LONG-TERM STABILITY OF A RUBIDIUM ATOMIC CLOCK IN GEOSYNCHRONOUS ORBIT

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Abstract

In general for a well-stabilized rubidium (Rb) atomic clock (i.e., the type flown on Milstar satellites), the output frequency of the device ages slowly over time in a linear fashion. However, when a Rb atomic clock is first turned on, the output frequency of the device changes relatively rapidly as the physics package "warms up," and it requires some time before the clock's frequency settles down to its quiescent aging behavior. This warm-up period is important to Milsatcom system planners, as it defines the time interval following turn-on before a satellite clock may be said to be "reference quality." We have assessed this warm-up period for the Milstar Flight-2 (FLT-2) Rb atomic clock using 2½ years of timekeeping data archived at the Milstar Auxiliary Support Center (MASC). The change in the clock's frequency aging rate is consistent with an exponential decay from an initially large absolute value (~ $-7x10^{-12}$/day) to a small steady-state value ($+7x10^{-14}$/day). The time constant for this decay is ~ 50 days, indicating that stabilization of a newly turned-on Rb atomic clock may take several months. In addition, we show that for 427 days of running at a stable aging rate, the Allan variance random-walk coefficient is $1x10^{-15}$/day.

I. INTRODUCTION

In general for well-stabilized rubidium (Rb) atomic clocks (i.e., the type flown on Milstar satellites), the output frequency of the device ages slowly over time in a linear fashion. However, when a Rb atomic clock is first turned on, the output frequency of the device changes relatively rapidly as the physics package "warms-up," and there is some period of time before the clock's frequency settles down to its quiescent aging behavior. The warm-up duration is important to Milsatcom system planners, as it defines a period of time following turn-on before a satellite clock may be said to be truly "reference quality" [1].

Figure 1 shows the present timekeeping system for Milstar. When complete, the Milstar constellation will consist of four satellites in geosynchronous orbit, each carrying a set of four clocks. Flight 1 (FLT-1), the first Milstar satellite, carries a set of crystal oscillator clocks, while FLT-2 (and all subsequent satellites) carries a set of rubidium (Rb) atomic clocks. FLT-1 was launched on Feb 7, 1994; Flight 2 on Nov 6, 1995. At any one time only one clock is operational on a given satellite. The satellites pass time and frequency information to each other via crosslinks and one satellite relays the information to the ground. Slave clocks tie their time and frequency to the master clock using timekeeping information passed along the satellite crosslinks [2]. The ground station or SMCS (Satellite Mission Control Subsystem) monitors and corrects the timekeeping of the master satellite's clock. The SMCS clock is referenced to the US Naval Observatory. Timekeeping information sent and received over uplink and downlink telemetry is archived at the MASC. We now have two and a half years of data on how the Rb clock on FLT-2 has been operating. In the present work we will concentrate on FLT-2 and its frequency history.

Figure 2 illustrates the physics package of a generic Rb atomic clock, which includes the lamp, filter-cell and resonance cell. Following turn on, these various elements heat up. In particular, the lamp intensity changes as the Rb vapor pressure within the lamp approaches its equilibrium value. The change in lamp intensity influences the output frequency of the clock as a consequence of a phenomenon called the light-shift effect [3], an atomic process whereby the lamp light perturbs the atom and causes a change in the clock's output frequency. Consequently, as the lamp warms up and its output intensity changes, so too does the clock's output frequency [4]. Experiments on commercial Rb clocks indicate that the major portion of this lamp-related clock warm up occurs within the first day or so after turn on [5]. Following this, the output frequency of the device appears to settle down to a slow linear variation with time.

II. FREQUENCY AGING OF THE FLT-2 RUBIDIUM ATOMIC CLOCK

Figure 3 shows the frequency history of the Rb clock onboard Milstar FLT-2 two weeks after turn-on. The data were obtained from the frequency corrections uploaded to FLT-2 by the Satellite Mission Control Subsystem (SMCS), which is responsible for maintaining synchronization between the space segment and the Milstar time scale. Frequency corrections from the ground have been subtracted so that the data represent the intrinsic frequency-offset history of the FLT-2 clock. Consistent with previous analyses, the major portion of the clock's warm up appeared to be completed within the first two days following turn on, and thereafter there was a slow linear variation of the output frequency with time. The estimated frequency aging coefficient for the linear region corresponds to $D = -6.9\times10^{-12}$/day.

Though the data of Figure 3 would suggest that FLT-2 has settled down to its quiescent linear frequency aging within one or two days following turn on, a different conclusion emerges if FLT-2's history is examined over a longer period of time following turn on. Figure 4 shows the same data as Figure 3, but now extended to 100 days following turn on. Clearly, the clock is continuing to warm up two months after turn on, and consequently the estimated linear frequency aging coefficient obtained from Figure 3 is not the true quiescent frequency aging rate of the clock. To explain the slow-down in the rate of frequency aging, we hypothesize that lamp and/or filter-cell stabilization in Rb clocks takes several months [4, 6], and that this long equilibration time is due to a migration of liquid Rb within the lamp [7] or filter-cell.

In order to study FLT-2's approach to true equilibrium, we grouped the data of Figure 4 into ten day intervals, and for each interval we estimated a linear frequency aging coefficient, D. Further, we had access to the actual SMCS estimates of FLT-2 frequency from 4 January 1997 to 9 March 1998 [8]. These frequency estimates, with ground corrections subtracted, are shown in Figure 5. They were grouped into 42-day intervals, and for each interval a value of D was determined. Figure 6 shows the results from this analysis, where D is plotted as a function of days since clock turn-on. The solid line corresponds to an exponential model for the temporal evolution of D:

$$D = D_o e^{-t/\tau} + A, \qquad (1)$$

where A is the steady-state linear aging rate of the clock frequency, and τ is a time constant. A fit to all the data shown in Figure 6 yields: $D_o = -7.5\times10^{-12}$/day, $\tau = 50$ days and $A = +7\times10^{-14}$/day. The general conclusion to be drawn from the data is that it may require several months before the frequency aging of a Milstar Rb clock is well approximated by its steady-state linear frequency aging value, A.

Evidence for a connection between decreasing lamp light and short-term aging is given in Figure

7, where it is seen that the voltage from the photo-detector of a standby Rb clock on FLT-2 decays exponentially by about 10% during 300 days of warm up, with a time constant of 55 days. Comparison of this decay time with that of the FLT-2 operational clock's short-term frequency aging (τ = 50 days) suggests that the frequency aging is caused by decreasing lamp light in the resonance cell and the light-shift effect.

FREQUENCY AGING RATE AND ALLAN VARIANCE

In order to assess the long-term frequency-aging rate and Allan variance of the clock, we employed the clock frequency estimate data, with ground corrections subtracted, shown in Figure 5. As discussed above, the data exhibit a linear, deterministic variation of fractional frequency with time for 427 days. The slope of this variation yields the FLT-2 clock's long-term linear frequency aging rate, which has the value $A = (+7.0 \pm 0.1) \times 10^{-14}$/day. This is a very good aging rate for a space-qualified Rb clock, as indicated by the data shown in Table I.

Following removal of the deterministic frequency aging, the data of Figure 5 may be linearly interpolated for subsequent statistical analysis [9]. The results of this analysis are illustrated in Figure 8, where the Allan standard deviation for the FLT-2 Rb clock is shown. The dashed line in the figure corresponds to a clock whose long-term frequency fluctuations are limited by random-walk frequency noise:

$$\sigma_y(\tau) \cong b\sqrt{\tau} = 1.0\text{x}10^{-15}\sqrt{\tau}.$$

This random walk coefficient has a respectable value for a space-qualified Rb atomic clock, as indicated by the data shown in Table I. [10, 11, 12, 13]

CONCLUSIONS

We have analyzed the frequency stability of the Milstar Flight 2 Rb atomic clock over a period of 2½ years of on-orbit operation. We have shown that its deterministic frequency aging rate has decreased exponentially with a time constant of about 50 days to a long-term linear aging rate of about $7\text{x}10^{-14}$/day. This implies that caution must be exercised in evaluating Rb clock aging rates from limited data sets immediately after turn on, even if those data sets correspond to months of operation. Additionally, we have examined the clock's frequency noise out to an averaging time on the order of 10^7 seconds. We find that even at this very low Fourier frequency the clock noise is still dominated by random-walk behavior.

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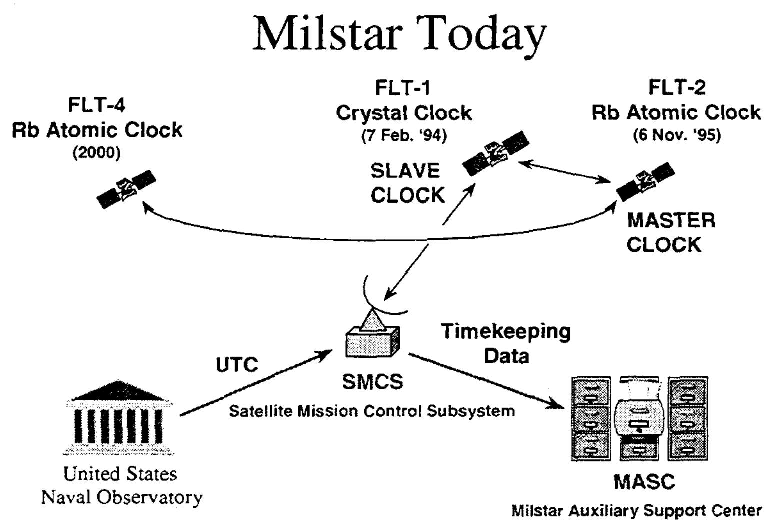

Figure 1: Overview of the present Milstar timekeeping system.

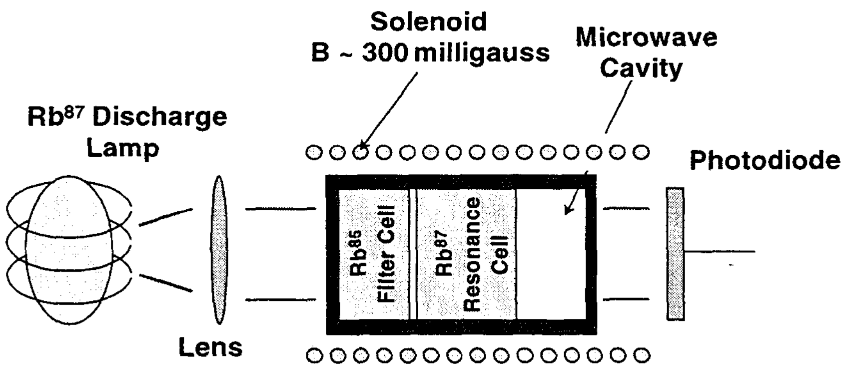

Figure 2: Physics package of a generic Rb atomic clock. Light from a Rb discharge lamp passes through a filter-cell and resonance cell both housed within a microwave cavity. The filter-cell tailors the spectral profile of the lamp light so that it can efficiently produce atomic clock signal in the resonance cell. The atomic clock signal is monitored by the amount of light transmitted by the resonance cell, which is detected by the photodiode. The microwave cavity is housed in a solenoid which produces a magnetic field that is used to tune the clock's output frequency.

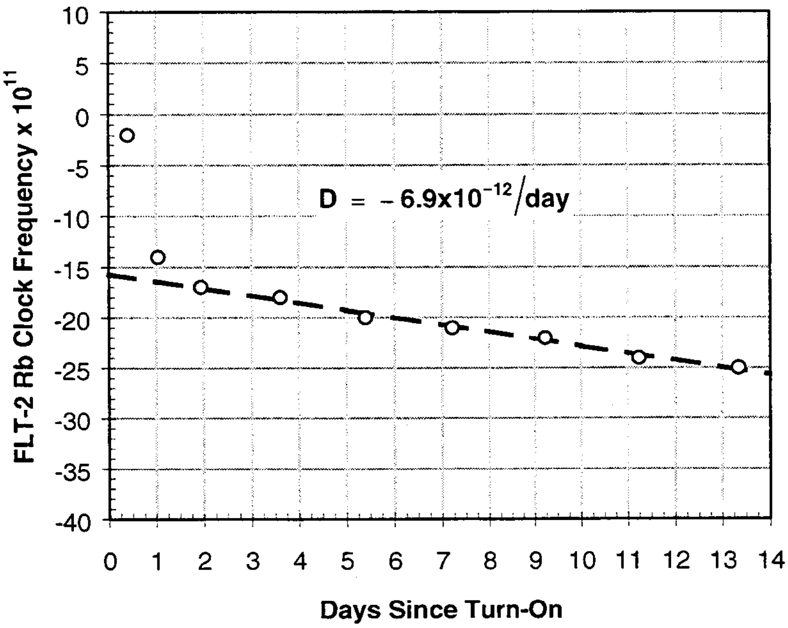

Figure 3: Two-week history of the Milstar FLT-2 Rb clock frequency following turn on. The data suggest that the clock warms up in the first day following turn on, and that afterwards the frequency of the device changes linearly with time at the rate of ~ -7×10^{-12}/day.

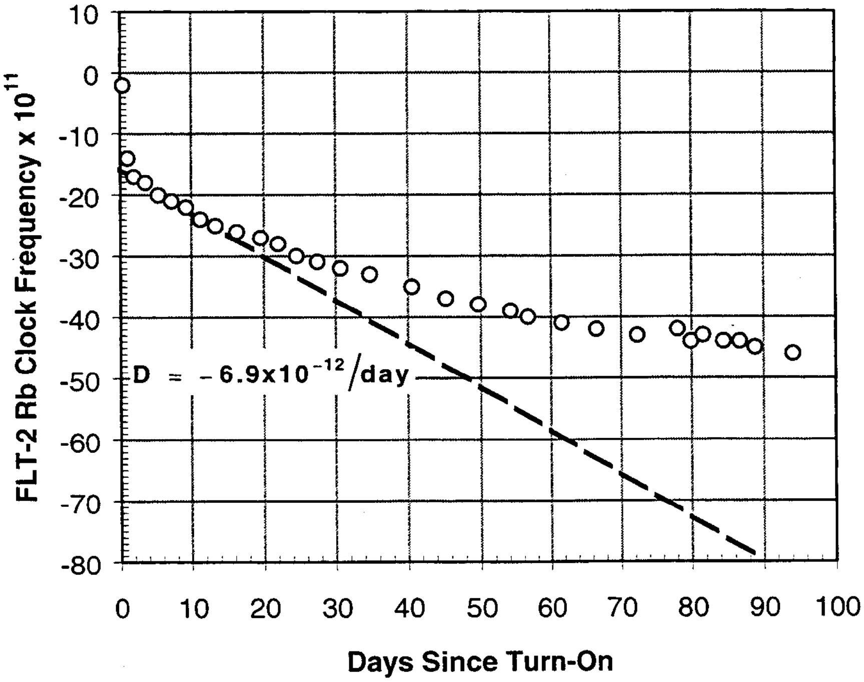

Figure 4: One hundred day frequency history of Milstar FLT-2 following turn on. Clearly, the clock is continuing to warm up two months following turn on.

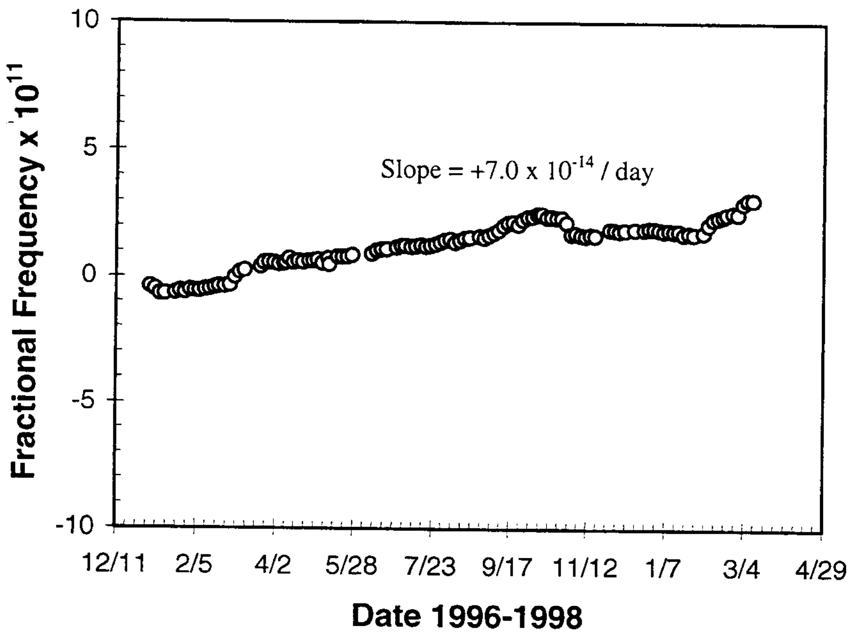

Figure 5: The SMCS estimate of FLT2's fractional frequency from its linear least-squares algorithm vs. Date. Minor divisions of the abscissa correspond to seven-day intervals.

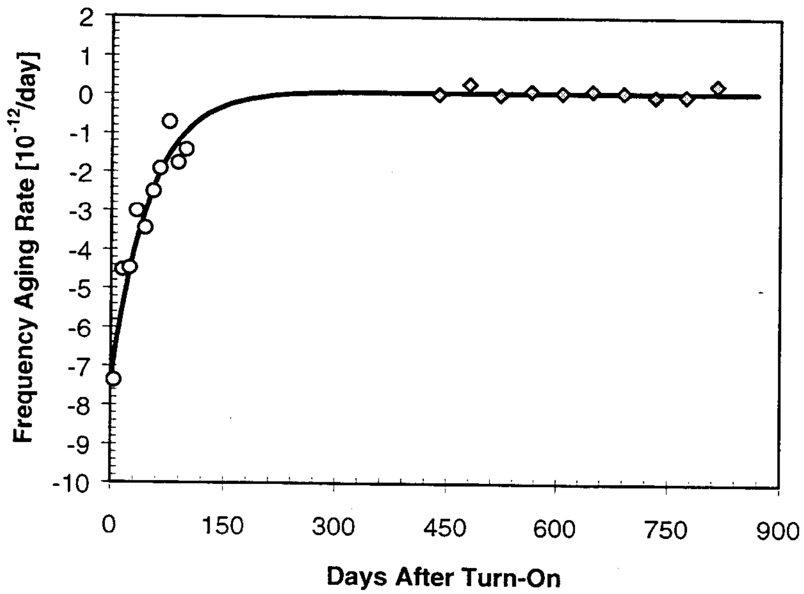

Figure 6: FLT-2 Rb clock frequency aging rate, D, as a function of time after clock turn on. Circles correspond to values obtained from the SMCS frequency corrections shown in Figure 4. Diamonds correspond to values obtained from SMCS frequency estimates. As described in the text, the solid curve is an exponential fit to the data.

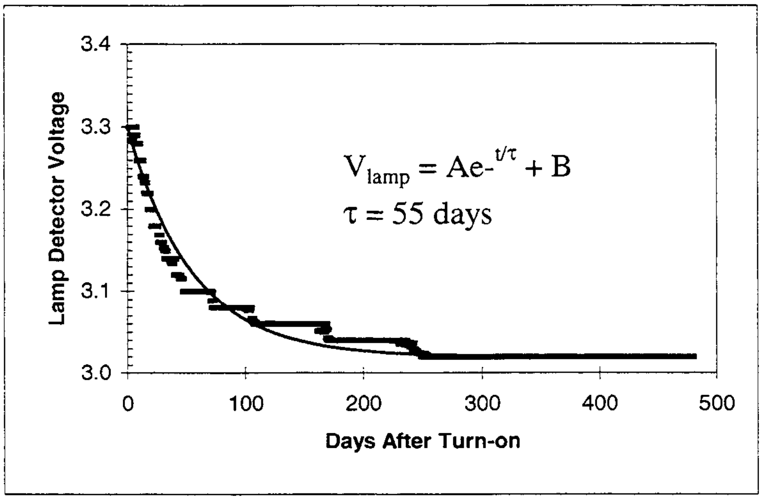

Figure 7. One of the telemetry parameters archived at the MASC is the DC Lamp Voltage from the photodetector. Note that for this clock on Flight 2 the Lamp Voltage took several months to stabilize. The time constant for stabilizing is 55.

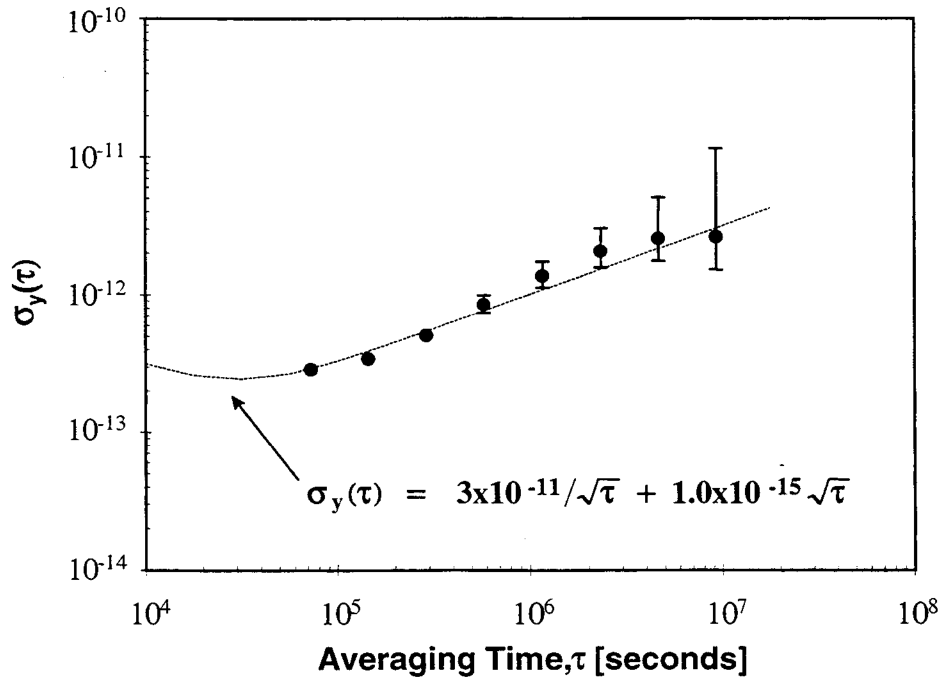

Figure 8: Allan standard deviation for FLT2 based on the data shown in Figure 5. The dashed line corresponds to the indicated Allan standard deviation.

Rb Clock	A	$\sigma_y(\tau = 10$ days)	T_{meas}	Data Source	Reference
Milstar FLT2	$+7.0 \times 10^{-14}$/day	9.3×10^{-13}	427 days	On-Orbit	
GPS Navstar 3	$+2.9 \times 10^{-14}$/day	4.1×10^{-13}	132 days	On-Orbit	[10]
GPS Navstar 10	-1.3×10^{-13}/day	3.3×10^{-13}	466 days	On-Orbit	[11]
GPS Navstar 11	-1.1×10^{-13}/day	3.4×10^{-13}	159 days	On-Orbit	[11]
GPS Navstar 25	-1.8×10^{-13}/day	2.2×10^{-13}	426 days	On-Orbit	[11]
EG&G 1	-1.8×10^{-14}/day	3.4×10^{-14}	40 days	Laboratory	[12]
EG&G 2	-0.8×10^{-14}/day	1.0×10^{-14}	40 days	Laboratory	[12]
EG&G 3	-4.5×10^{-14}/day	1.0×10^{-14}	107 days	Laboratory	[13]

Table I: Comparison of various space-qualified rubidium clock aging rates and long-term frequency fluctuations; T_{meas} refers to the data length used to estimate A.