Effects of Radiation on Performance of Space-Borne Quartz Crystal Oscillators

M. Bloch, O. Mancini, T. McClelland
Frequency Electronics, Inc.
55 Charles Lindbergh Blvd.
Mitchel Field, NY
martinb@freqelec.com, oliem@freqelec.com, tomm@freqelec.com

Abstract - **An essential component of any space vehicle is the onboard master oscillator. The proper operation of the entire payload is dependent on the performance of the master oscillator (or onboard clock). One of the major concerns for quartz clocks in space is the effect of space radiation. Quartz is inherently sensitive to naturally occurring radiation in space. The exact nature of the radiation experienced in space is a function of the orbital dynamics of each particular application, and the impact of that radiation on quartz oscillator performance depends on each particular mission's requirements. Extensive tests on Earth have revealed some very interesting results that can be used to predict performance in space. This has made possible the development of a radiation compensated quartz crystal oscillator, with improved frequency aging performance. The frequency aging rate is extremely important for predicting the expected performance of these oscillators after 10 or 15 years in space. In this paper we will present data on the effects of oscillator aging-rate performance when subject to some commonly encountered space radiation environments.**

I. INTRODUCTION

Quartz Clocks are operating in numerous spacecraft, and the on-orbit performance is actually much better than originally anticipated. Analysis of laboratory test data and on-orbit data for quartz clocks manufactured by FEI leads to the conclusion that performance in space is predictable from tests performed in laboratories.

For quartz clocks the conclusions are as follows:

- A total of 90 to 180 days of laboratory testing is adequate to predict end of life on-orbit performance ≈ 15 to 20 years.
- Radiation has an effect and can be used to our advantage to predict performance.
- Variations in temperature, power, vibration, solar flares, and other environmental perturbations affect performance but are predictable and controllable.

II. AGING AND RADIATION

As a result of tests on Earth the following major parameters are predictable for quartz clocks:

- aging rate
- total effect on frequency at end of life ≈ 15 to 20 years.

Extensive tests on earth coupled with on-orbit-derived data indicate that to achieve optimal performance in space the clock must be robustly designed and embody the following characteristics:

1) Usage of "Premium Q Swept Quartz" or radiation hardened quartz material.
2) SC-cut crystals (SC-cut crystals stabilize faster than AT-cut crystals. The retrace of SC-cut crystals is orders of magnitude better than AT-cut crystals).
3) 5th overtone resonators (aging is significantly affected by the thickness of the resonator, hence, the thickest quartz blank should be used at the highest practical overtone for best aging performance.).
4) Crystals exhibiting monotonically-positive aging slope (radiation offsets the positive aging trend of quartz as further explained below).

A. *Premium Q Swept Quartz*

The process of sweeping quartz to improve its radiation hardness has been well documented in the literature [1]. All space clocks designed and manufactured by FEI contain crystal resonators manufactured from raw materials of premium Q swept quartz bars. Figures 1 below demonstrates a high precision, quartz-based, multi-output, triple-redundant space master oscillator. Typically, these oscillators utilize a dual-oven construction, and a 5 MHz or 10 MHz, 5th overtone, SC-cut crystal resonator. As will be discussed below a 5 MHz, 5th overtone, SC-cut crystal resonator provides the optimal aging performance.

B. *SC-Cut, Crystal Resonators*

As stated above FEI only utilizes 5 MHz or 10 MHz, 5th overtone, SC-cut crystal resonators for precision space oscillators. Extensive data has been published regarding the advantages of SC-cut crystals over AT-cut crystals. For example, the combination of a low frequency, high overtone SC-cut crystal significantly increases the aging

978-1-4244-3510-4/09/$25.00 ©2009 IEEE

performance of the oscillator as shown from the test data presented in Figure 2. The significant difference in aging between the various resonators shown in Figure 2 is due to the much thicker crystal blank utilized to achieve a 5.0 MHz, 5^{th} overtone, SC-cut resonator. Both in operational and non-operational conditions the frequency aging due to mass migration is significantly reduced as a function of quartz resonator thickness. This is explained by the fact that deposition or removal of a given mass from a more massive (thicker) crystal resonator has a lesser effect on frequency than deposition or removal of that same mass from a lesser massive (thinner) crystal resonator. For each case the change in frequency is due to the relative change in mass of the crystal resonator. In a massive crystal, depositions of a monolayer of some contaminant has a much smaller relative effect than for a thin less massive crystal. A 5.0 MHz, 5^{th} overtone, SC-cut quartz resonator has a thickness of approximately 0.070", whereas the 32 MHz, fundamental (overtone of 1), AT- cut quartz resonator has a thickness of approximately 0.002".

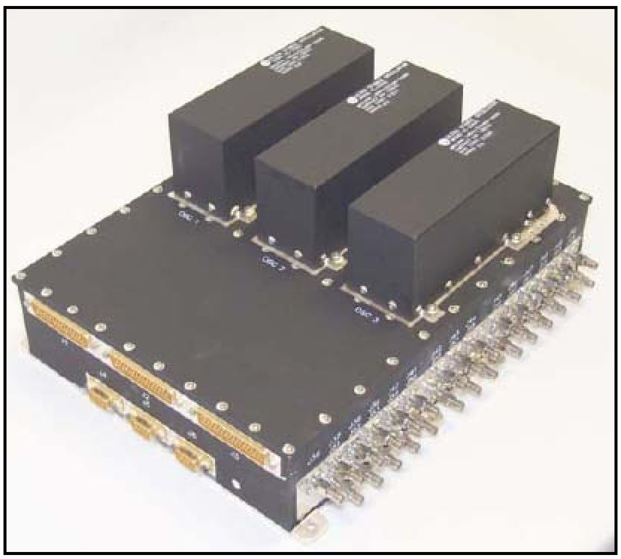

Figure 1. Triple-redundant space master oscillator

C. *Crystals exhibiting monotonically-positive aging slope*

Crystals are known to age either positive or negative as documented by Dr. John Vig [2] and shown in Figure 3.

For space applications Crystals exhibiting monotonically-positive aging slope are utilized because radiation offsets the positive aging trend of quartz as explained below.

A major concern for quartz clocks in space is the effect of radiation. Quartz is sensitive to space radiation, and the performance of extensive tests on Earth have revealed some very interesting results that can not only be used to predict performance in space, but can also be utilized to compensate the aging of the device. Figures 4 and 5 demonstrate the radiation effects on aging of two quartz oscillators in a controlled test environment [3].

- Radiation is applied to the OCXO Proto/Qual Unit on Day 0, and initially a short positive-transient aging response is observed, but over time (days 1 - 10) radiation is observed to be causing a negative trend in the aging process. The same phenomenon was also observed on the OCXO Engineering Model as shown in Figure 5.
- The average rate of space radiation has been calculated to be ≈ 6 rads/day for satellites in geostationary orbit [4] and the effect of 1 rad on a quartz crystal results in $\Delta f/f \approx -1 \times 10^{-12}$ with a total daily result of $\Delta f/f \approx -6 \times 10^{-12}$.

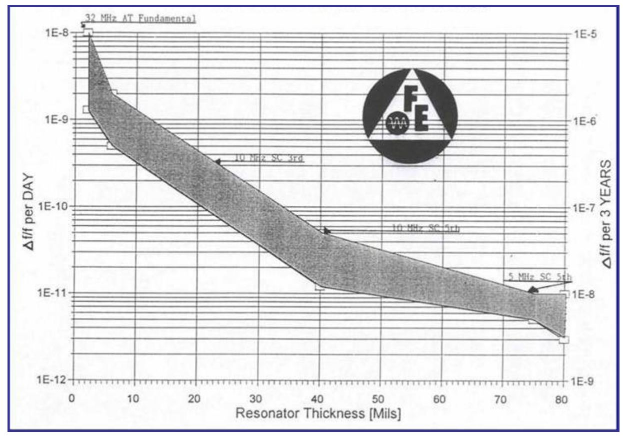

Figure 2. Relationship between resonator thickness and frequency aging

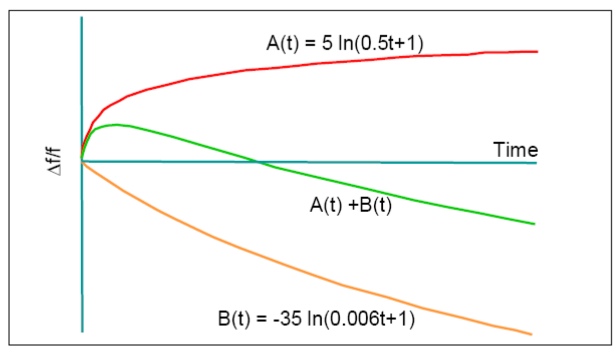

Figure 3. Theoretical aging of a quartz crystal oscillator

The plots in Figures 4 and 5 and the above equations demonstrate that radiation affects the aging process in a negative direction, and, therefore, it can be stated that radiation is "beneficial" and can be advantageously utilized to actually compensate the aging trend of a monotonically- positive-aging clock. In other words, the radiation effect offsets the positive aging of the crystal and acts as a compensatory mechanism.

A quality quartz clock that is robustly designed and incorporates the characteristics described above, typically exhibits aging rates in the range of 10^{-11}/day after being tested and aged on Earth for a period of 90 to 180 days. This type of a clock can be expected to display on-orbit performance in the range of 10^{-12}/day.

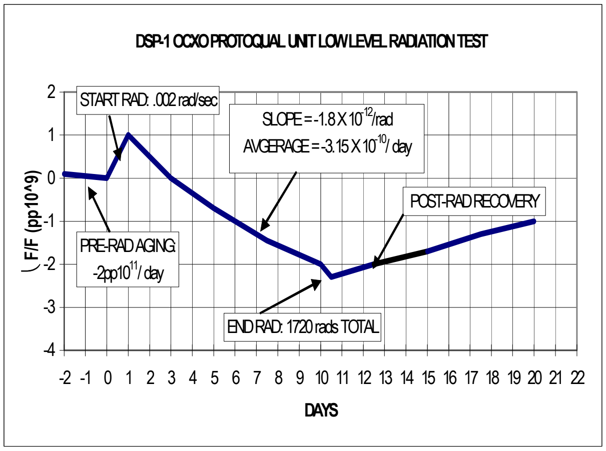

Figure 4. Radiation effect on DSP-1 OCXO Proto/Qual Unit

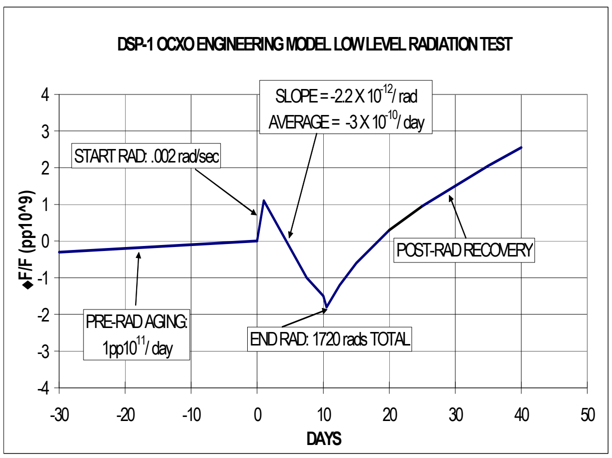

Figure 5. Radiation effect on DSP-1 OCXO Engineering Model

These expectations are supported with test results conducted on Earth, and with on-orbit-derived data from numerous space programs including Argos, Voyager, Fleet Sat Com, MILSTAR, IntelSat, etc.

III. ON-ORBIT AGING DATA

On-orbit-derived aging data from FEI delivered clocks is presented below.

Argos clocks:

The following data was derived from 6 clocks

Aging on Earth	Aging on-orbit
≈ +2 x 10^{-11}/day for typical unit	≈ 6 x 10^{-12}/day after 5 years for typical unit
≈ +9 x 10^{-11}/day for worst clock	≈ 9 x 10^{-12}/day after 5 years for worst unit

Voyager clocks:

The following data was derived from clocks on 2 satellites, and an average aging rate was calculated as follows:

Aging on Earth	Aging on-orbit
≈ +3 x 10^{-11}/day	≈ 3.4 x 10^{-12}/day after 10 years

Note: This clock is not in Earth's orbit.

Fleet Sat Com clocks:

Data derived from a fleet of 13 satellites.

Aging on Earth	Aging on-orbit
≈ +2 x 10^{-11}/day to +4 x 10^{-11}/day	≈ 2 x 10^{-12}/day to 4.4 x 10^{-12}/day after 15 years

The on-orbit data was reported in the range of

+1.1 to +2.4 x 10^{-8}/15 years

Assuming a worst case linear function, the aging rate per day is calculated as follows:

$(1.1x10^{-8})/(365days\ x\ 15years) \approx 2x10^{-12}/day$

$(2.4\ x10^{-8})/(365days\ x\ 15years) \approx 4.4x10^{-12}/day$

Milstar clocks (See Figure 6):

Aging on Earth	Aging on-orbit
≈ +3 x 10^{-11}/day	≈ 1.4 x 10^{-12}/day after 2 years ≈ 2 x 10^{-13}/day (8 year average)

Figure 6 shows frequency aging for an eight year period for oscillators on the MILSTAR program. The pronounced downward excursion in about month 72 in figure 14 was due to solar flares as reported in Presser and Camparo [5]

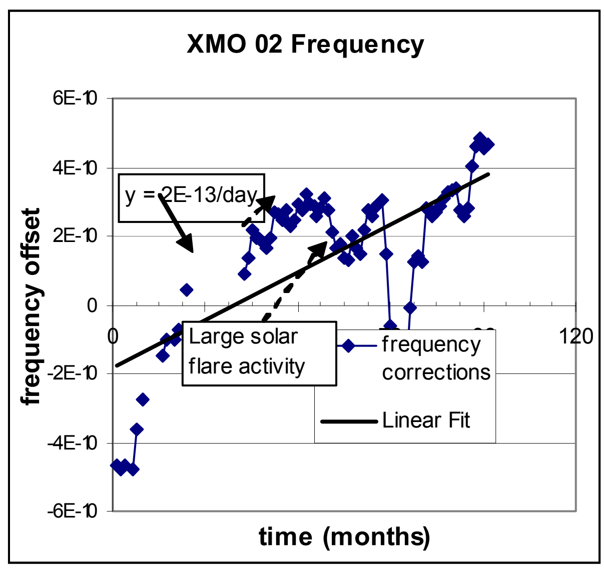

Figure 6. Long-term Aging of Quartz Oscillator on MILSTAR Satellite

It is interesting to note, that in contrast to quartz clocks, the effect of radiation on rubidium based clocks is not a major concern. Aging data shown in Figure 7 suggest that radiation effects on rubidium clocks is at least down to the $\sim 10^{-14}$ level. This is further supported from data presented by Camparo, et al. on the effects of solar flares on clocks in space [6,7].

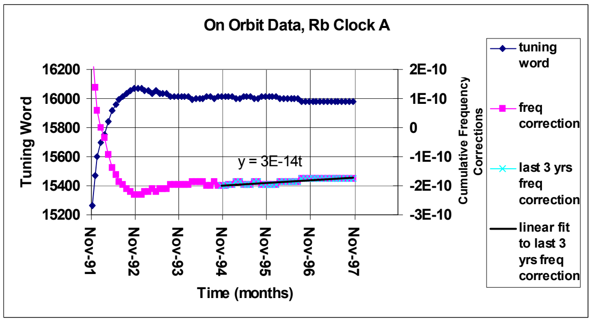

Figure 7. On Orbit Aging of Rubidium Clock

IV. CONCLUSION

Data has been presented on quartz clocks that support the statements that performance in space is predictable from modeling and tests carried out on Earth. For quality quartz clocks that embody 5 MHz or 10 MHz 5th overtone , SC-cut crystal resonators, the drift rate is affected by radiation, but radiation can be utilized as a compensatory mechanism to improve a monotonically positive-aging crystal. The drift performance for a quartz clock can be expected in the 10^{-12}/day range after several years in space. Ample on-board-derived aging data has been presented to substantiate that the on-orbit performance is actually much better than originally anticipated by performing tests on Earth.

REFERENCES

[1] F. E. Froehlich, A. Kent, C. M. Hull, "Encyclopedia of Telecommunications" Volume 3, p 486-487

[2] J. Vig, Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications - A Tutorial, Rev. 8.5.3.0, (February, 2005), US Army Communications-Electronics Research, Development & Engineering Center, Fort Monmouth, NJ, AD-M001251 (revised).

[3] J. Ho, *"Crystal Radiation Test Final Report for DSP-1 OCXO"*, Frequency Electronics, Inc. Report A36026-9573

[4] B. R. Bhat, N. Upadhyaya, & R. Kulkarni, Total radiation dose at geostationary orbit, IEEE Transactions on Nuclear Science, 52(2), April 2005, 530-534

[5] Presser, A.; & Camparo, J., *"Examination of a crystal oscillator's frequency fluctuations during the enhanced space-radiation environment of a solar flare,"* IEEE Transactions on Nuclear Science, 49 (5), Oct 2002, 2605 - 2609

[6] J. C. Camparo, S. C. Moss, *"Satellite Timekeeping in the Presence of Solar Flares: Atomic Clocks and Crystal Oscillators,"* Submitted to Proceedings IEEE

[7] J. G. Coffer, J. C. Camparo, *"Long-Term Stability of a Rubidium Atomic Clock in Geosynchronous Orbit,"* 31st Annual Precise Time and Time Interval(PTTI) Systems and Applications Meeting, December 1999.