pulse-per-second (PPS).

The SA.45s 1 PPS output may be synchronized to an external timing reference, such as GPS, to within one clock cycle (+/- 100 ns) of a pulse applied to the 1 PPS input. For improved timing and frequency synchronization, an internal phase meter with resolution of < 500 ps allows the SA.45s to self-discipline its phase and frequency to an applied reference source.

A voltage tuning input allows the frequency of the SA.45s to be tuned with an analog voltage for retrofit into legacy (quartz oscillator) applications. In new applications, the frequency of SA.45s is typically digitally tuned via the serial communications interface.

TYPICAL PERFORMANCE

This section presents illustrative performance data for the SA.45s. Insofar as possible, these are truly “typical” randomly-selected data sets from production devices.

SHORT-TERM STABILITY

Figure 4 shows the short-term stability (Allan deviation) of an SA.45s. The instability at averaging time of $\tau = 1$ second is $\sigma_y = 8 \times 10^{-11}$. For intermediate averaging time, τ, the stability improves according to the $1/\tau^{1/2}$ character which typifies passively-interrogated atomic frequency standards. For longer times, $\tau > 10^4$

seconds, the stability is degraded due to the long-term frequency drift of the physics package, in this case $\approx 3 \times 10^{-10}$/month.

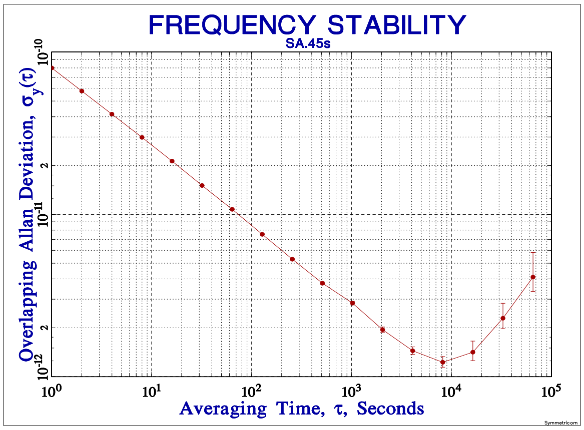


Figure 4. SA.45s typical short-term stability.

LONG-TERM STABILITY

Figure 5 shows frequency and power performance of an SA.45s over a 9 month interval, beginning shortly after the device was assembled. This graph illustrates what we have found to be characteristic frequency aging performance of the SA.45s, i.e. it is fairly steep early in life but continues to improve for as long as the SA.45s is operating. Note the discontinuity in the data collection for this device, around MJD 55650, when the test equipment (and the SA.45s) was powered down for several days and relocated to a different facility. The power consumption of the SA.45s, shown in the upper trace of Figure 5, shows diurnal fluctuations in response to changes in ambient temperature, but otherwise holds fairly constant, to within 1 mW, over the dataset.

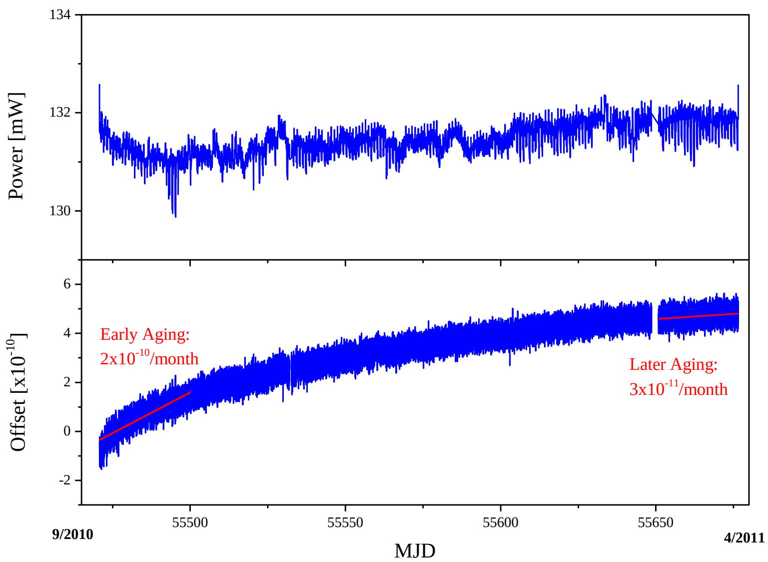


Figure 5. Long-term frequency drift.

Really Long-Term Data

Figure 6 shows the latest frequency data from a very early CSAC prototype, SN084, which was built in 2006 and has been operating nearly continuously for over 5 years. Note that this is a very long dataset on a very early prototype, so some allowance must be made for the various power cycles, data outages, etc. on the plot. Following an initial period of rapid negative frequency aging, CSAC SN084 evolved to a positive aging curve quite similar to that which we observe on the modern SA.45s. After the first year of operation, the aging was below 5 x 10^{-11}/month and, for the most recent three years, has been consistently below 1 x 10^{-11}/month. Note that this compares quite favorably to conventional high-power rubidium oscillators, which are typically specified at 5 x 10^{-11}/month.

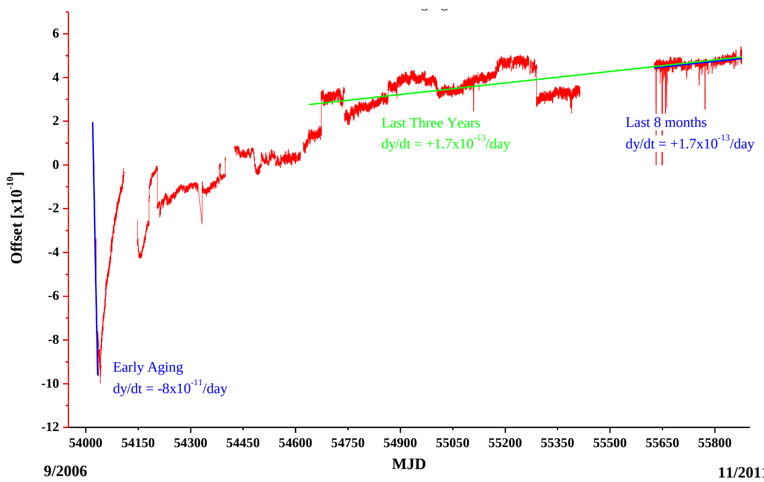


Figure 6. Good ol' SN084 frequency aging data.

There is an interesting story about the 9 month data outage around MJD 55500. We had a power outage in our building in June, 2010, after which SN084 failed to reacquire atomic lock. Because this was such an early prototype, with prototype electronics and firmware, and because it had already served its useful purpose, we decided that it was not worth the time or effort to attempt to diagnose the failure. The device was forgotten, ignored and left (powered on) in a corner of the laboratory. Nine months later, with no external intervention, SN084 reacquired lock, as shown in Figure 6, and the frequency and aging behavior picked up essentially where they had left off 9 months earlier.

Performance over Temperature

Figure 7 shows typical performance for an option -002 SA.45s when operated in a temperature-controlled environmental chamber over the range of -40°C to +85°C. The upper and middle plot show the frequency offset and power consumption, respectively. Over the 125°C temperature range, the frequency offset varies by roughly 4 parts in 10^{10}, though it's interesting to note that, at least for this unit, nearly three-quarters of the error accumulates between 70°C and 85°C.

The power consumption of the SA.45s varies by 20 mW over the 125°C temperature range, about 20%. This is a remarkable result because, based solely on the thermal resistance of the physics package (5°C/mW), one would expect somewhat higher power consumption at lower temperatures. However, as Figure 7 shows, the increase in power consumption of the physics package is somewhat offset at lower temperatures by increased efficiency of the microwave VCO and synthesizer electronics.

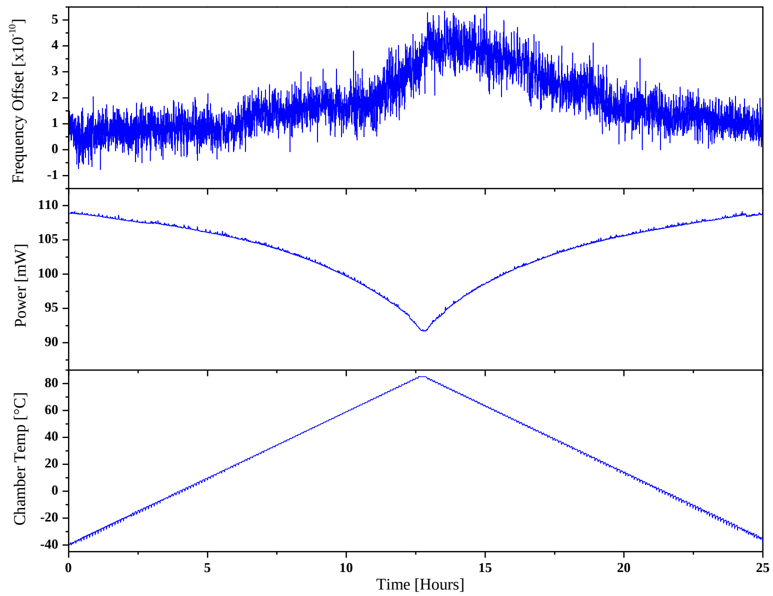
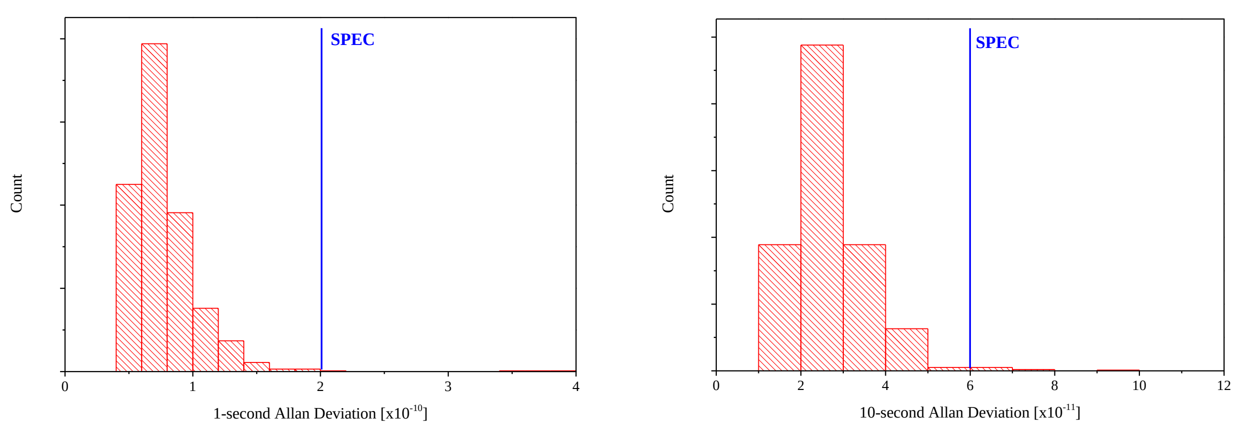


Figure 7. SA.45s Temperature sensitivity.

PRODUCTION STATISTICS

This section presents statistical analysis of key performance parameters, based on a statistically significant sample of nearly identical SA.45s CSACs delivered to customers between February, 2011 and November, 2011. It is important to note that these statistics include both options of SA.45s, -001 and -002, which have slightly different specifications. Where relevant, the distinctions between the specifications are identified.

SHORT-TERM STABILITY



(a) (b)

Figure 8. Variance of production SA.45s Allan deviation (a) τ = 1 s and (b) τ = 10s.

Figure 8 shows the production statistics for the Allan deviation short-term stability of the delivered SA.45s CSACs at (a) τ = 1 second and (b) τ = 10 seconds. These distributions have medians of 7.1 x 10^{-11} and 2.4 x 10^{-11} respectively, each roughly 2-3X superior to specification.

POWER CONSUMPTION

Figure 9 shows the production statistics for power consumption of SA.45s, measured at room temperature, ≈ 25°C. The median of this distribution is 102 mW, approximately 20% superior to specification.

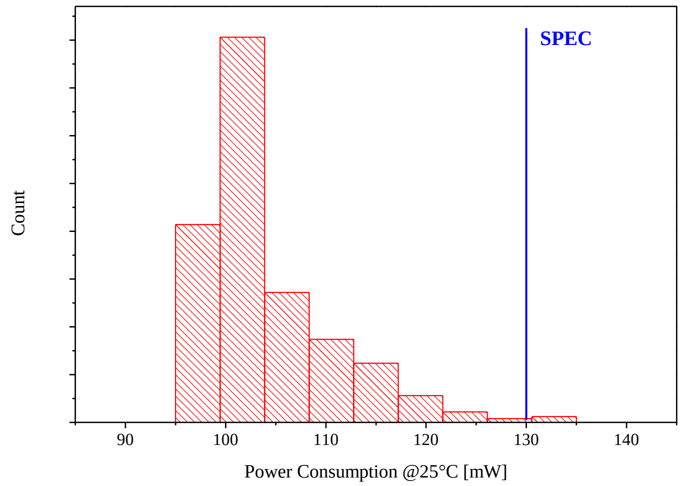


Figure 9. Variance of SA.45s power consumption production units at 25°C.

Figure 10 shows the variance of the physics package heater power for the production SA.45s devices. The median of this distribution is 11.3 mW. Again, this shows good margin with respect to our design objectives and production specifications.

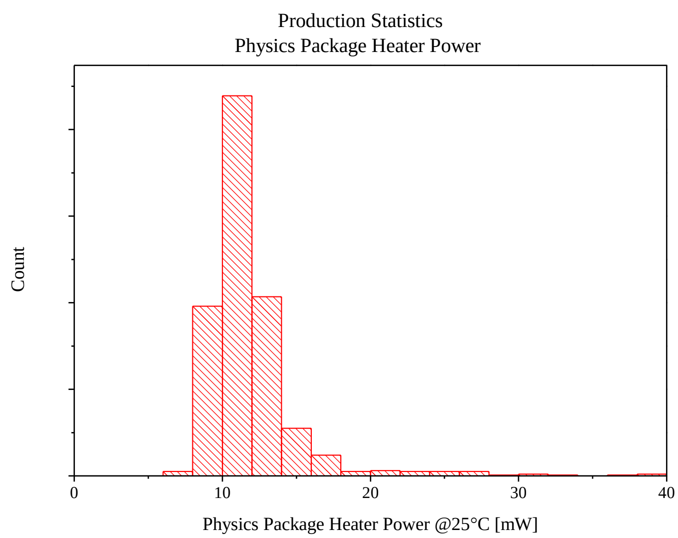


Figure 10. Variance of production SA.45s physics package heater power.

TEMPERATURE SENSITIVITY

Figure 11 shows the production statistics for the maximum frequency variation as each SA.45s is operated over its full temperature range, in an environmental test chamber, as part of its factory test procedure. The median of this distribution is 1.6 x 10^{-10}, well within the -002 specification of 2 x 10^{-9}. Note that this data includes both -001 and -002 SA.45s CSACs, which have different specified temperature ranges, -10°C to +70°C and -40°C to +85°C, respectively but that, for each case the total frequency error is specified *over the specified range for the device*.

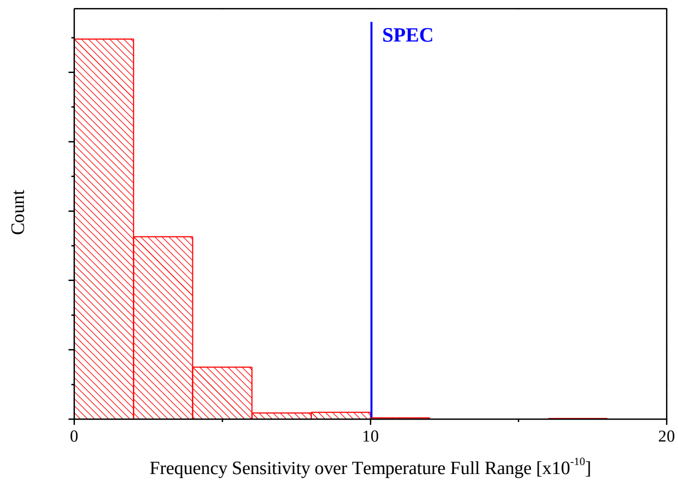


Figure 11. Frequency sensitivity to temperature over full operating ambient.

EXTREME ENVIRONMENTAL TESTING

This section describes extreme environmental testing that has been performed on a limited number of SA.45s CSACs.

PERFORMANCE UNDER VIBRATION

The functional performance of the SA.45s CSAC under vibration is not specified on the Symmetricom Data Sheet since it is impossible to predict how a customer will secure the unit in a particular application. Nonetheless, many applications require survivability and performance in high vibration environments and controlled testing is of value when evaluating the SA.45s for those applications.

Table 1. Vibration Profiles Mil-STD-810G.

Frequency (Hz)	0 dB Test	+6 dB Test
	PSD Level (g^2/Hz)	PSD Level (g^2/Hz)
20	0.04	0.16
1000	0.04	0.16
2000	.0100475	0.0401902
Overall (grms)	**7.70**	**15.40**

A sample of five randomly selected SA.45s CSACs were subjected to random vibration at integrated levels of 7.70 grms and 15.4 grms per Mil-STD-810G, Method 514.6, Procedure I, Category 24, General Minimum Integrity, as shown in Table 1.

The output frequency and ADEV were monitored continuously as each CSAC was sequentially subjected to the specified vibration profile along each of its three principal axes.

Typical results for one SA.45s at 7.7 grms are shown below in Figure 12; others are similar.

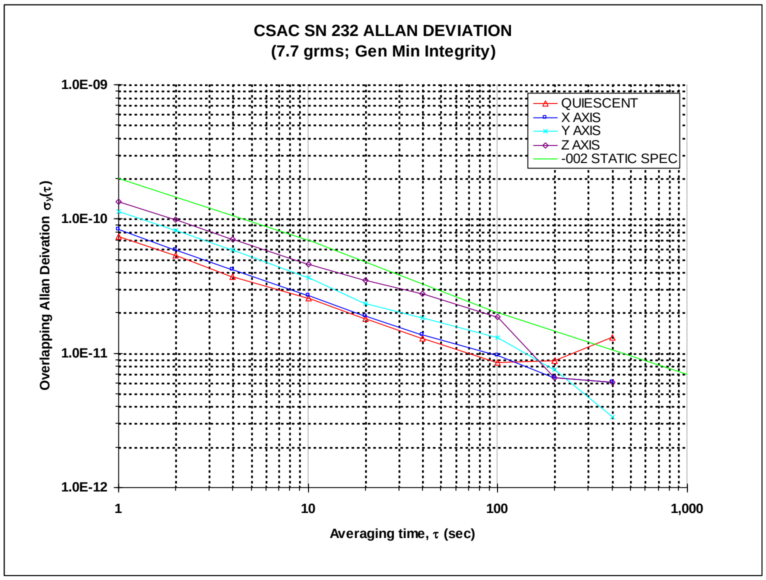


Figure 12. Frequency stability of SA.45s under 7.7 grms random vibration.

Figure 12 shows the specified stability for the SA.45s -002 (green line) along with the static performance (red line) and the performance while the devices was randomly shaken, according to the 7.7 grms profile of Table 1. Of the five devices tested, all were quite similar: at 7.7 grms along the *x*- and *y*-axes (in plane), the SA.45s shows little degradation of performance. Only when shaken out of plane (orthogonal to the broad face of the SA.45s) is significant degradation observed.

This is extraordinarily good performance for an atomic clock. Conventional mil-spec rubidium oscillators are generally specified to maintain lock up to 7.7 grms, but the stability is typically degraded by several orders of magnitude. We attribute the high level of vibration insensitivity of the SA.45s to the low-mass, integrated design, and mechanical suspension of the physics package. Note that this result suggests that, in high vibration environments, the SA.45s CSAC could be expected to outperform conventional rubidium oscillators, despite having inferior quiescent specifications.

The five SA.45s CSACs were further subjected to additional testing at 2X the vibration levels, 15.4 grms, according to the second column of Table 1. All five devices maintained lock in all orientations at 15.4 grms, though the stability was visibly degraded. Nonetheless, four of the five devices still met the quiescent spec when vibrated in-plane, while all five exceeded the spec by approximately 10X when vibrated out-of-plane.

The complete results of the vibration testing (and shock testing, below) are documented in Symmetricom document # 796-00680-000 **[7]**.

Mechanical Shock

Five SA.45s CSAC units were subjected to mechanical shock testing per MIL-STD-202G, Method 213, Test Condition E. The devices were subjected to three 0.5 msec half-sine shock pulses in each direction (+/- Axis), in each axis, for a total of 18 shocks at each shock level.

Due to instrumentation problems, not all of the five units were tested to the full 1000 g shock level, as specified in MS-202G. Two units were only tested to 500 g, while one was tested to 1500 g and two were tested to 2000 g. The units were tested un-powered, and after each test axis, the units were functionally tested.

No failures were detected in any of the shock testing.

While it would be desirable to test additional units, as well as to continue testing to determine the limit of failure, we conclude at this time, based on this testing, that the SA.45s CSAC design will meet the Test Condition E, 1000 g, 0.5 msec shock test requirement.

Exposure to Ionizing Radiation

Two SA.45s CSACs were subjected to Total Ionizing Dose (TID) high-energy gamma ray exposure at the University of Massachusetts, Lowell, "gamma cave" facility. SA.45s performance was continually monitored as repeated exposures were performed.

Figure 13 shows the data set from the testing of one of the two devices. The lowermost trace (red) indicates the total accumulated dose over a time span of approximately 30 minutes. Not surprisingly, the performance of the CSAC is seriously degraded during the exposure intervals, but it recovers between exposures. The plot ends after total exposure of 12 kRad, at which point the SA.45s lost lock and failed to recover. It is important to note that the most critical component of the physics package, the VCSEL, appears to be unaffected by the exposure, as indicated in the second plot from the bottom. Also, the physics package "contrast" (second from top), which is an indicator of the overall state-of-health of the physics package, degraded by only 1% over the total exposure.

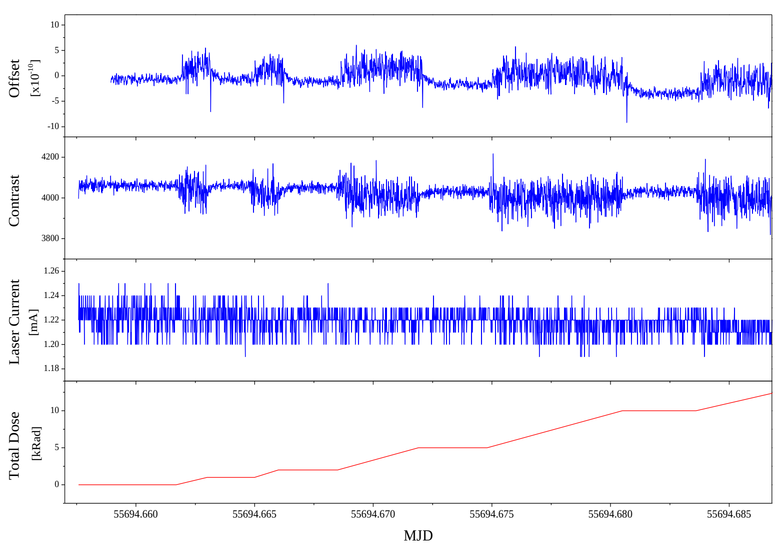


Figure 13. Impact of total dose radiation exposure on SA.45s CSAC.

The effect of TID on the output frequency of the SA.45s can be estimated by reducing the data in the quiet intervals between exposures, as plotted below in Figure 14.

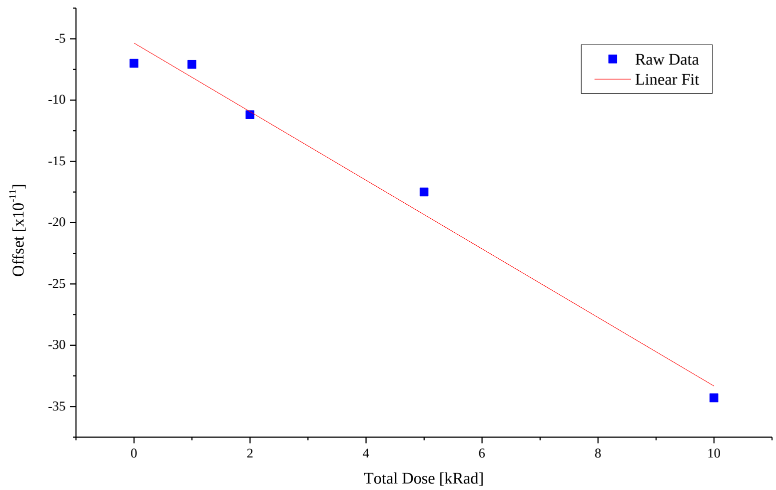


Figure 14. Frequency Offset due to TID exposure.

Up to 10 kRAD TID, the SA.45s showed total frequency offset of ≈ 3 x 10^{-10}. The linear fit in Figure 14 has a slope of -2.8x10^{-11}/kRad and fit quality of adj-R^2=0.98.

The performance of the second SA.45s subjected to TID exposure was virtually identical to the first, and failed irreversibly between 11 and 12 kRad. The frequency sensitivity of the second device was measured to be -2.2x10^{-11}/kRad.

Following TID testing, the two devices were returned to Symmetricom engineering for diagnosis. It was determined that, in both devices, the principal failure mechanism was one of the signal recovery operational-amplifiers, whose input impedance had dropped to zero. One of the two also indicated a failure of the TCXO. The components were replaced and both SA.45s devices were tested to comply with original specifications.

These are very promising results for the application of CSAC to low-earth orbit (LEO) applications, where the TID over a mission lifetime is typically < 100 kRad. Calculations show that a 10X shielding factor could be accomplished with a modest increase in the thickness of the outer mu-metal housing of the SA.45s. This suggests that, with a minor packaging modification, the “standard” factory SA.45s could provide a low-cost, low-power precise timing source for small LEO satellites.

ACKNOWLEDGEMENTS

The SA.45s has been born of the tireless efforts of dozens of dedicated professionals, each of whom has stretched his unique talents to new extremes. In broad categories, the author gratefully acknowledges the original CSAC development team including the Symmetricom Research Group, led by R.M. Garvey, the MEMS Group at The Charles Stark Draper Laboratory, led by M. Varghese and M. Mescher, and the Opto-Electronics Group at Sandia National Laboratories, led by D.K. Serkland. The Symmetricom Engineering Group, led by J. Dansereau, turned the DARPA CSAC into the SA.45s product. Transition to production was accomplished by the Symmetricom Operations and Manufacturing Engineering Groups. The mechanical shock and vibration testing and the radiation testing were performed by L. Zanca and M. Stanczyk, respectively.

REFERENCES

[1] R. Lutwak, et al., 2002, *"The Chip Scale Atomic Clock – Coherent Population Trapping vs. Conventional Interrogation,"* in Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 2002, Reston, Virginia, pp. 539-550.

[2] R. Lutwak, et al., 2004, *"The Chip Scale Atomic Clock – Low-Power Physics Package,"* in Proceedings of the 36th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 2004, Washington, D.C., pp. 339-354.

[3] R. Lutwak, et al., 2005, *"The MAC – A Miniature Atomic Clock,"* in Proceedings of the 2005 International Frequency Control Symposium, 29-31 August 2005, Vancouver, Canada, pp. 752-757.

[4] R. Lutwak, et al., 2007, *"The Miniature Atomic Clock – Pre-Production Results,"* in Proceedings of the 2007 Joint Meeting of the European Time and Frequency Forum and the IEEE Frequency Control Symposium, 29 May – 1 June 2007, Geneva, Switzerland, pp. 1327-1333.

[5] M. Mescher, R. Lutwak, and M. Vaqrghese, 2005, *"An Ultra-Low-Power Physics Package for a Chip-Scale Atomic Clock,"* in Transducers '05, IEEE International Conference on Solid-State Sensors and Actuators, 5-9 June 2005, Seoul, South Korea.

[6] D. K. Serkland, et al., 2007, "VCSELs for Atomic Sensors," **Proceedings of the SPIE**, **Vol. 6484**.

[7] Symmetricom document 796-00680-000. Available on request.