RESPONSE OF A GEOSYNCHRONOUS SPACECRAFT'S CRYSTAL OSCILLATOR TO SOLAR FLARES: RESULTS OF A "SPACE EXPERIMENT"

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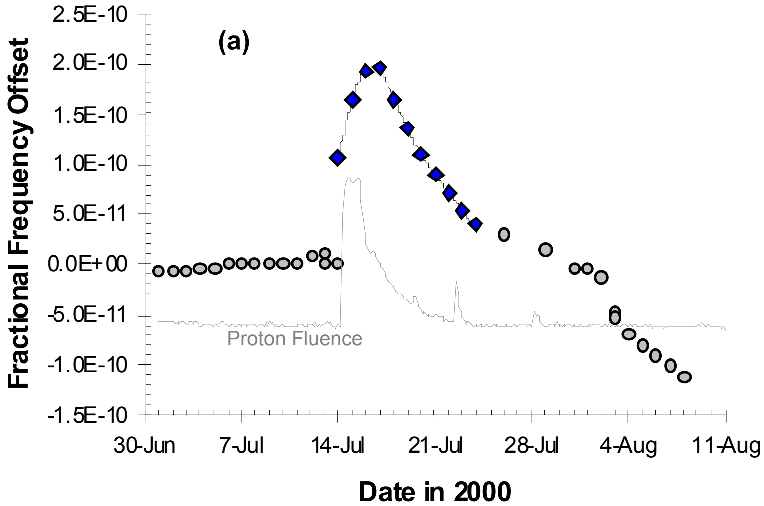
Abstract

Viewing the frequency history of the high-quality quartz crystal oscillator onboard Milstar FLT-1 as a "space experiment," we examined the response of the crystal to various solar flares occurring over the past 4 years. One of the questions we address concerns the influence of enhanced space radiation on a crystal oscillator's random frequency fluctuations, which, in addition to radiation-induced deterministic effects, could affect the oscillator's timekeeping ability. Examining the response of the Milstar FLT-1 crystal oscillator to the large solar flares of 14 July and 9 November 2000, we find clear evidence of a flare-induced deterministic change in oscillator frequency. However, examining the random fluctuations of the oscillator's frequency about this deterministic variation, we find no evidence of a concomitant change in the nature of the oscillator's stochastic behavior. Additionally, we examined the magnitude of the radiation-induced frequency excursion for a number of solar flares, obtaining a scaling relation between maximum frequency excursion and solar proton fluence as measured by GOES satellites. The results show that even for the largest flares, timekeeping onboard a geosynchronous communications satellite need not be unduly perturbed by the enhanced space-radiation environment of a solar flare, so long as a ground station can take mitigating action within a few hours of the flare's onset. Though limited to a unique satellite experiment, the results reported here bode well for satcom timekeeping during periods of solar maximum.

INTRODUCTION

Though the radiation associated with a large solar flare will cause a quartz crystal oscillator's frequency to change in a deterministic fashion **[1]**, the extent to which the radiation influences the device's stochastic frequency fluctuations is debated. Specifically, at the radiation levels expected inside a spacecraft at geosynchronous altitude **[2]**, some reports suggest that the radiation's contribution to the crystal's frequency fluctuations will be well below its intrinsic root-mean-square noise level **[3]**, while others indicate a much larger effect of the radiation on stochastic frequency fluctuations **[4]**, perhaps an order-of-magnitude increase in random-walk frequency noise. This issue has relevance, since it bears directly on how fast satellite time-error builds up during periods of enhanced solar activity.



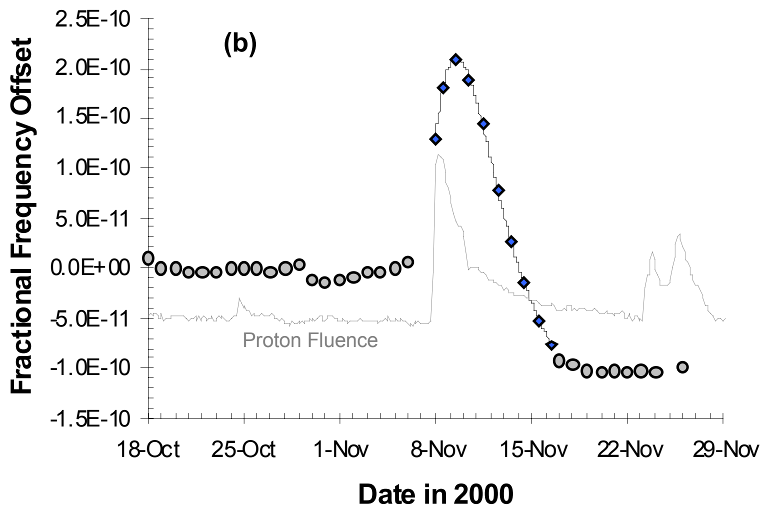


Figure 1. (a) Fractional frequency offset for the FLT-1 crystal oscillator clock during July: circles represent crystal behavior prior to and after the flare; diamonds correspond to the period during the flare. The black curve connecting the data points is a fit employing a sum of six Chebyshev polynomials; the thinner-lined curve corresponds to the logarithmic flux of energetic protons with E > 50 MeV as measured by a GOES satellite. (b) Same as (a) except for the November time frame, and a sum of four Chebyshev polynomials. The change in behavior of the circular data points before and after the flare is not due to a long-term radiation-induced effect. Rather, when we examine many months of FLT-1 data, we see similar changes in the absence of flares, suggesting that these variations are manifestations of the oscillator's nominal stochastic behavior.

To investigate this question, we considered the response of the crystal oscillator onboard Milstar FLT-1 to the large solar flares of 14 July and 9 November 2000. Milstar is the newest generation of military satellite communications system **[5]**, and is meant to provide secure antijam communication capabilities for United States armed forces in the early part of the 21st century. Milstar FLT-1, launched on 7 February 1994, carries a complement of high-quality, SC-cut, quartz crystal oscillators for timekeeping. The second Milstar satellite, FLT-2, launched on 6 November 1995, carries a complement of rubidium (Rb) atomic clocks. Soon after completion of initial FLT-2 testing, the active crystal oscillator onboard

FLT-1 was “slaved” to the active Rb atomic clock onboard FLT-2. In the slaving procedure, the Slave ties the frequency of its oscillator and the time-reading of its clock to the Master using information passed along the satellite crosslinks in a standard two-way time-comparison procedure **[4]**. The constellation-control ground station downloads and archives telemetry information from the spacecraft, including the autonomous frequency adjustments that FLT-1 implements in order to tie its crystal frequency to FLT-2’s atomic clock. These archived data can be used to reconstruct a history of the FLT-1 oscillator frequency (relative to FLT-2), as discussed further below.

On 14 July and 9 November 2000, two anomalously large solar flares occurred, both of which had observable effects on the FLT-1 quartz crystal oscillator, as presented in Figure 1. In the figure, the oscillator’s frequency is shown as a function of date and the thinner-lined curve is a logarithmic plot of high-energy proton fluence, as measured by a GOES satellite **[6]**; the magnitude of each proton peak corresponds to a $\sim 10^4$ increase in solar protons with E > 50 MeV. (The magnitude of the secondary peak in proton fluence around 23 November was only $\sim 10^2$ larger than background). As the figures clearly show, the 14 July flare caused a deterministic change in the oscillator’s frequency with a peak value of $+2.0\text{x}10^{-10}$, while the 9 November flare caused a similar change with a peak offset of $+2.4\text{x}10^{-10}$. (We note that all ground corrections to the spacecraft clock have been removed from the data of Figure 1.)

RADIATION-INDUCED STOCHASTIC EFFECTS

In order to determine the Allan variance during the flare, we needed to examine the residuals about the deterministic change. To this end, we fit the oscillator’s frequency change during the flare to a sum of N Chebyshev polynomials **[7]**, where N ranged from $2 \rightarrow 10$; examples of these polynomial fits are illustrated in Figure 1 by the black curves connecting the data points. Then, examining the residuals about the fit we evaluated the corresponding Allan deviation, which we defined as $\sigma_y(\tau;N)$. Figure 2 shows $\sigma_y(\tau;N)$ as a function of N for the 9 November flare and τ equal to 1 day. As the figure shows, $\sigma_y(\tau;N)$ first decreases as a function of N, since the polynomials are better able to fit the deterministic change in oscillator frequency as more Chebyshev terms are added to the sum. Eventually, $\sigma_y(\tau;N)$ becomes relatively insensitive to N, indicating that further increases in the number of Chebyshev terms have little effect on the quality of the deterministic fit. As more Chebyshev polynomials are added to the sum, we begin to include stochastic frequency fluctuations into the fit, and the Allan deviation again decreases. Following a criterion discussed by Hayes **[8]**, we take the horizontal region of Figure 2 between N = 4 and N = 6 as the true Allan deviation, $\sigma_y(\tau)$, assuming that for these N-values the deterministic variation in oscillator frequency is well-fit but that stochastic variations are not removed from the residuals. We note that the set of Allan deviations shown in Figure 2 is representative of the data for both flares and all averaging times that we investigated.

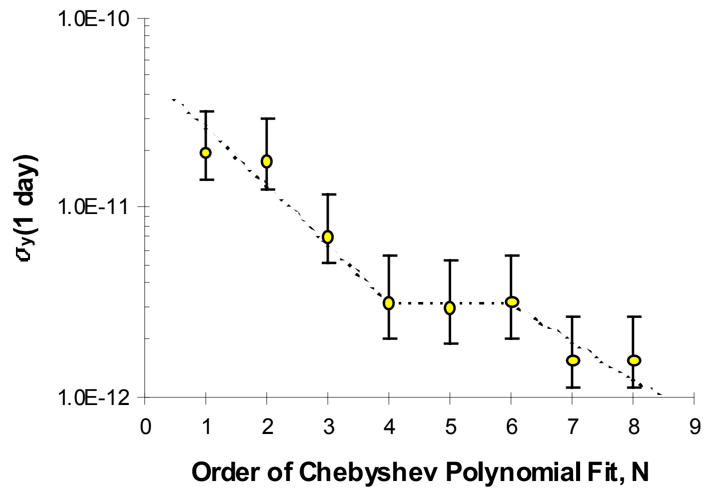


Figure 2. Hayes criterion for determining the appropriate Chebyshev fit: Allan deviation, $\sigma_y(\tau, N)$, is considered as a function of the number of Chebyshev polynomials in the fit, N. Error bars correspond to the 90% confidence interval on the estimated $\sigma_y(\tau, N)$.

Figures 3 and 4 show the Allan deviation of the crystal oscillator as a function of averaging time prior to the flares (diamonds), during the flares (circles), and after the flares (squares); error bars correspond to 95% χ^2-confidence intervals on the $\sigma_y(\tau)$ values **[9]**. The dashed line shows the long-term behavior of a very high quality crystal oscillator exhibiting random-walk frequency noise at a level of $10^{-14}\tau^{0.5}$ **[10]**. As the figure clearly shows, this oscillator exhibited excellent long-term performance prior to and after solar activity. Additionally we see *no effect* of the enhanced solar activity on the oscillator's stochastic behavior **[11]**.

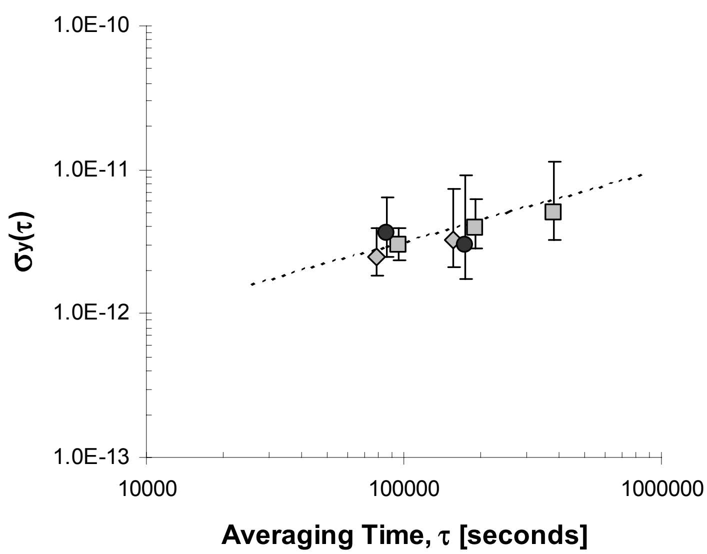


Figure 3. Allan deviation prior to (diamonds), during (circles), and after (squares) the large solar flares for 14 July 2000. (The data points for the three intervals are plotted with a slight offset in their averaging times for clearer presentation.) The dashed line indicates the random-walk frequency noise of a very high quality crystal oscillator with $\sigma_y(\tau) = 10^{-14}\tau^{0.5}$.

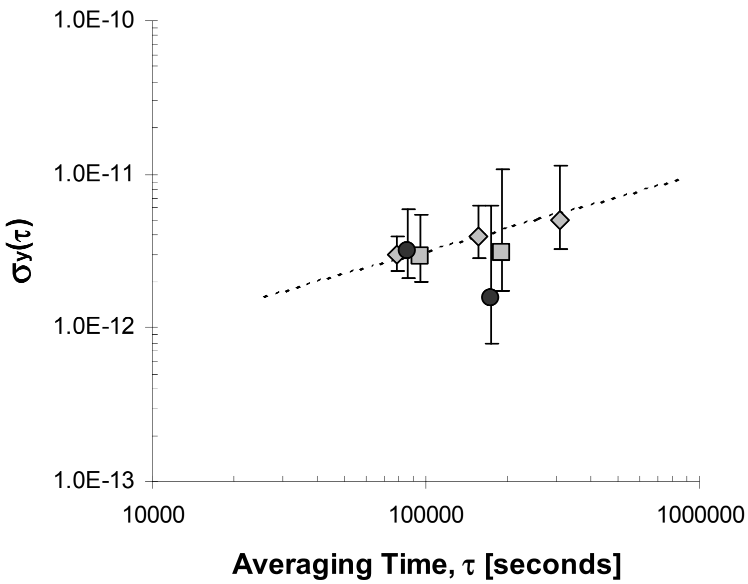


Figure 4. Allan deviation prior to (diamonds), during (circles), and after (squares) the large solar flares of 9 November 2000. (The data points for the three intervals are plotted with a slight offset in their averaging times for clearer presentation.) The dashed line indicates the random-walk frequency noise of a very high quality crystal oscillator with $\sigma_y(\tau) = 10^{-14}\tau^{0.5}$.

RATE OF TIME-ERROR BUILDUP

Given the results of the previous section, we conclude that, during a large solar flare, the time-error buildup of a "FLT1-type" crystal oscillator will likely be driven by the oscillator's deterministic radiation-induced frequency shift. As we are now in the peak of solar cycle 23, there have been a number of relatively large solar flares over the past 4 years, and as mentioned above the space-radiation data for these events are archived in the GOES database. While these solar events have not adversely affected Milstar operations, they have caused observable changes in the FLT-1 crystal oscillator frequency. Figure 5 is a summary of the maximum solar-flare-induced frequency changes for the FLT-1 crystal oscillator over this time period, where error bars correspond to our best estimate of the maximum frequency excursion's uncertainty. In the figure, the frequency shift is plotted as a function of the peak 1-day average solar proton fluence of the flare for protons with energies greater than 50 MeV, $F_1(50)$. In order to keep our frequency-shift uncertainty to a reasonable minimum, we ignored any possible effects associated with flares having a peak $F_1(50)$ less than 30 protons/(cm^2·sec·sr).

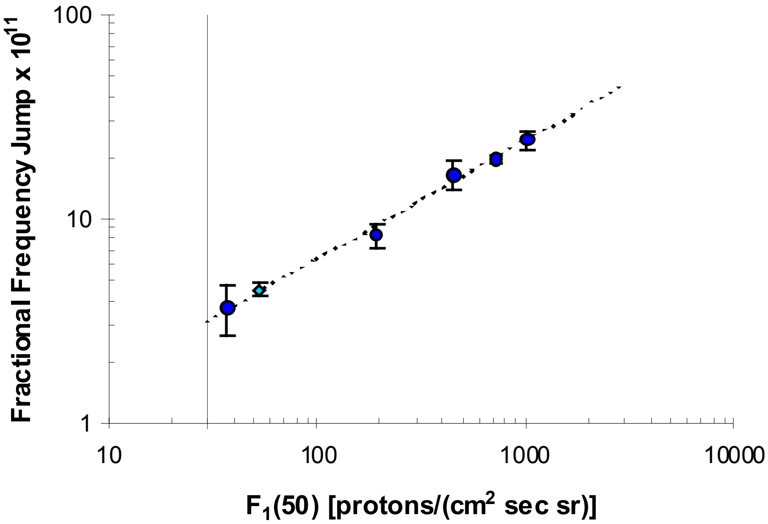


Figure 5. Maximum frequency excursion of the FLT-1 crystal oscillator as a function of $F_1(50)$ as measured by the GOES satellites.

As the figure shows, the data are well fit by a power law: $\Delta f/f_o = A[F_1(50)]^\alpha$, with $A = 4.4\times10^{-12}$ and $\alpha = 0.58$. We note that in all cases except one, the peak of the crystal's transient frequency response occurred within 24 hours of the flare's peak. The one anomalous case is indicated by a diamond data point in Figure 4, where the peak frequency response appeared to occur ~ 6 days after the flare's onset. This data point was excluded from the power law fit, though we note that it nonetheless fits the power law quite well.

In order to investigate the effects of solar flares on synchronization, we modeled the crystal's solar-flare induced temporal response with a Rayleigh function **[12]**:

$$\Delta f(t)/f_o = A[F_1(50)]^\alpha (t/\tau_R) \exp[0.5(1-(t/\tau_R)^2)]U_H(t), \tag{1}$$

where τ_R is the Rayleigh time constant and $U_H(t)$ is the Heaviside unit step function. Our examination of the data suggests that τ_R is relatively insensitive to solar proton fluence and has a value of about 2.5 days. With regard to satcom synchronization, the issue is not how much total time-error could possibly build up, but how long it will take for the time-error to reach the microsecond level. Presumably the ground will know that a flare has occurred, for example by monitoring the GOES data. If it takes a fairly long time for the spacecraft's clock to build up a microsecond of time-error (i.e., on the order of hours), then the ground has sufficient time to take remedial action, and hence the flare should have little effect on nominal satcom operations.

Employing Eq. (1), we obtained an expression for the amount of time the crystal oscillator requires in order to build up a given time-error, $T(\Delta t_{error})$. Figure 6 shows this time as a function of $F_1(50)$ for the case of $\Delta t_{error} = 1$ μsec, and as clearly shown for a flare of $F_1(50) \sim 10^3$ protons/(cm^2·sec·sr), microsecond time-errors would not be achieved until about 10 hours after the flare's onset. Thus, it appears that even for the largest flares there should be adequate time for a ground station to take appropriate mitigating action. Of course, for navsat applications **[13]**, where nanosecond time-errors are important, a similar analysis indicates that a ground station would only have about 17 minutes to take corrective action.

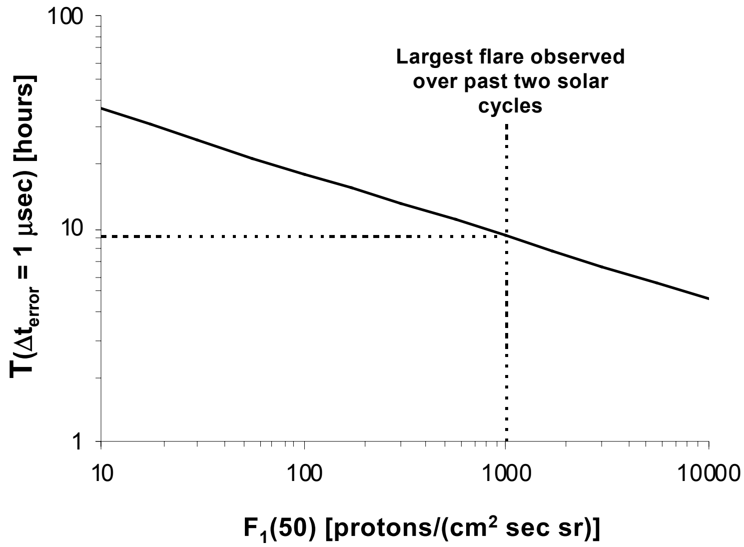


Figure 6: Estimate of the time required to reach a time-error of 1 μsec as a function of $F_1(50)$, the 1-day average solar proton fluence for protons with E > 50 MeV.

SUMMARY

In this work, we have examined the frequency response of a crystal oscillator onboard a geosynchronous spacecraft to solar flares of various magnitude. We find that: 1) the enhanced space-radiation environment of solar flares did not noticeably affect the stochastic character of the oscillator's frequency fluctuations, and 2) that the oscillator was not so severely perturbed as to impact nominal satcom requirements (i.e., microsecond synchronization levels and parts in 10^9 syntonization levels). Specifically, we found that the largest flares caused maximum fractional frequency excursions less than 10^{-9}, and time-error did not occur so rapidly that a ground control station could not have acted to mitigate the effect. Though our results are specific to a single crystal oscillator onboard Milstar FLT-1, they nonetheless bode well for other high-quality spacecraft crystal oscillators.

ACKNOWLEDGMENT

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[6] GOES is an acronym for Geosynchronous Operational Environmental Satellites. Data from the satellites is available from the Space Physics Interactive Data Resource Web page (i.e., SPIDR) at *http://spidr.ngdc.noaa.gov/.*

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[11] To be more specific, if our null hypothesis states that enhanced solar activity has *no* effect on the crystal's stochastic variations, then we *cannot reject* the null hypothesis at the 95% confidence level based on the data of Figures (3) and (4).

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