PERFORMANCE OF RUBIDIUM AND QUARTZ CLOCKS IN SPACE

M. Bloch (martinb@freqelec.com), O. Mancini (oliem@freqelec.com), T. McClelland (tomm@freqelec.com)

Frequency Electronics, Inc.
55 Charles Lindbergh Blvd., Mitchel Field, NY 11553

Abstract - **Space programs requiring precision time-keeping and stable frequency generation have been fitted with atomic frequency standards and super-stable quartz oscillators. The challenge has been to predict the clock performance in space based on tests conducted on Earth. This paper focuses on the actual performance of rubidium atomic frequency standards and quartz oscillators in space, and demonstrates that the performance in space is predictable from modeling and tests carried out on Earth. Actual test data obtained on Earth and data from space is presented. Aging performance and the effects of natural radiation is addressed. Data is presented from a space-based rubidium clock, designed and manufactured by Frequency Electronics, Inc., that is achieving fractional-frequency aging rates of 3 x 10^{-14} / day and long-term Allan deviation of 1 x $10^{-15}\sqrt{t}$, and similarly, quartz clocks that are realizing aging rates of 1-2 x 10^{-12} / day and long-term Allan deviation of 1.6 x $10^{-14}\sqrt{t}$. The paper also addresses performance in the presence of solar flares and other space phenomena.**

1. INTRODUCTION

Rubidium Atomic Clocks (Rb) and Quartz Clocks are presently flying 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 both Rb and Quartz clocks manufactured by FEI leads to the conclusion that performance in space is predictable from tests performed in laboratories.

For Rb clocks the following conclusions have been reached:

- Performance in space will be better than performance in a laboratory vacuum-controlled-environment.
- The improved performance in space is partially due to the elimination of helium from resonance and filter cells of the Rb clock.
- Space radiation has negligible effect on the clock performance.

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.

2. RUBIDIUM CLOCKS

Rb oscillators manufactured by FEI utilize a resonance cell fabricated from borosilicate glass. These cells are very reliable and relatively easy to fabricate due to the low thermal expansion characteristics of this type of glass. However, borosilicate glass is relatively permeable to helium, and helium atoms inside a Rb resonance cell produce a positive buffer gas frequency shift. The consequence of this is that Rb oscillators which utilize a borosilicate resonance cell can exhibit frequency aging which is dominated by the permeation of helium through the glass walls of the resonance cell. This aging can be positive or negative depending on the relative concentration of helium between the inside of the cell and the outside. Of particular interest are the following:

CONDITION	ACTION	EFFECT
1. Newly-manufactured cell without helium contamination – earth atmosphere	Helium diffuses from atmosphere into cell.	Positive aging
2. Cell with helium contamination – vacuum environment	Helium diffuses from inside cell to vacuum.	Negative aging

Tests performed on Rb Clock B in laboratory vacuum-controlled environments are shown in Fig. 1. The laboratory life test data presented in Fig. 1 is for the period starting at day 280 and ending on day 455. The results indicate that the drift is in the range of 10^{-13} per day, but during vacuum failure the performance changed. The sharp upward vertical change (point A) is associated with a loss of vacuum, and is due to temperature and pressure sensitivities. The sloping curve (point B) is consistent with helium permeation through the glass walls of the resonance cells (condition 1). The downward response (point C) is the result of returning to vacuum conditions, and the return to aging (point D) is consistent with the effect of helium atoms diffusing from the device (condition 2). The periodic variations between days 350-385 are due to temperature-cycling of the base plate.

To support the above statements, data is presented in Fig. 2 for the exact same clock (Clock B) on-orbit that had been turned off for 5 years. At turn-on (after 5 years) the performance almost immediately approaches its quiescent aging behavior of 2x10^{-13}/day which correlates with 3.6x10^{-13}/day observed on Earth (Fig.1) in vacuum environments. Therefore, the most likely explanation for this aging behavior is that the helium atoms had all diffused from the device during the 5 years in space prior to turn-on.

As further evidence, data is presented in Fig. 3 for a Rb device (Clock A) that was turned on at launch. The figure plots 6 years of data, and demonstrates that long exposure to a space vacuum environment improves the clock's aging. It eventually reached a quiescent aging

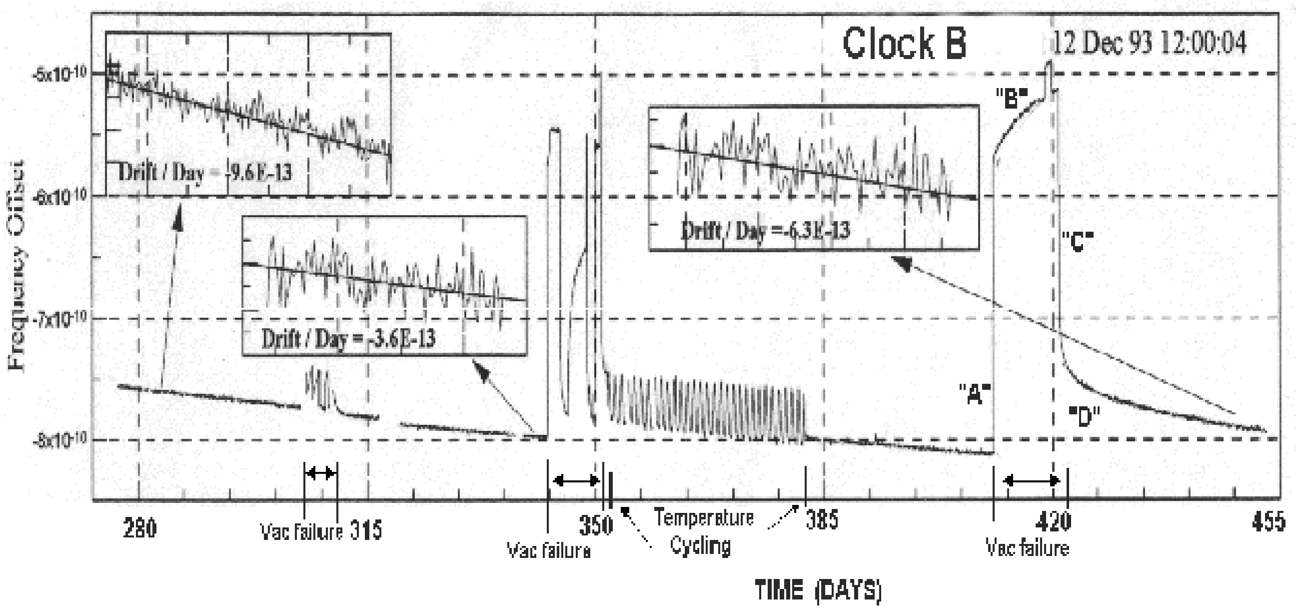

Fig. 1. Life-test of Rb Clock B

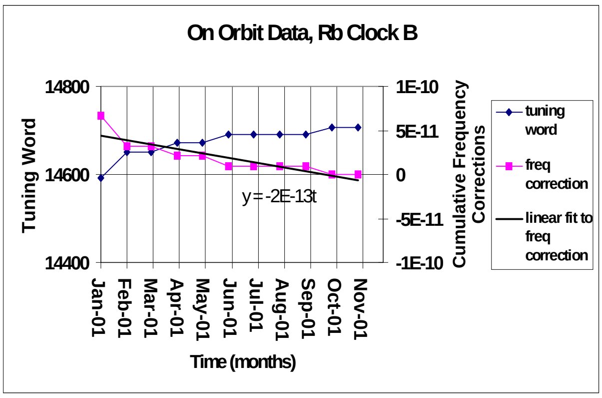

Figure 2. Rb clock turned on after 5 years in orbit

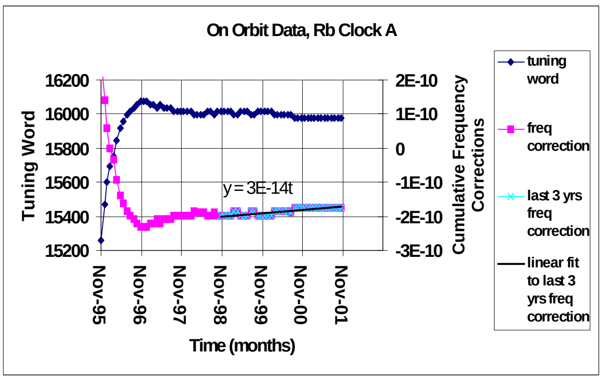

Figure 3. Clock A On-Orbit Data

rate of $3x10^{-14}$/day. At the start of the mission the aging was in the range of less than $1x10^{-11}$/day, but as the helium diffused the performance improved. It is important to note that the Rb clocks described in this report were fabricated in the same time period, with identical part lots and identical rubidium physics packages.

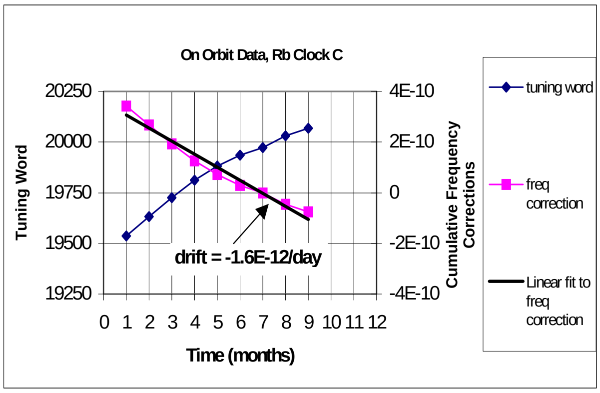

Figure 4. Rb clock turned on at launch (young clock).

Another interesting observation is the data presented in Figure 4, where the aging of a "young" clock in space is shown. In this case the clock has not yet diffused all of the helium and is approaching an aging of $2x10^{-12}$. Based on the experience with sister clocks A and B, we predict that the aging will reach the range of 10^{-14}. The above data indicates that a benign vacuum space environment eventually results in the diffusion of all helium from the resonance cell of the Rb clock, and leads to a "steady state" aging of $\sim 10^{-14}$/day. Although the early aging is attributable primarily to helium diffusion, the "steady-state" aging is probably due to light-shift effects, as discussed in more detail by Camparo, et. al. – Ref . 5.

This data also suggests that radiation has minimal effect on performance, 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 – Refs 3-4.

3. QUARTZ CLOCKS

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) 5^{th} 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).

One of the major concerns 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. Figs. 5 and 6 demonstrate the radiation effects on aging of two quartz oscillators in a controlled test environment – Ref 8.

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 6.

The average rate of space radiation has been calculated to be ≈ 6 rads / day, 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 $\Delta f/f \approx -6 \times 10^{-12}$.

The plots in Figs. 5 and 6 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 above four described characteristics 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.

These expectations are supported with test results conducted on Earth, and with on-orbit-derived data from numerous space programs including Argos, Voyager,

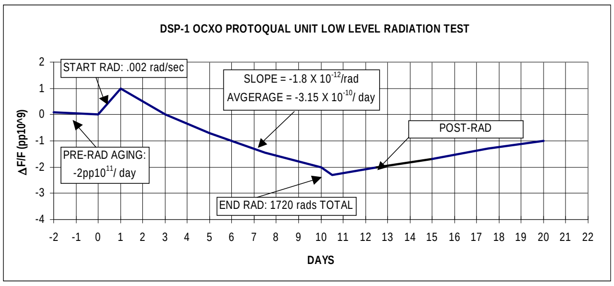

Figure 5. Radiation Effect on DSP-1 OCXO Proto/Qual Unit

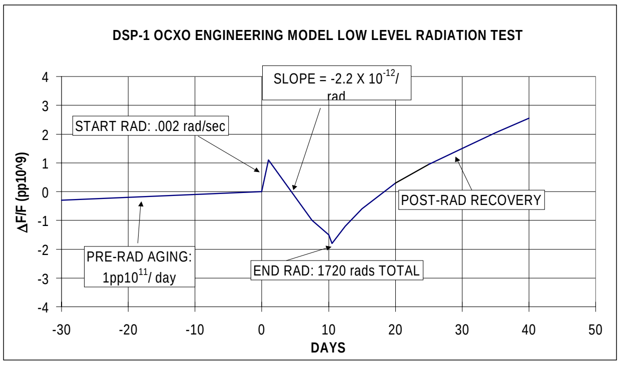

Figure 6. Radiation Effect on DSP-1 OCXO Engineering Model

Fleet Sat Com, Milstar, IntelSat, etc.

Fig. 7 shows the long-term aging of crystal oscillators in Argos satellites.

A. Argos clocks:

The following data was derived from 6 clocks as shown in Figure 7.

Aging on Earth ≈ $+2 \times 10^{-11}$/day for typical unit
≈ $+9 \times 10^{-11}$/day for worst clock

Aging on-orbit ≈ 6×10^{-12}/day after 5 years for typical unit
≈ 9×10^{-12}/day after 5 years for worst unit

B. Voyager clocks:

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

Aging on Earth ≈ $+3 \times 10^{-11}$/day

Aging on-orbit ≈ 3.4×10^{-12}/day after 10 years

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

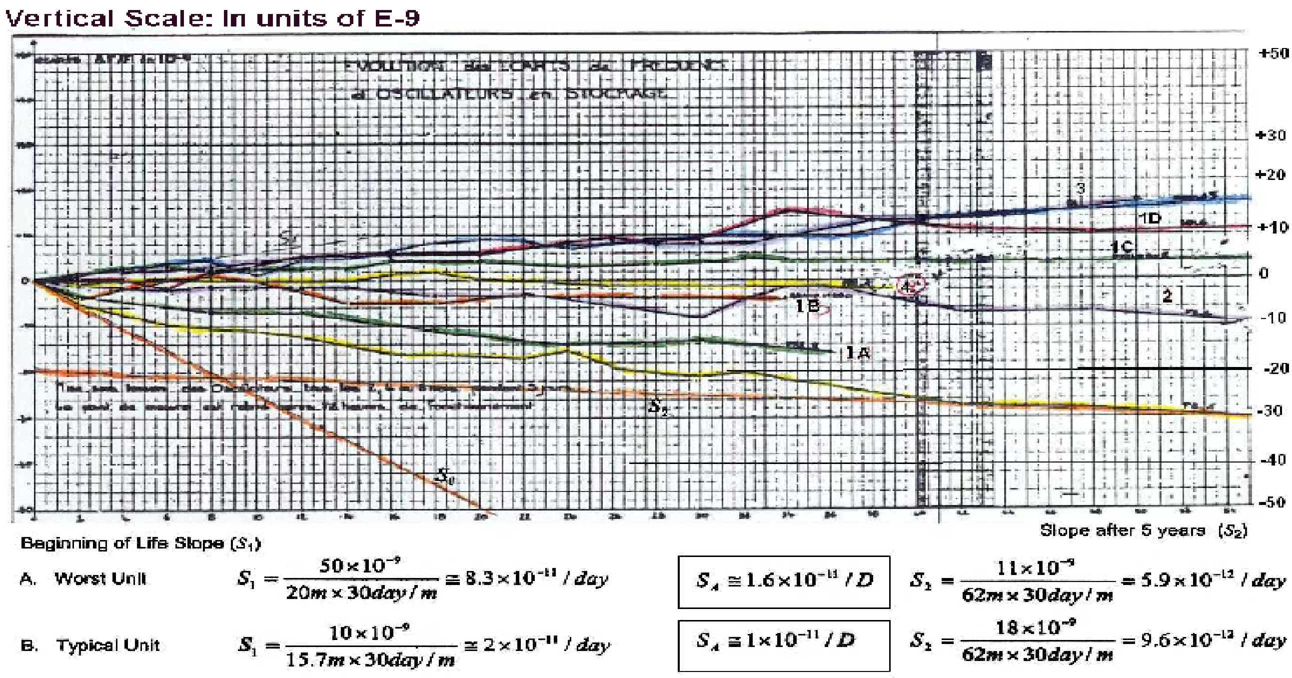

Figure 7. Long-term Crystal Oscillator Aging in Argos Satellites

C. Fleet Sat Com clocks:

Data derived from a fleet of 13 satellites.

Aging on Earth ≈ +2 x 10^{-11}/day to +4 x 10^{-11}/day

Aging on-orbit ≈ 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:

$(1.1\times10^{-8})/(365\text{days} \times 15\text{years}) \approx 2\times 10^{-12}/\text{day}$

$(2.4 \times10^{-8})/(365\text{days} \times 15\text{years}) \approx 4.4\times10^{-12}/\text{day}$

D. Milstar clocks (See Fig. 8.):

Aging on Earth ≈ 3 x 10^{-11}/day

Aging on-orbit ≈ 1.4 x 10^{-12}/day after 2 years [1]

≈ 2 x 10^{-13}/day (8 year average)

The space environment is relatively benign and the effects of changes in temperature, power, vibration, etc. are well understood, controllable and predictable. The effects of solar flares on the performance of quartz clocks have been addressed extensively by J. Camparo et al. – Refs 3-4.

4. CONCLUSION

Data has been presented on Rb and quartz clocks that support our statements that performance in space is predictable from modeling and tests carried out on Earth. For carefully designed Rb clocks, the drift rate improves as helium is diffused from resonance and filter cells.

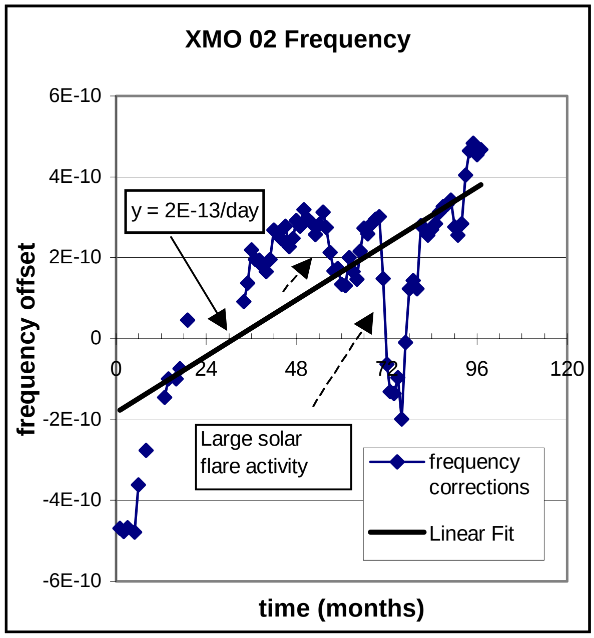

Fig. 8. Long-term Aging of Quartz Oscillator on Milstar Satellite

Radiation has a negligible effect, and drift performance is predicted to be in the 10^{-14}/day range. For quality quartz clocks 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.

REFERENCES

[1] N. D. Bhaskar et al., "On-Orbit Performance of Milstar Rubidium and Quartz Frequency Standards," *1997 IEEE International Frequency Control Symposium,* pp. 329 – 337

[2] M. Bloch et al., "Performance Data on The Milstar Rubidium and Quartz Frequency Standards: Comparison of Ground Tests in a Simulated Space Environment to Results Obtained on Orbit," *1996 IEEE International Frequency Control Symposium,* pp. 1057 – 1065.

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

[4] J. C. Camparo, S. C. Moss, "Solar Flares and Precise Satellite Timekeeping," *Proc. 33rd Precise Time & Time Interval (PTTI) Systems and Applications Meeting.*

[5] 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.

[6] T. McClelland et al., "Development of a Rubidium Frequency Standard for the Milstar Satellite System," in *Proceedings, IEEE Aerospace Conference,* February, 1997.

[7] A. Presser, J. C. Camparo, "Examination of Crystal Oscillator Frequency Fluctuation During the Enhanced Space-Radiation Environment of a Solar Flare," *Submitted to IEEE Transactions Nuclear Science.*

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