Long Term Behavior of Quartz Oscillators in Space

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Abstract—The generic, very long duration performance of quartz oscillators in space has implications ranging from deep-space missions to the outer planets to global-navigation satellite systems like Galileo and GPS. Here, using telemetry and frequency tuning data collected from spacecraft clocks that have been in operation continuously for anywhere from 2 to 17 years, we consider the performance and viability of quartz oscillators for very long duration space missions. The quartz oscillators considered in this study are actually modules within a family of Rb clocks. By studying the corrections made to the quartz oscillator by the rubidium frequency control loop, information on the underlying frequency variation of the quartz oscillator can be inferred. While the results that we present are general in nature, and in no way system specific, they are nonetheless important for space mission planners given the extremely limited availability of very long duration clock data. In particular, since the performance of quartz oscillators in the space environment can be significantly different from what is observed in the terrestrial environment, the data and analysis presented in this paper will be important for understanding the general capabilities and limitations of these clocks for long duration space missions. Our analysis will consider the long-term frequency aging of the oscillators, and also the effect of natural radiation on the oscillators' performance. Of special interest is the effect of solar flares on the frequency of quartz oscillators. By studying the response of multiple oscillators to the same solar flares, insight into the range of sensitivity to solar flare radiation is provided. Additionally, the analysis will examine the correlation between the oscillators' frequency stability and the devices' various operational parameters.

Key words:* *quartz oscillator, frequency stability, Global Navigation Satellite System (GNSS), ionizing radiation, solar flare

I. INTRODUCTION

Quartz crystal oscillators remain the workhorses of timekeeping in space systems. In general, quartz crystal oscillators have excellent phase noise, which for many applications is an important requirement. Related to the phase noise performance of these oscillators is the short term stability, typically measured as Allan deviation. Precision quartz oscillators exhibit Allan deviation, $\sigma_y(\tau = 1 \text{ second})$, of 1×10^{-13} to 5×10^{-13}, which is better than can be achieved with any other technology which has been used in space. In many cases, free-running quartz oscillators are adequate for use as a frequency and time reference in satellite systems; however, even in cases which require the better long term stability of atomic clocks, quartz oscillators are used as the local oscillator in the frequency control loop of the spacecraft atomic reference.

Despite the advantages of quartz crystal oscillators, they have the disadvantage of being inherently sensitive to several environmental factors; radiation [1] and low level vibration being the most problematic for space applications. The natural radiation environment in space is known to affect the frequency of quartz resonators significantly, so the long term frequency stability of quartz oscillators in space does not necessarily replicate the observed performance on the ground (where radiation exposure is negligible). Despite the potential differences between observed performance on earth and actual performance in space, it turns out that very little data exists regarding the actual performance of quartz oscillators in space. This results from the fact that, traditionally, information regarding satellite subsystem performance in space is only made available when a catastrophic failure occurs. Thus, for programs in which the satellites continue to meet mission requirements, typically no data is available regarding oscillator performance. The only conclusion possible in this "no news is good news" situation is that the oscillator frequency stability probably lies within some rather wide performance bounds (given the fact that specifications on space hardware tend to have considerable performance margin built in, it is not even guaranteed that the oscillators meet their design requirements in this case).

In contrast to the typical scenario outlined above, considerable data has become available regarding the performance of the frequency and time references on the Milstar satellites. With operating times in space of up to 18 years, it is thus possible to investigate in some detail the actual long term performance of these devices in space. It is the primary goal of this paper to provide real data from quartz oscillators operating in the space environment, as an aid to space system designers.

In particular, we address several specific questions regarding the long term performance of the Milstar quartz oscillators:

- What is the long-term frequency aging of a high-quality crystal oscillator?
- What is the cumulative impact of solar-flare radiation on oscillator frequency?
- After an extended life in space, what noise process dominates the crystal's long-term frequency stability?
  - Normally, for $\tau > 10^3$ sec, $\sigma_y(\tau) \sim \tau^{1/2} \Rightarrow$ random-walk frequency noise.
  - After an extended period of time in space, for $\tau > 10^3$ sec, $\sigma_y(\tau) \sim$?
- Even if $\sigma_y(\tau) = b\tau^{1/2}$ in the long term, does the random-walk noise coefficient "age" over time in the space environment (i.e., is b time dependent in space)?

II. DATA COLLECTION PROCESS

The stable RF output frequency of the operational clock on each Milstar satellite can be adjusted by the constellation-control ground station. (See Figure 1.) A Cs clock at the ground station is tied to UTC(USNO) via GPS. Frequency and telemetry data, including a record of frequency tuning corrections, are collected by the ground station, and archived. The archived data provide the raw material upon which this analysis is based [2].

The first Milstar satellite, FLT-1, carries a compliment of high-quality quartz crystal oscillator clocks, one of which has been operational since 1994 [1],[2]. All other Milstar satellites carry Rb atomic clocks, and these can operate in one of two modes [3]:

- Rb Atomic Clock mode (i.e., RMO mode) – the VCXO in the Rb clock has its frequency locked to the ^{87}Rb ground-state hyperfine splitting.
- Crystal-Oscillator Backup (COB) mode – the VCXO in the Rb clock is disconnected from the physics package, so that the clock's output is that of a free running crystal.

Every so often, for diverse reasons, a Rb atomic clock will be commanded by the ground station to operate in its COB mode. Consequently, satellite timekeeping data collected by the ground-station during COB mode operation provides a window into the crystal oscillator's performance in space.

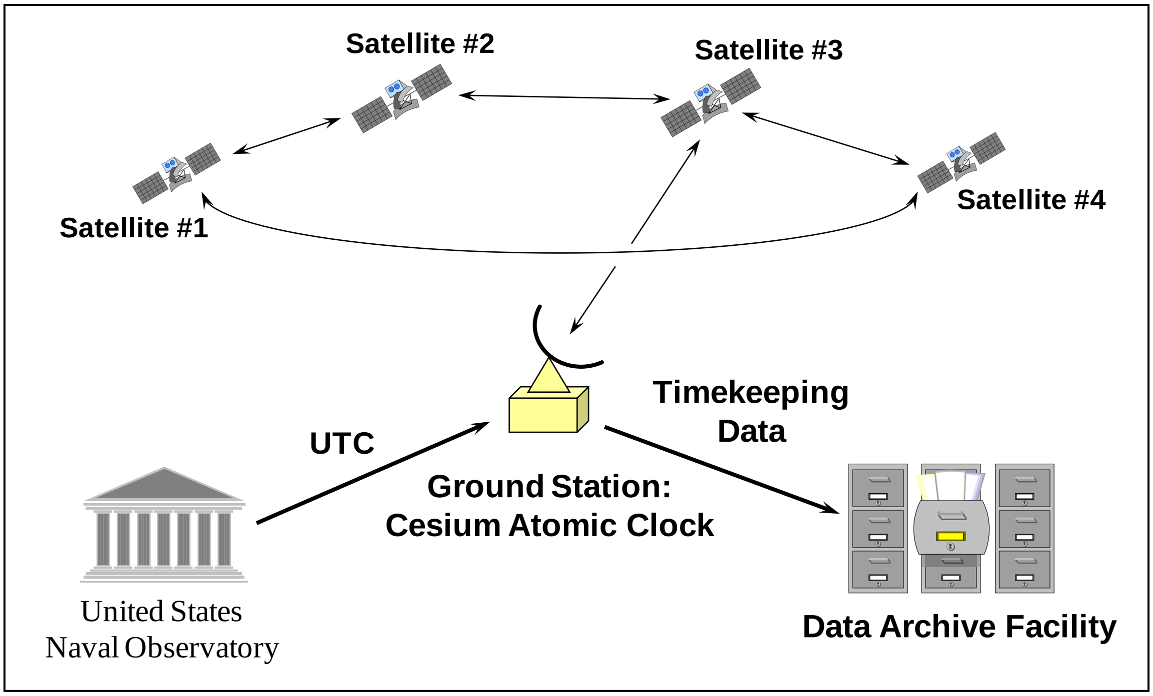

Figure 1. Diagram depicting the control of satellite Rb atomic clocks from the ground.

III. MILSTAR CRYSTAL OSCILLATOR DESIGN CONSIDERATIONS

There are some important differences between the crystal oscillators on the FLT-1 satellite, and the crystal oscillators on the rest of the Milstar satellites. The FLT-1 oscillators were designed to operate as stand-alone clocks. They are physically larger than the crystal oscillators in the Rb clocks, and they provide better temperature control of the quartz resonator. This is due in part to more careful oven design, and in part to more careful adjustment of the oven operating temperature (in order to operate at the zero-slope point of frequency vs. temperature for the resonator). Conversely, the quartz oscillators in the Rb atomic clocks were designed to operate while controlled by the Rb atomic system. They are considerably smaller than the FLT-1 oscillators, and they were designed with less demanding requirements for environmental frequency sensitivity (i.e., temperature, magnetic field, input voltage, etc.). These differences are important to keep in mind as the data from space are analyzed.

In contrast, the quartz resonators in both the FLT-1 oscillators and the Rb clock quartz oscillators are of identical design, and in fact were selected from the same manufacturing lot. Since the response of quartz oscillators to radiation is dominated by the crystal resonator response, it is anticipated that all the Milstar quartz oscillators should behave similarly in the presence of the space radiation environment.

IV. MEASUREMENT CONSIDERATIONS

For the FLT-1 oscillators and those Rb atomic clocks operated in the COB mode, the frequency information is obtained from ground based frequency tuning corrections which are used to keep the clocks tuned to their nominal frequencies. In this case, the frequency history reported here displays the evolution of the oscillators' frequency ***which would have occurred if the clocks were not updated from the ground***.

For the clocks operated in the Rb atomic clock mode, the situation is different. In this case the quartz oscillator frequency information cannot be obtained from ground based tuning corrections because these reflect the behavior of the Rb atomic system. Instead the crystal oscillator frequency information must be inferred from the control voltage which is continuously updated by the Rb control loop in order to keep the crystal oscillator on frequency. Telemetry of the control voltage is monitored and archived by the ground station. It is important to note, however, that the resolution of the control voltage telemetry limits the resolution of the inferred frequency information to a greater extent than the information obtained from the frequency tuning data available from the FLT-1 and COB clocks. This will be discussed in more detail later. Independent of resolution considerations, the frequency information reported here for crystal oscillators operating in the Rb atomic clock mode displays the frequency ***which would have occurred if the oscillators were not tuned to nominal.***

V. MILSTAR QUARTZ CRYSTAL OSCILLATOR PERFORMANCE

A. Overview

Figure 2 shows the long term frequency aging of all five of the quartz oscillators studied here. Several features are worth noting. One of the oscillators (orange) exhibits no discernible frequency change over an eight year period of time. Due to the limitations of the telemetry resolution, this means that the frequency stayed within a frequency window of ±4 x 10^{-10} over this period of time, which translates into an average daily aging of no more than ±3 x 10^{-13}/day. The other oscillators all exhibit positive frequency aging, with the worst case (red) being +4.3 x 10^{-12}/day. The longest record, 18 years, is for the FLT-1 oscillator (blue). A linear fit to the entire 18 year record for the FLT-1 oscillator exhibits an average aging rate of 4.3 x 10^{-13}/day.

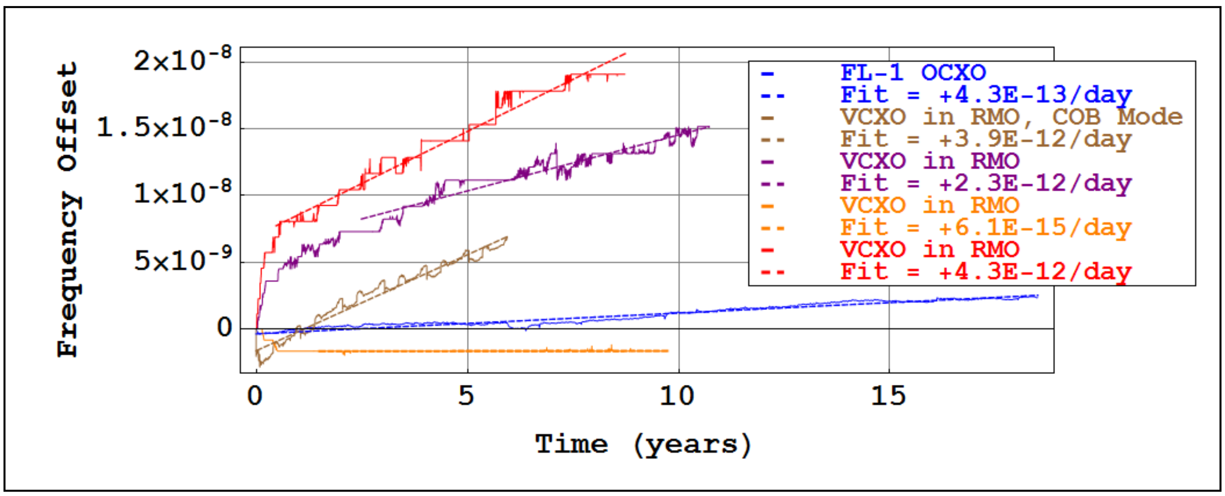

Figure 2. Summary data showing long term aging for all of the crystal oscillators studied here. In each case the derived frequency along with a linear fit to the data is provided.

B. FLT-1 Oscillator

Because the ground based tuning data for the FLT-1 oscillator is of higher resolution than the telemetry data available for other oscillators, and also because this record covers the longest time period; it is worthwhile to analyze the data for this oscillator more carefully. As a first step in this process, the data record was fit to a logarithmic function (frequency aging which slows down with time). The residuals remaining after subtracting the fit function from each data point were then statistically analyzed. This process is illustrated in Figures 3 and 4.

In general, tuning data for the FLT-1 oscillator are separated by one day intervals. However, there are some exceptions to this in which a longer time interval occurred between frequency tuning corrections. This is clearly illustrated by the distribution of measurement (tuning) intervals shown in Figure 5.

In order to make an estimate of the Allan deviation associated with the frequency residuals, calculations were limited to periods of one week or longer during which daily data exists without any gaps. The resulting one day Allan deviation estimates are shown in Figure 6.

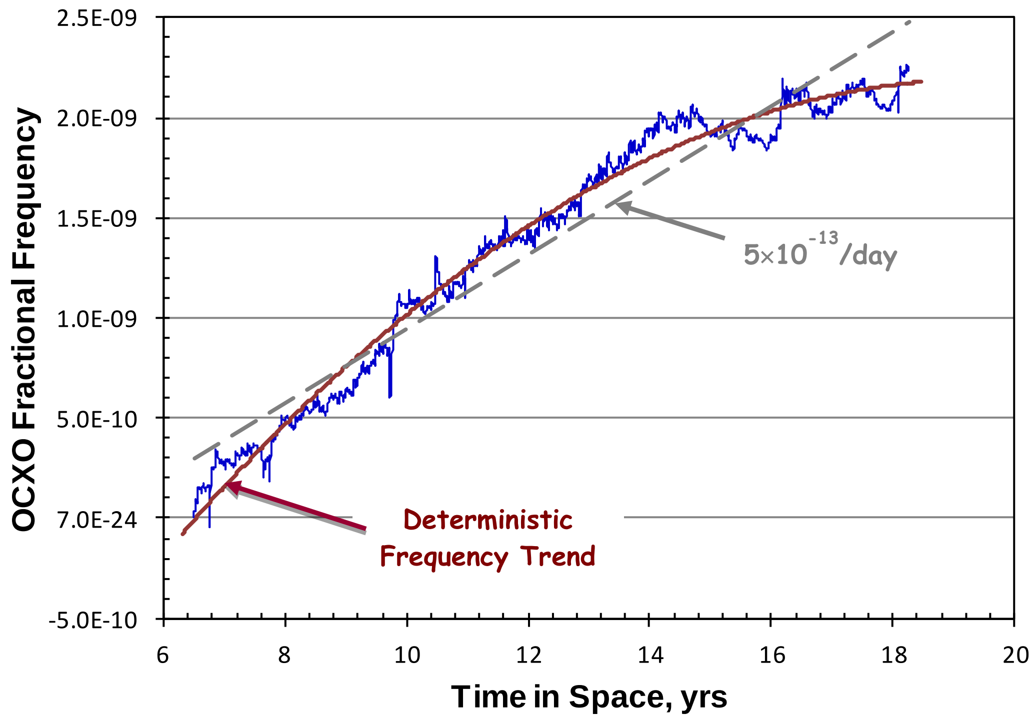

Figure 3. Frequency data for FLT-1 oscillator during the last 12 years of the 18 year data record. A logarithmic fit to the data is shown in red, and a linear slope of 5 x 10^{-13}/day is shown, for reference, as a dotted line.

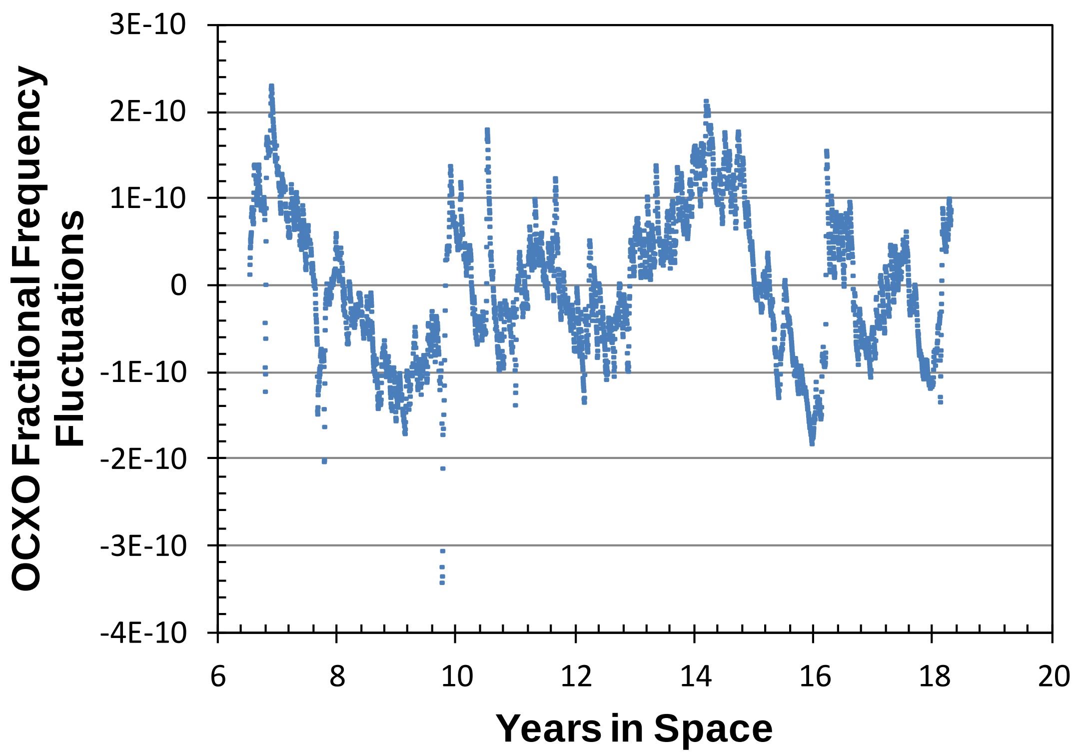

Figure 4. FLT-1 oscillator frequency residuals, after subtracting the logarithmic function shown in Figure 3.

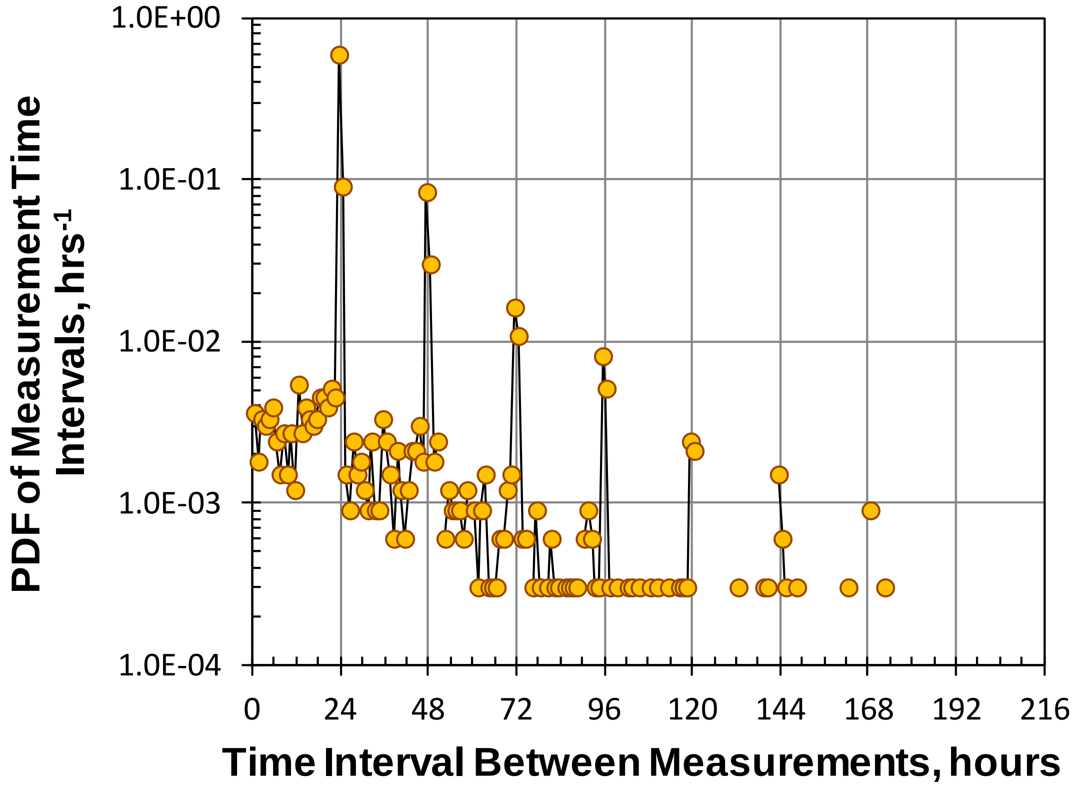

Figure 5. Distribution of measurement time intervals.

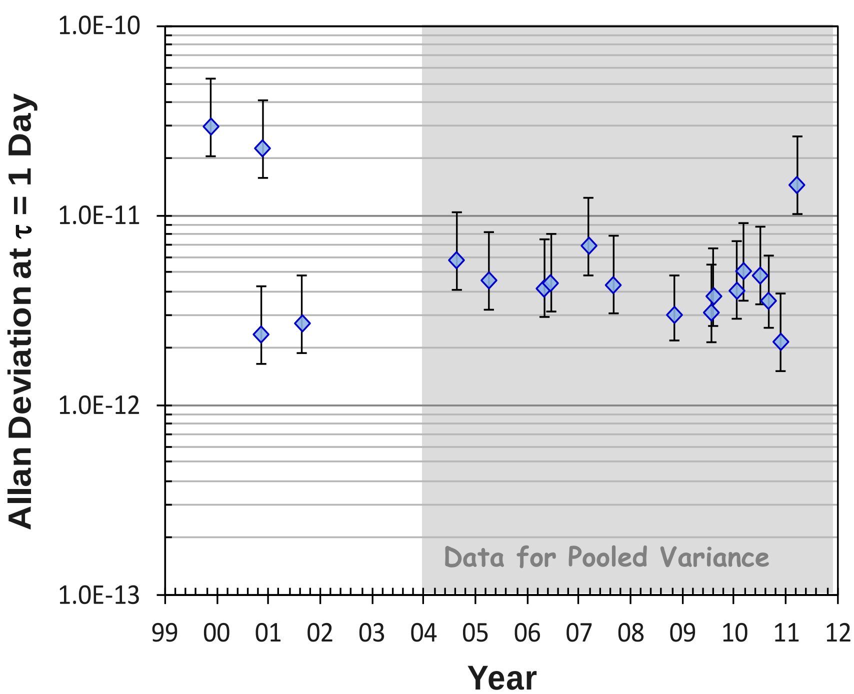

Figure 6. One day Allan deviation calculations for the FLT-1 oscillator. Error bars correspond to 90% confidence intervals.

Although it might be imagined that the one day Allan deviation estimates would change over time, this does not appear to be the case for the FLT-1 oscillator. In fact, it is found that:

$$\frac{d}{dt}\left(Log_{10}\left[\sigma_y(1\text{-}day)\right]\right) = \left(-3.0 \pm 1.9\right)\times 10^{-2}\ \text{yr}^{-1}, \qquad (1)$$

hence there is no statistically significant variation in these values over time. Because there is no apparent variation in the Allan deviation over time, values accumulated over the past eight years were pooled in order to obtain a better estimate for both the one day and two day averages. The result of this calculation is shown in Figure 7, and indicates that the long term frequency fluctuations of the FLT-1 oscillator are consistent with a random walk process:

$$\sigma_y(\tau) = 2.2 \text{ x } 10^{-14}\ \tau^{1/2} \qquad (2)$$

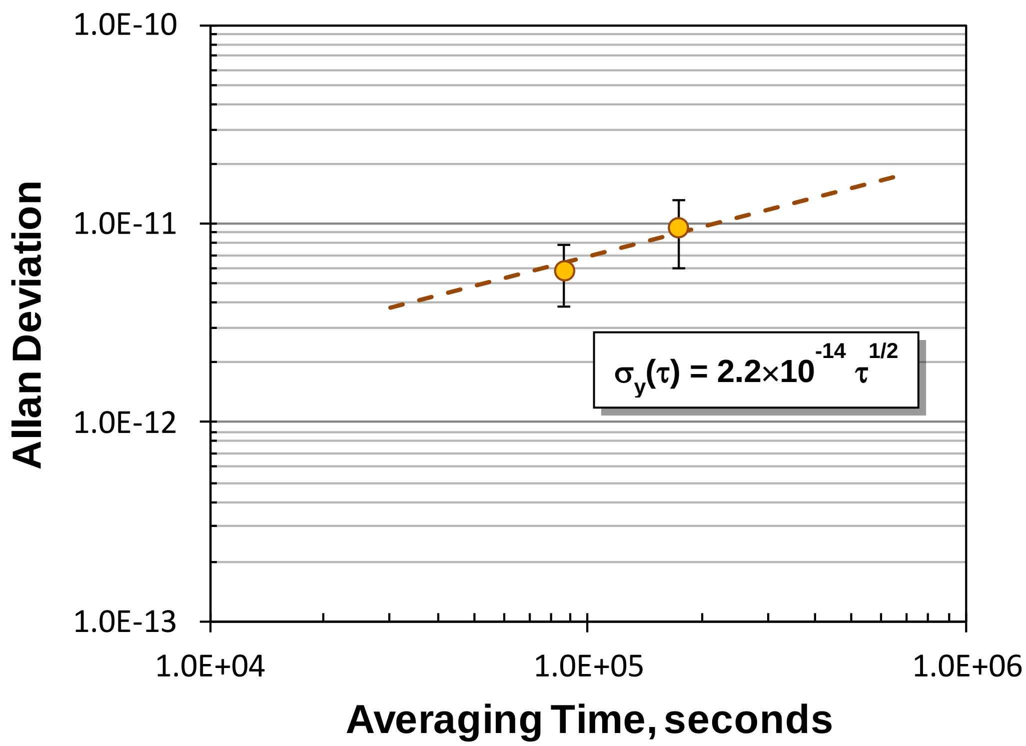

Figure 7. Pooled Allan deviation calculation suggesting a random walk noise fluctuation proportional to $\sqrt{\tau}$.

C. Rb Atomic Clock Oscillator, COB Mode

One of the Rb atomic clock oscillators has operated for an extended period of time in the crystal oscillator backup mode (COB). This unit can therefore be analyzed in much the same fashion as the FLT-1 oscillator. Accordingly, the frequency measurements were fit to a logarithmic aging function, and the residuals after subtraction of this function were analyzed statistically. The fit function is shown in Figure 8, and the residuals are plotted in Figure 9.

It is apparent from either Figure 8 or Figure 9 that a periodic, approximately annual variation in the frequency is present for this oscillator. These annual variations are well correlated with the telemetry measurements of the unit's temperature, and indicate that it is much more sensitive to temperature variations than the FLT-1 oscillator.

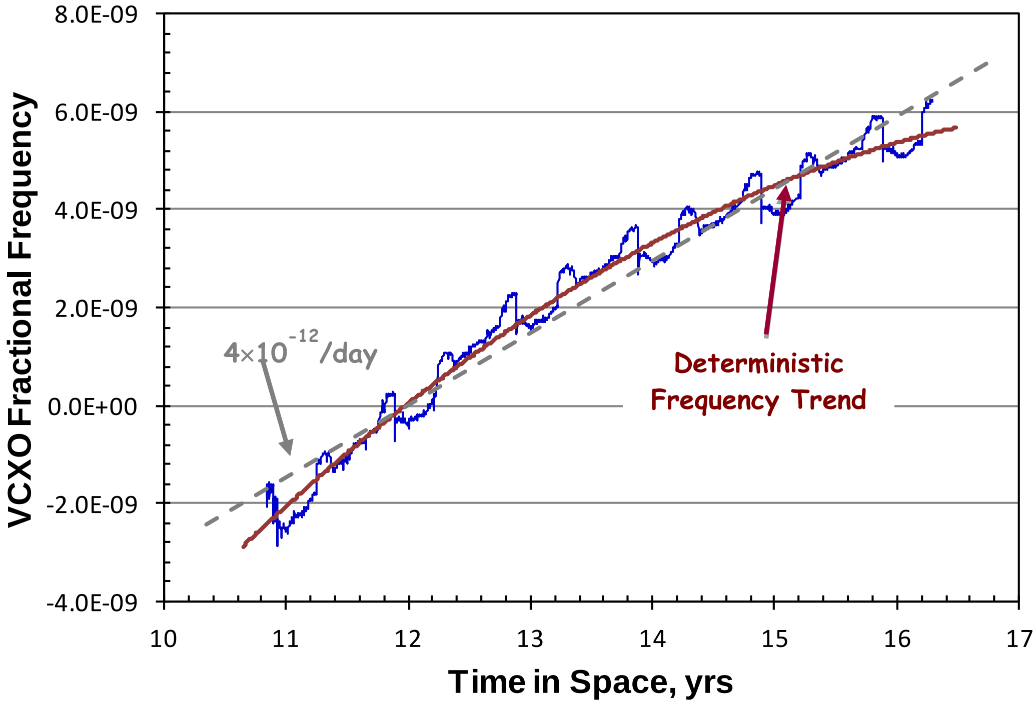

Figure 8. Rb atomic clock oscillator in Crystal Oscillator Backup (COB) mode. Logarithmic fit is shown in red, and linear slope of 4 x 10^{-12}/day is shown for reference.

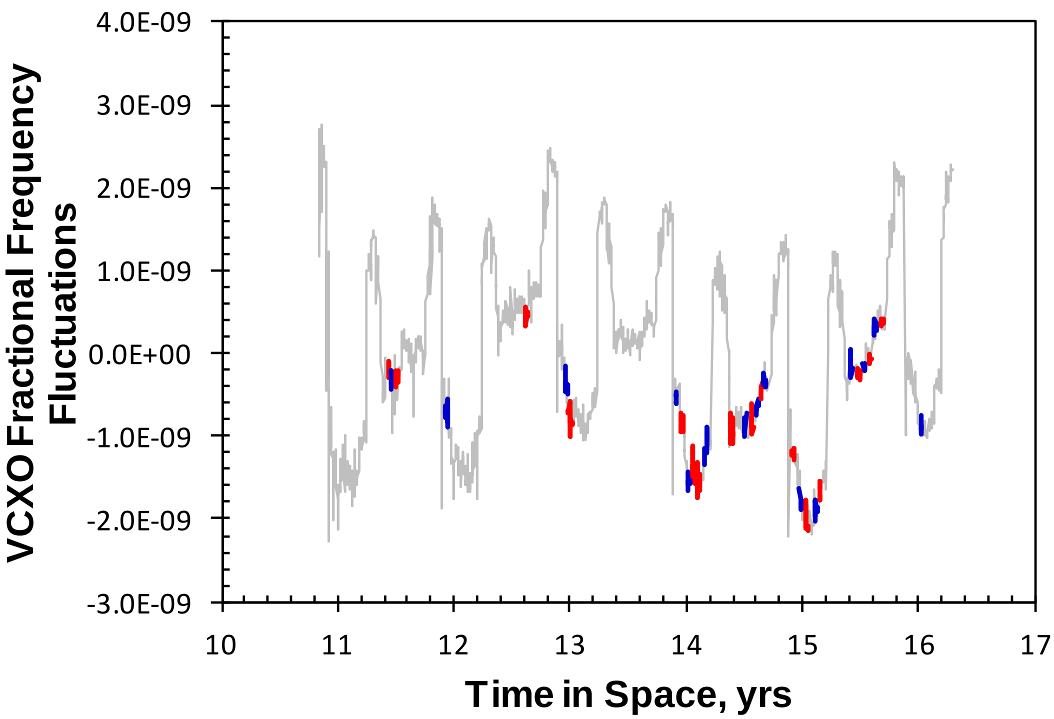

Figure 9. Frequency residuals for the Rb clock oscillator. Analyzed portions of the record are shown colored in red and blue.

In order to study the residual frequency fluctuations of this oscillator, time periods were selected in which the annual frequency variations were less prominent. As with the FLT-1 oscillator, periods of at least a week, in which continuous one day measurements were available, were selected (See Figure 9).

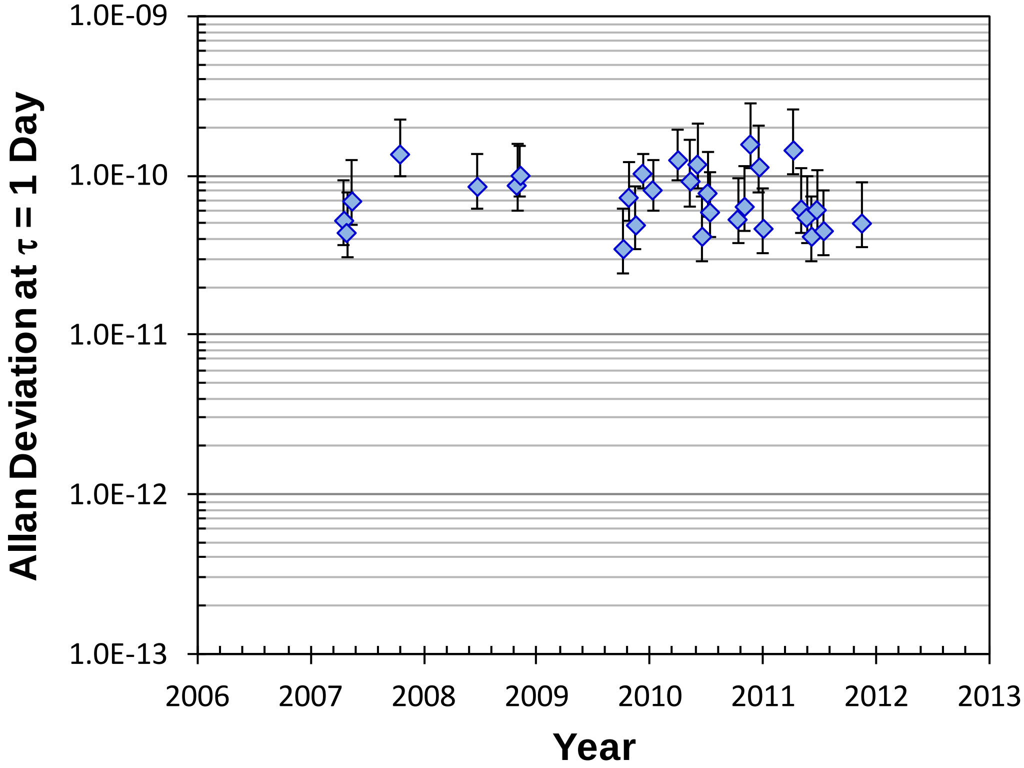

Figure 10. One day Allan deviation calculations for Rb atomic clock oscillator, operating in the Crystal Oscillator Backup (COB) mode. Error bars correspond to 90% confidence intervals.

As with the FLT-1 oscillator, there is no apparent linear trend in the Allan deviation values:

$$\frac{d}{dt}\left(Log_{10}\left[\sigma_y(1\text{-}day)\right]\right) = (-1.2 \pm 2.6)\times 10^{-2}\ \text{yr}^{-1}. \quad (3)$$

However, it appears that a periodic variation in the Allan deviation values does exist:

$$\left(Log_{10}\left[\sigma_y(1\text{-}day)\right]\right) = A\,\text{Sin}[2\,\pi(t-t_0)/T]\ , \quad (4)$$

With A = 0.152, t_0 = November 11, 2010, and T = 365 days.

A regression test was performed to shed light on this apparent periodic variation. The results are shown in Figure 12, and indeed they support the existence of an annual oscillation in the Allan deviation. Although it has not been verified, it is likely that this variation is a residual temperature effect, with perhaps some contribution from other environmental sensitivities.

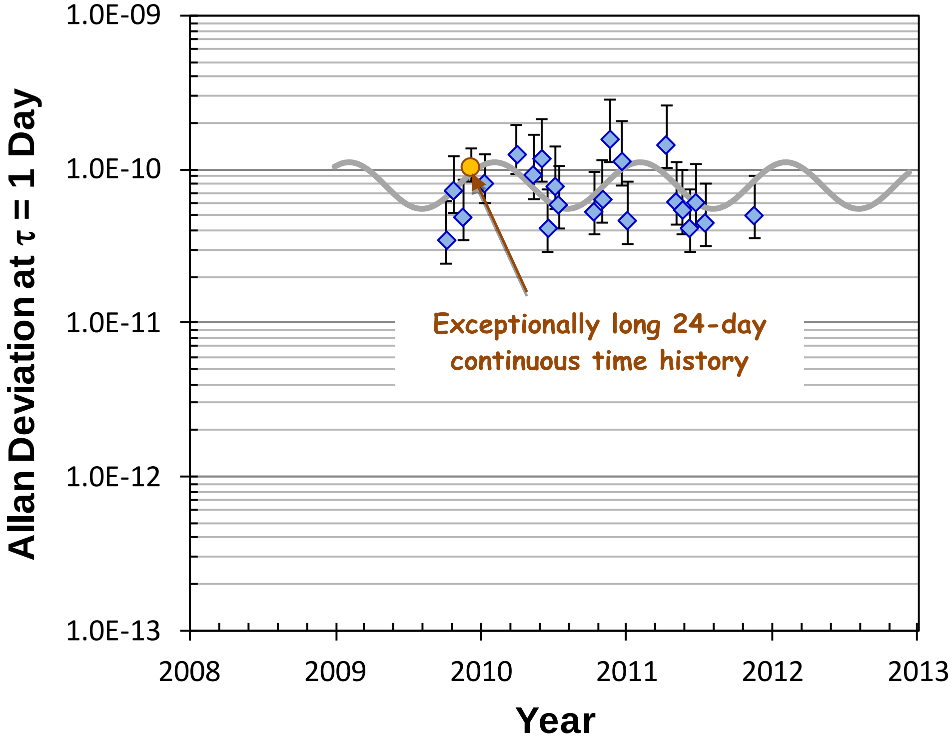

Figure 11. Plot of Rb atomic clock one day Allan deviation values from Figure 10 with hypothesized annual variation shown.

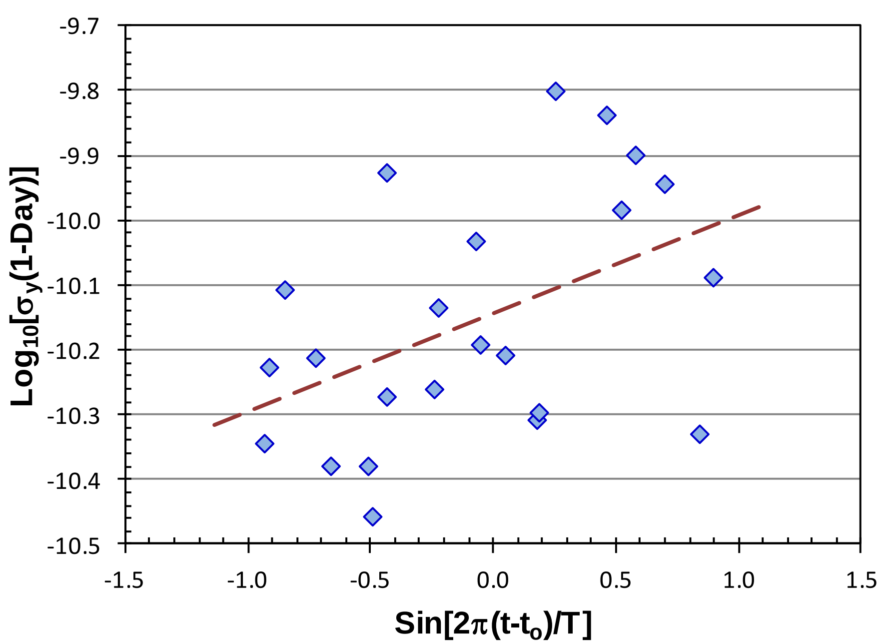

Figure 12. Results of regression test: Slope = 0.152 ± 0.06, p = 0.026, and r^2 = 0.21. At a 95% confidence level this indicates that $\sigma_y(\tau)$ does vary annually ($p < 0.05$), and that 21% of the variance in Log10[$\sigma_y(\tau)$] is explained by this annual oscillation.

In order to obtain a better estimate of the Allan deviation, data were pooled as with the FLT-1 oscillator. The results are shown in Figure 13. Also shown in the Figure are Allan deviation results measured in the laboratory on a Rb clock oscillator from the same family. As indicated in the figure, the current results are roughly consistent with the ground based measurements. This suggests that the underlying frequency stability of the oscillator has remained constant throughout its life; both on the ground, and during its multi-year existence in the space environment.

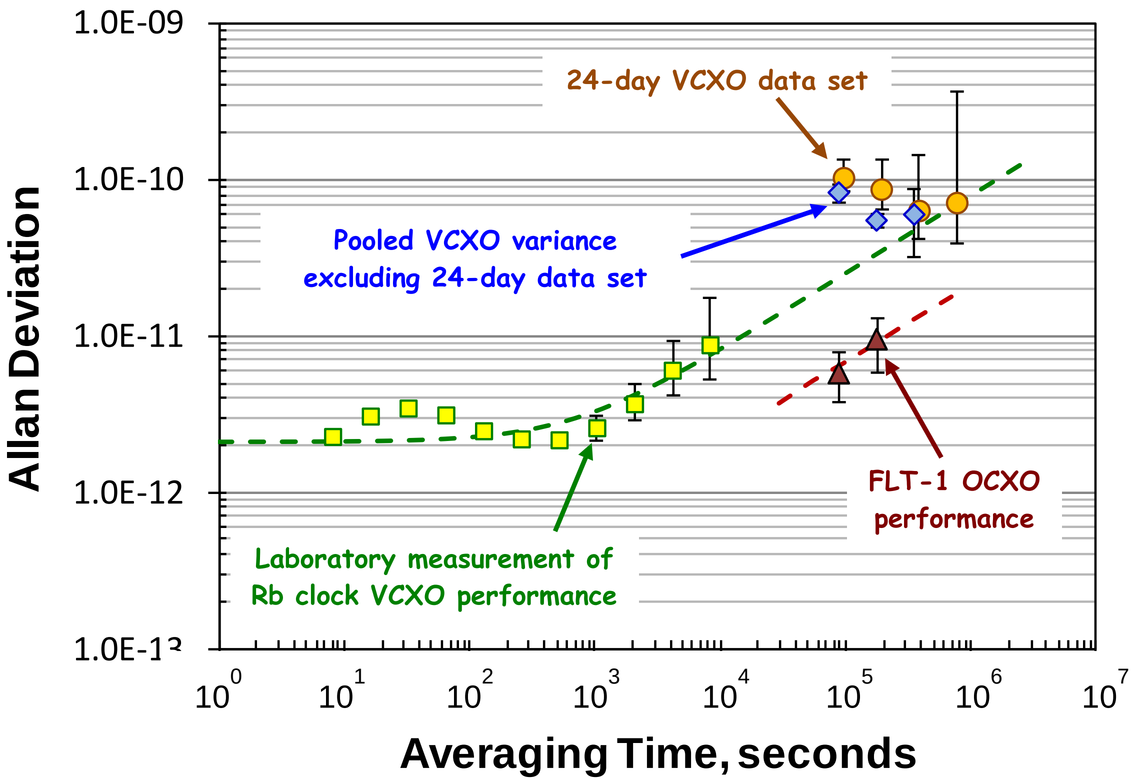

Figure 13. Allan deviation results for Rb clock oscillator in COB mode. Results are consistent with measurements made on the ground with a similar Rb clock oscillator. These results suggest that the Rb clock oscillator Allan deviation is approximately a factor of 5 larger than the FLT-1 oscillator value.

D. Ionizing Radiation Performance

Quartz crystal oscillators have been shown to exhibit a frequency response to radiation, with the best oscillators changing by ~1 x 10^{-12}/rad, ***in the negative direction*** [4]. It is also known that satellites in geosynchronous orbit are subjected to a natural radiation dose of 5 to 10 rads/day, which by itself would be expected to result in quartz oscillator frequency variation of -5 x 10^{-12} to -1 x 10^{-11}/day. If a quartz oscillator subjected to this environment exhibits positive frequency aging, independent of radiation, then compensation of the normal aging by the radiation induced aging results. The quartz resonators were carefully selected in the Milstar clocks in order to insure this result. These oscillators all exhibited ***positive*** frequency aging on the ground prior to launch of parts in 10^{-11}/day. The observed long term aging in space for these oscillators, which in the worst case is 4 x 10^{-12}/day, is undoubtedly attributable to this compensation effect.

In addition to the fairly constant background radiation, oscillators in space are exposed to relatively large transient doses of radiation resulting from solar flares. The effect of this transient radiation on the FLT-1 oscillator has been previously reported[1], [5]. In particular, the effect of solar flares during the active 1994 – 2003 time period were studied [5]. The results of this study indicated that the FLT-1 oscillator responded primarily to the high energy (>50 MeV) proton radiation resulting from the solar flare. It was observed that frequency changes of approximately -3 x 10^{-10} accompanied the proton radiation. Although accurate solar flare radiation measurements at the location of the Milstar satellites is not available, other measurements of solar flare radiation in geosynchronous orbit have yielded typical radiation doses of 100 to 1000 rads, occurring over a period of several days. The observed solar flare effect on the FLT-1 oscillator frequency is more or less consistent, both in sign and magnitude, with the expected sensitivity of -1 x 10^{-12}/rad.

However, proton radiation tests on quartz oscillators performed in the laboratory have yielded transient radiation effects which are much more variable than suggested by the simple relationship above [6]. Both positive and negative frequency responses have been observed, and effects several orders of magnitude larger than the benchmark, 1 x 10^{-12}/rad, have been observed. These results suggest that the immediate response to transient solar flare radiation could be quite different from what would be predicted for background radiation with equivalent total dose. Accordingly, it is instructive to consider the response of all of the members of this family of quartz oscillators to solar flare radiation.

A record of high energy proton radiation, as measured by the GOES satellites from 1999 to the present, is provided in Figure 14. The GOES satellites, which are in geosynchronous orbit, contain proton detectors capable of discriminating particle energy [7]. The figure shows background radiation punctuated by many discrete peaks, a few of which are greater than 10 protons/(cm^2 Sec Sr MeV). In 1999, 2001, and 2003 peaks above 50 protons/(cm^2 Sec Sr MeV) are evident. These peaks are indicative of large solar flares. It should be noted that although measurements from multiple satellites have been combined in order to prepare Figure 14, the particle detectors on the various GOES satellites are of identical design. Camparo, et. al. previously studied the effects of these large solar flares (1996-2002) on the FLT-1 oscillator [1].

Note that since the large solar flare in 2003 there have not been any further flares with high energy proton fluxes above ~15 protons/(cm^2 Sec Sr MeV). In fact, from January, 2007 to January, 2011, no proton activity whatsoever above the noise floor was measured by the GOES high energy proton detectors! All of the oscillators reported on in this paper were operational during the large solar flare in October, 2003, however most were not operational during the previous large flares in 1999 and 2001. In particular, the Rb clock oscillator operating in the COB mode was not operating in this mode in 2003. As a consequence of this, the only large solar flare to be studied is that in 2003, and only Rb clock oscillator response to that flare is available (other than the FLT-1 oscillator which has been previously studied [1]).

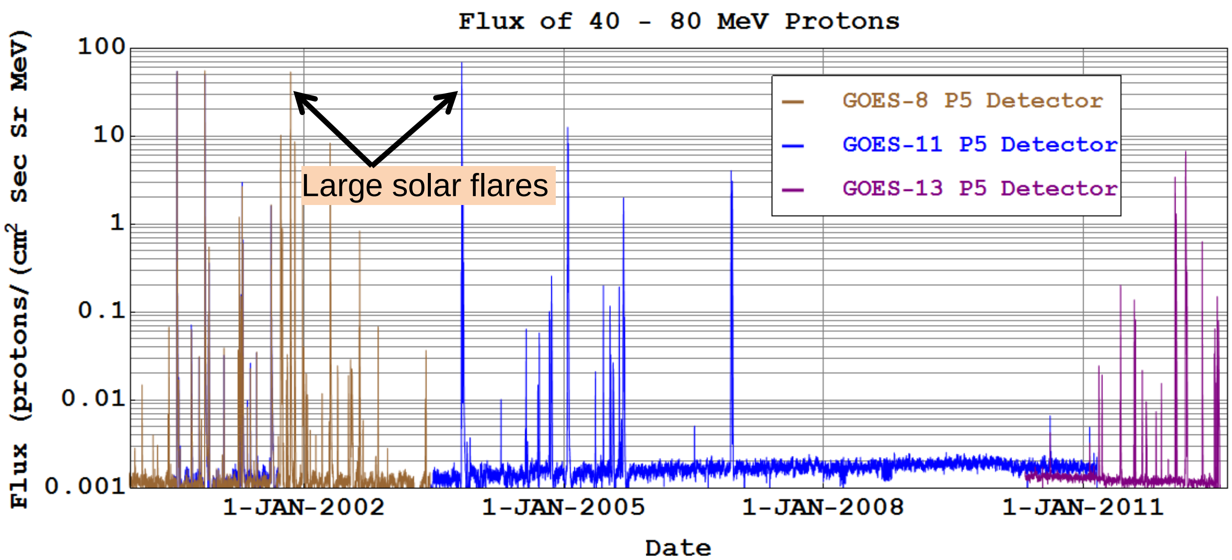

Figure 14. Flux of high energy protons, as measured by the GOES satellites. Large solar flares are indicated when peaks above 10 protons/(cm^2 Sec Sr MeV) are measured by the satellite proton detectors.

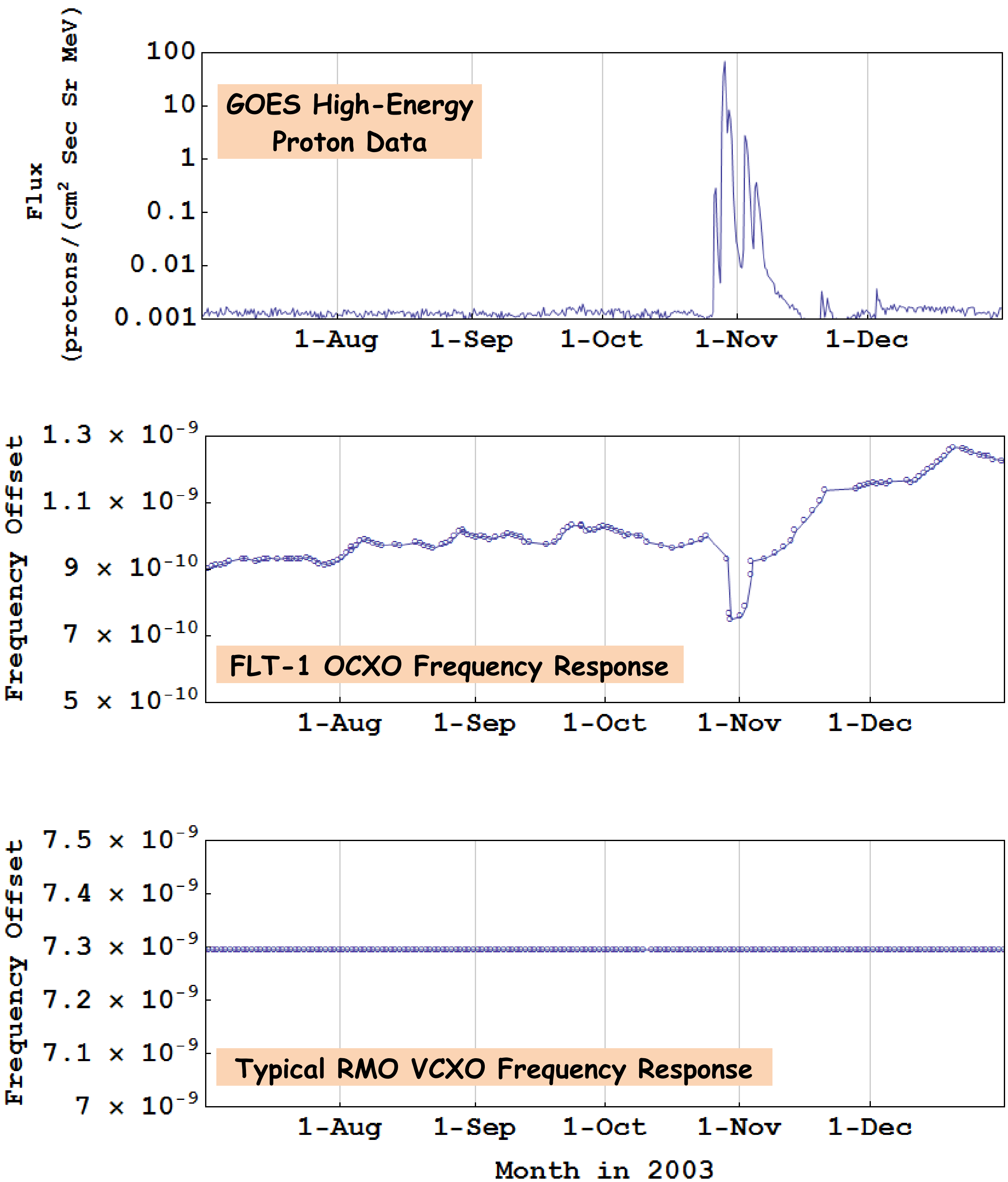

Figure 15. Oscillator frequency response to the large solar flare in 2003.

A closer look at oscillator response to the large 2003 solar flare is provided in Figure 15. The response of the FLT-1 oscillator is clearly evident, the overall frequency change being approximately -3×10^{-10}. However, the Rb clock oscillator response is completely absent. This same lack of measurable response is seen for all the Rb clock oscillators which were in operation during this solar flare. Given the limited resolution of frequency measurements extracted from the Rb oscillator control voltage telemetry, this is not completely surprising. Although nothing can be said of the *sign* of the response of the Rb clock oscillators to this 2003 event, an upper bound on the *magnitude* of the response can be inferred from the lack of response. This upper bound is conservatively placed at 5 x 10^{-10} for all the Rb clock oscillators measured, and indicates that none of these oscillators have sensitivity significantly greater than that of the FLT-1 oscillator. It is possible that some of these oscillators are significantly *less* sensitive to the high energy proton radiation from this solar flare, however, the data do not allow any conclusion to be drawn one way or the other in this regard.

VI. SUMMARY

The long term frequency stability of precision ovenized quartz oscillators in the space environment has been studied. All the oscillators studied exhibit long term linear frequency aging of less than 5 x 10^{-12}/day, and the best have aging less than 3 x 10^{-13}/day.

The response of these oscillators to the October, 2003 solar flare has also been studied. The FLT-1 oscillator exhibited a response of ~-3 x 10^{-10} to this flare, whereas the other (Rb atomic clock) oscillators exhibited no measurable response to this flare. This puts an upper bound of ~5 x 10^{-10} on the magnitude of response of any of these oscillators to this solar flare.

The random noise component of the frequency output of two of these oscillators has also been studied. It is found that the Allan deviation contains a random walk component, for averaging times greater than one day, which is constant in time. For the FLT-1 oscillator, this random walk contribution is:

$$\sigma_y(\tau) = 2.2 \text{ x } 10^{-14}\ \tau^{1/2}.$$

For the Rb atomic clock oscillator studied, the random walk component is:

$$\sigma_y(\tau) = 8 \text{ x } 10^{-14}\ \tau^{1/2}.$$

This Rb clock oscillator also exhibits a sinusoidally varying component on the frequency, with a period of one year. In particular,

$$\left(Log_{10}\left[\sigma_y\left(1\text{-}day\right)\right]\right) = A\,\mathrm{Sin}[2\,\pi(t-t_0)/T]\ ,$$

With A = 0.152, t_0 = November 11, 2010, and T = 365 days. Although detailed analysis has not been performed at this time, it is likely that this is due to temperature sensitivity of the Rb clock oscillator, combined with an annual temperature variation on the satellite.

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