SOLAR FLARES AND PRECISE SATELLITE TIMEKEEPING

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Abstract

On 14 July 2000 and 9 November 2000 two large solar flares occurred. As measured by the GOES-8 and GOES-10 satellites, these flares were accompanied by an increase in the flux of energetic particles at geosynchronous altitudes. Here, we discuss the effect of these flares on communication satellite timekeeping, specifically timekeeping onboard the Milstar FLT-1 and FLT-2 satellites. FLT-1's timekeeping device is a crystal oscillator clock, whose time-reading and oscillator frequency are tied through a satellite crosslink to the atomic clock carried onboard Milstar FLT-2. It is well known that crystal oscillator clocks have sensitivity to radiation, while atomic clocks, like the one onboard FLT-2, are relatively insensitive to space radiation. The solar flares had a noticeable impact on the FLT-1 quartz crystal oscillator, causing the oscillator frequency to change by ~ $2x10^{-10}$. However, the flares had little if any observable effect on the FLT-2 Rb atomic clock. Since the crystal oscillator's frequency was "slaved" via crosslinks to FLT-2, the slaving procedure compensated for the radiation induced changes in the quartz crystal oscillator. Consequently, crosslink slaving of FLT-1 to FLT-2 mitigated the influence of the flares on FLT-1's actual timekeeping, and hence the satellite communications system.

INTRODUCTION

An important element of satellite communications, in particular communications that employ spread-spectrum techniques, is the degree of synchronization and syntonization among spacecraft clocks. Though the levels of synchronization and syntonization demanded by any system will depend on a number of specific system details, it is probably fair to say that modern satellite communications are adequately served by microsecond synchronization levels, and 10^{-9} levels of fractional frequency syntonization. Under benign operating conditions, both crystal oscillator clocks and atomic clocks can achieve this degree of synchronization and syntonization. However, given the relatively long lifetimes of today's satellite missions, system design must anticipate and plan for operation during periods of solar maximum, when the spacecraft clocks experience an enhanced space-radiation environment. Though atomic clocks are essentially insensitive to solar radiation [1], timekeeping with crystal oscillator clocks can be significantly degraded during a solar flare. Consequently, in order to ensure operability during solar maximum, one might feel compelled to place either atomic clocks or well-shielded crystal oscillator clocks on all system spacecraft.

An alternative to placing atomic clocks (for example) on all spacecraft is to place radiation-insensitive clocks on only a few spacecraft and then to use satellite crosslinks to tightly tie other spacecraft clocks to these few high quality devices. If the crosslink synchronization and syntonization procedures can be made robust, the radiation insensitivity of atomic clocks would then be passed to lower quality clocks with potential savings in size, weight, power consumption, and cost. Here, we describe the efficacy of this approach using the Milstar communications satellite system as an example. Milstar is the newest generation of United States milsatcom, and the system is meant to provide secure communications for United States Department of Defense operations in the first decade of the 21st century [2]. Following a brief overview of Milstar's approach to timekeeping, we examine the system's performance during the solar flare of 14 July 2000. Specifically, we show that even though the crystal oscillator clock onboard Milstar FLT-1 was significantly perturbed by the solar radiation, crosslink synchronization and syntonization procedures tightly tied this crystal oscillator to the rubidium (Rb) atomic clock carried onboard FLT-2. The crosslink information allowed FLT-1 to correct its crystal clock, so that communications timekeeping as monitored on the ground was unaffected by the flare.

MILSTAR TIMEKEEPING

Milstar FLT-1 was launched on 7 February 1994 and its SC-cut crystal oscillator has been performing quite well [3]. Specifically, the FLT-1 crystal oscillator displays a long-term Allan deviation, $\sigma_y(\tau)$, of $1.6 \times 10^{-14}\sqrt{\tau}$ and a fractional-frequency aging rate of approximately -1×10^{-12}/day; both of these parameters are quite good for crystal oscillators [4, 5]. The second Milstar satellite, FLT-2, was launched on 6 November 1995, and its Rb atomic clock has also been performing well [6]: in the long-term $\sigma_y(\tau) \cong 1.0 \times 10^{-15}\sqrt{\tau}$, and the clock displays a linear frequency aging rate of about $+7 \times 10^{-14}$/day.

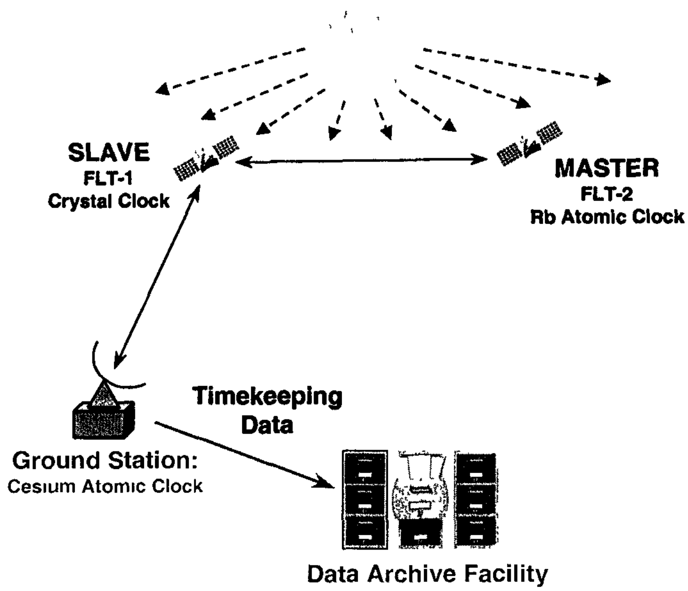

Figure 1. Illustration of the Milstar system as described in the text.

Soon after the completion of initial FLT-2 testing, FLT-1 was "slaved" to FLT-2, as illustrated in Figure 1. In the slaving procedure, the Slave ties the frequency of its oscillator and the time reading of its clock to a Master satellite using information passed along the satellite crosslinks in a standard two-way time-transfer procedure. Briefly, at epoch e_1 the Slave and Master send signals to one another, with each recording their times of transmission using their own clocks (i.e., $t_{trn}^{S}(e_1)$ and $t_{trn}^{M}(e_1)$ for the Slave and Master, respectively). Though the Slave and Master clocks will indicate that they transmitted these messages at the same time, in reality the transmission times will be different due to the Slave clock's time-error, δt [7]:

$$t_{trn}^{S}(e_1) = t_{trn}^{S,true}(e_1) + \delta t = t_{trn}^{M}(e_1) + \delta t, \tag{1}$$

where $t_{trn}^{S,true}(e_1)$ is the "true" time of transmission, which for the Slave satellite is defined by the Master satellite's clock. If R is the range between the two satellites, then the satellites will receive signals at a time R/c later, which they then record as $t_{rec}^{S}(e_1)$ and $t_{rec}^{M}(e_1)$. The Slave and Master satellites then compute the difference between their receive and send times, $\Delta t_{arrival}^{J}(e_1) = t_{rec}^{J}(e_1) - t_{trn}^{J}(e_1)$:

$$\Delta t_{arrival}^{S}(e_1) = t_{trn}^{M}(e_1) + \delta t + \frac{R}{c} - t_{trn}^{S}(e_1). \tag{2a}$$

$$\Delta t_{arrival}^{M}(e_1) = t_{trn}^{S}(e_1) - \delta t + \frac{R}{c} - t_{trn}^{M}(e_1). \tag{2b}$$

In the following epoch, e_2, the Master sends its $\Delta t_{arrival}^{M}$ value to the Slave, which then computes its clock offset and makes the appropriate correction:

$$\delta t(e_2) = \tfrac{1}{2}\left[\Delta t_{arrival}^{S}(e_1) - \Delta t_{arrival}^{M}(e_1)\right]. \tag{3}$$

Keeping track of the $\delta t(e_i)$ values from time $t(e_1)$ to $t(e_n)$, the Slave can also determine the fractional frequency offset of its clock, δy, and can make the appropriate frequency corrections:

$$\delta y = \left[t(e_n) - t(e_1)\right]^{-1} \sum_{i=1}^{n} \delta t(e_i). \tag{4}$$

Analysis has shown that this procedure is very effective, and that FLT-1 can by synchronized to FLT-2 to better than 150 ns [3].

In 2000, FLT-1 was in view of the constellation-control ground station, while FLT-2 was out of view. A few times a day, the ground station made time-offset measurements to the Master satellite clock via the FLT-1 to FLT-2 crosslink, and every few days uploaded a time and frequency correction to the Master, again via the FLT-1 to FLT-2 crosslink. The ground station maintains time with a cesium atomic clock referenced to Universal Coordinated Time (UTC) as provided by the United States Naval Observatory. In this way, the entire constellation is synchronized to UTC. Additionally, the ground station downloads and archives telemetry information from the spacecraft. Of particular relevance is the archive file of the FLT-1 autonomous frequency adjustments. Since this archive data file contains the corrections that FLT-1 autonomously implements in order to tie its crystal oscillator frequency to FLT-2's atomic clock, the file can be used to reconstruct a history of the FLT-1 oscillator frequency (relative to FLT-2).

SOLAR FLARE OF 14 JULY 2000

As we are now in solar maximum for solar cycle 23, spacecraft are experiencing heightened radiation levels due to the increased solar activity. Figure 2 shows the energetic proton data collected from GOES-8 over 17 months in the 1999-2000 time frame, where the data correspond to protons with energies greater than 50 MeV averaged over 3 hours **[8]**. As is clearly discerned, there were two large flares in the latter part of 2000, one on 14 July and the other on 9 November, displaying peak proton fluxes of 1247 and 1799 counts/(cm^2·sec·sr), respectively. This proton flux data are shown more clearly in Figures 3a and 3b, where the data are from GOES-10 and corresponds to 5-minute averages of E > 50 MeV protons. In order to put the magnitude of these flares in perspective, Figure 4 shows energetic proton data from GOES-7 during the maximum of solar cycle 22; as in Figure 2, the data correspond to protons with E > 50 MeV averaged over 3 hours. Clearly, during 1989 there was only one flare that produced an energetic proton flux greater than 10^3 counts/(cm^2·sec·sr), indicating that the flares of 14 July and 9 November were exceptionally large. Though in what follows we concentrate on the 14 July flare, we have found that similar effects and conclusions pertain to the 9 November flare.

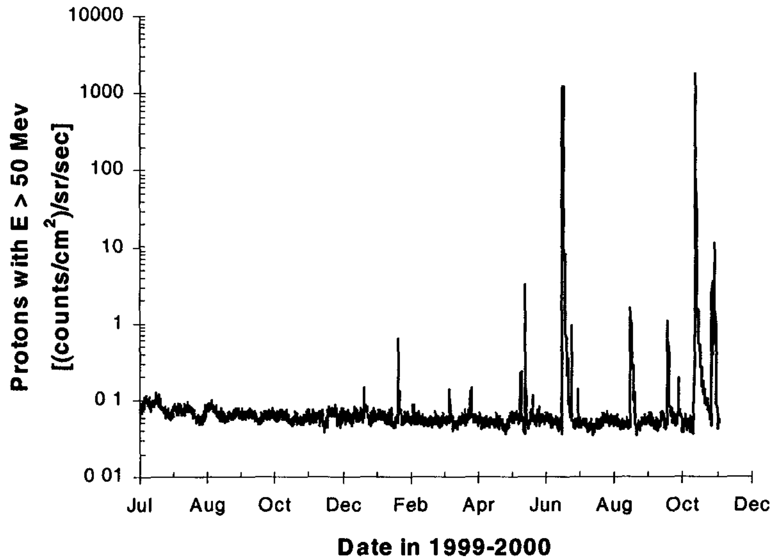

Figure 2. Three-hour average data from GOES-8 satellite showing flux of protons with energies greater than 50 MeV from 1 July 1999 to 30 November 2000.

CLOCK PERFORMANCE DURING A SOLAR FLARE

As part of satellite telemetry data, FLT-1 downloads the autonomous frequency adjustments that it applies in order to tie its quartz crystal oscillator to the Rb atomic clock onboard FLT-2. From the adjustments, it is possible to determine the fractional frequency offset of FLT-1 relative to FLT-2, and these are shown in Figure 5 as a function of date. Also reproduced are the solar proton data of Figure 3 for the July time frame. As Figure 5 shows, the flare caused a jump in the quartz crystal's frequency with a peak value of 1.4×10^{-10}. A similarly large jump was observed for the 9 November flare, with a peak $\Delta f/f_0$ of 2.0×10^{-10}.

Though the 14 July and 9 November flares had observable effects on the quartz crystal oscillator frequency, it must be remembered that these were observed in the *autonomous frequency corrections* applied by the spacecraft in order to keep its crystal clock tied to FLT-2's Rb atomic clock. As a result of those corrections, a user communicating through FLT-1 would have been unaffected by the flare *if* the

FLT-2 atomic clock was unaffected by the flare, and *if* the slaving of FLT-1 to FLT-2 was effective in mitigating the influence of the flare on FLT-1 timekeeping.

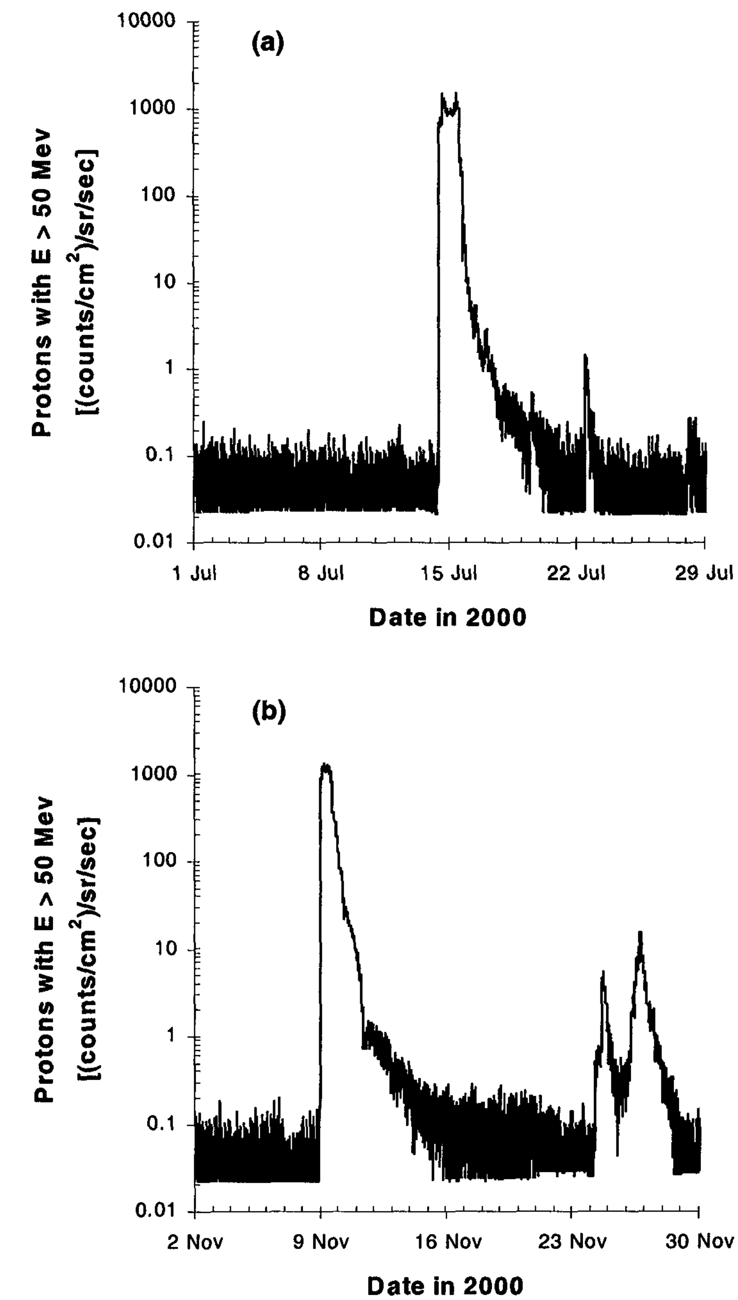

Figure 3. (a) Five-minute average data from the GOES-10 satellite showing flux of protons with energies greater than 50 MeV in July 2000; (b) same as (a) except for November 2000.

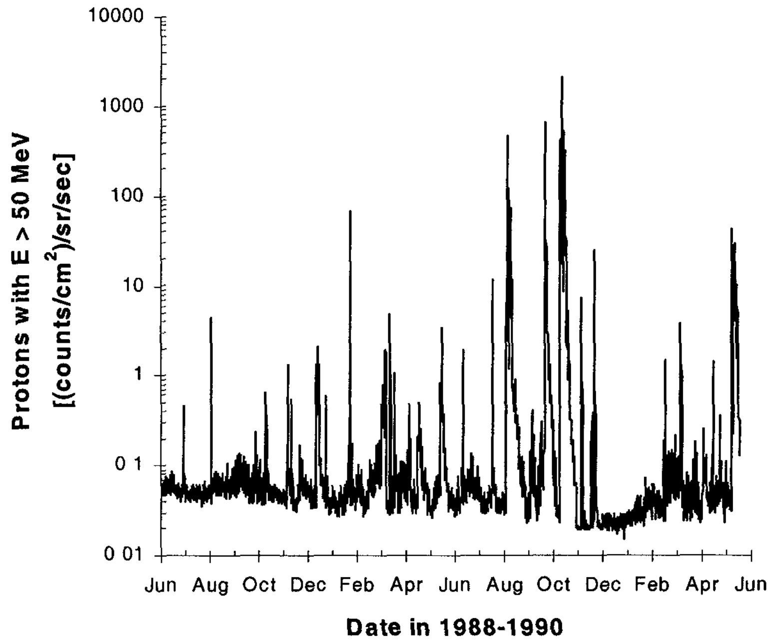

Figure 4. Three-hour average data from GOES-7 satellite showing flux of protons with energies greater than 50 MeV for solar cycle 22.

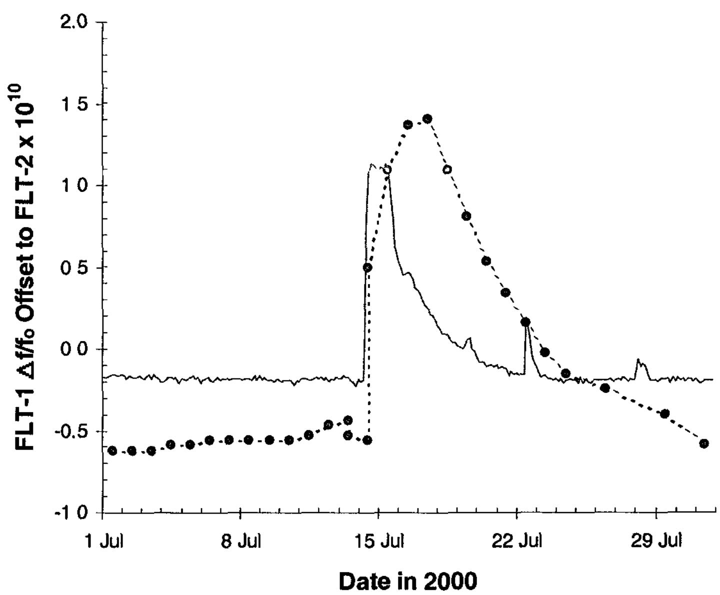

Figure 5. Archived, autonomous frequency corrections for the quartz crystal oscillator onboard FLT-1. These are the corrections that were applied by the spacecraft in order to tie its oscillator's frequency to the FLT-2 Rb atomic clock. The gray curve is a reproduction of Figure 3a to simply illustrate the timing of events.

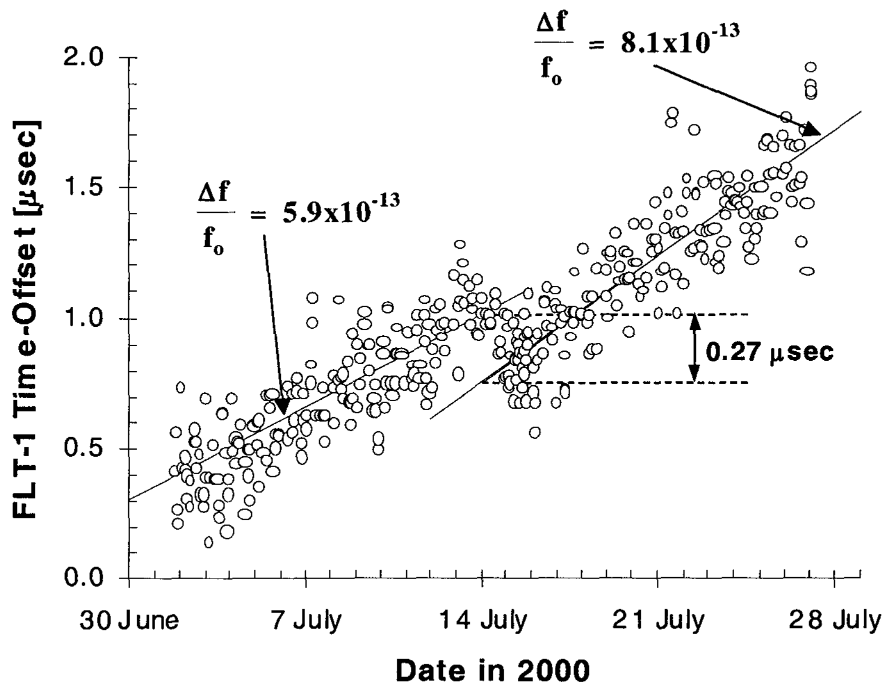

Figure 6. Time offset data as a function of date. Circles correspond to the measurements of FLT-1's actual time offset as made by the ground control ground station. Time corrections commanded to FLT-2 during this interval have been removed from the data. The solid lines are fits prior to and after 14 July.

The robustness of atomic clock timekeeping and satellite clock slaving is verified by the data of Figure 6. In this figure, time-offset data between FLT-1 and the ground station (filled circles) are plotted as a function of date in July 2000. Time and frequency corrections commanded to FLT-2 from the ground have been removed from the data, so that the data represent generic spacecraft timekeeping uncoupled from specific Milstar-system details. Basically, the time-offsets of Figure 6 represent the time-errors that would have been observed by a user had the two satellites been operating without the benefit of ground control (i.e., independent of any specific system). As is clear from the figure, FLT-1 would have picked up a maximum of about 2 μsec of error during the entire month of July, due primarily to the (normal) random and deterministic timekeeping variations associated with the FLT-2 Rb atomic clock to which it was slaved **[6,10]**. Note that on 14 July there is a discontinuity in the timekeeping data. Specifically, it appears that there is a time-jump of about 250 ns and a fractional frequency-jump of about $2x10^{-13}$. These effects could be due to the solar flare's effect on the FLT-2 Rb atomic clock; they could be due to flare induced effects in the satellite-to-satellite time-transfer process; they could be due to some satellite-to-ground time-transfer effect, or they could be due to some portion of the crystal's radiation sensitivity not mitigated by the slaving process. At the present time we cannot distinguish among any of these possibilities. Notwithstanding this uncertainty, these errors are essentially within the timekeeping noise, and have no significant effect on timekeeping for communication purposes.

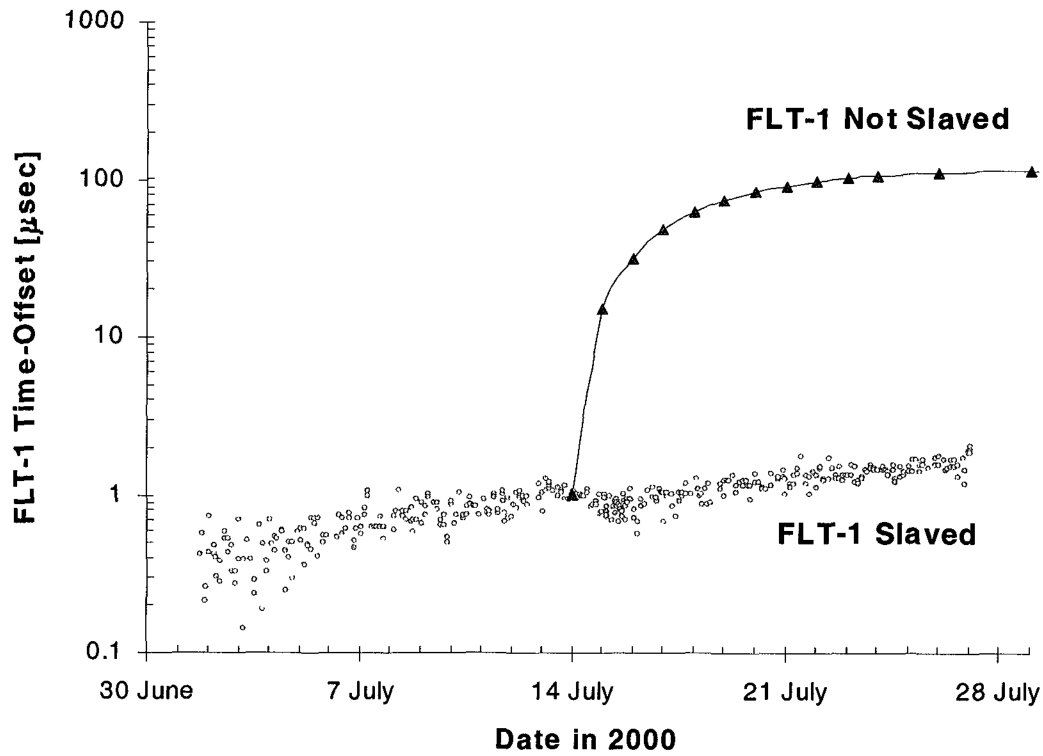

Figure 7. Time offset data as a function of date illustrating the effect of the flare on FLT-1 timekeeping *if* the satellite had not been slaved to FLT-2.

If FLT-1 had not been slaved to FLT-2, then the radiation-induced frequency change of FLT-1's quartz crystal oscillator would have given rise to significant timing-errors. Using the frequency-offset data of Figure 5, we can compute the timing-error FLT-1 would have displayed if it had not been slaved. This is shown by the triangles in Figure 7. Thus, even though the 14 July solar flare had a significant effect on the quartz crystal oscillator of FLT-1, and could have seriously degraded the spacecraft's timekeeping, the spacecraft's actual timekeeping was not perturbed due to the radiation insensitivity of atomic clocks and the efficacy of the satellite slaving procedures.

CONCLUSIONS

As satellite communications systems continue to develop, they will place increasing demands on spacecraft timekeeping. In particular, precise time will need to be maintained during periods of heightened solar activity. Here, we discussed the efficacy of a slaving solution to this problem, where atomic clock timekeeping is combined with crosslink time transfer. Examining the Milstar system's performance during the large solar flare of 14 July 2000, we found that even though the quartz crystal clock onboard FLT-1 was (predictably) perturbed by the space radiation, the effect on system timekeeping was mitigated by FLT-1's slaving to the Rb atomic clock carried onboard FLT-2. Atomic clock timekeeping and satellite slaving is, therefore, an effective procedure for creating a radiation insensitive, autonomous satellite timekeeping system.

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[7] For the purpose of illustrating the slaving process, we ignore delays in the transmission and reception of timing signals due to satellite electronics. Moreover, we ignore the satellites' relative velocity.

[8] All GOES data were obtained from SPIDR (Space Physics Interactive Data Resource), a service provided by the National Geophysical Data Center, Solar-Terrestrial Physics Division. The data may be accessed at *http://spidr.ngdc.noaa.gov*

[9] All GOES data were obtained from SPIDR (Space Physics Interactive Data Resource), a service provided by the National Geophysical Data Center, Solar-Terrestrial Physics Division. The data may be accessed at *http://spidr.ngdc.noaa.gov*

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