SPACE-SEGMENT TIMEKEEPING FOR NEXT GENERATION MILSATCOM

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Abstract

Though the level of precise timekeeping for military satellite communications (milsatcom) applications may not be as stringent as that required for satellite navigation, milsatcom poses its own unique timekeeping problems. For example, milsatcom timekeeping must be precise without putting an undue burden on a ground station's workload. Further, milsatcom timekeeping must be robust, with the ability to autonomously detect and correct timekeeping problems during protracted periods when the ground control station is either unavailable or burdened with other pressing tasks. Here, we discuss three different space-segment timekeeping systems that could be employed in milsatcom, and our numerical simulations investigating their various attributes. These systems include a Master/Slave system (similar to present day Milstar), an Ensembling system (based on NIST's AT1 algorithm),and a Kalman-Filter system (similar to GPS when it goes to crosslink ranging). The timekeeping performance of the three systems is characterized by the median time interval between ground station updates,given a somewhat arbitrary 2-µsec requirement for space-segment timekeeping. Among other effects, our simulations include: satellite temperature variations, satellite clock random noise, satellite clock frequency aging, time-transfer noise between satellites,as well as time-transfer noise between satellites and the ground station. As we will show, milsatcom timekeeping involves a complicated interplay between satellite timekeeping hardware and the space-segment timekeeping system. Judicious choice of the hardware and space-segment system can allow weeks between ground station updates of the constellation's timekeeping.

INTRODUCTION

In order to take advantage of spread–spectrum communication techniques, military satellite communications (milsatcom) requires precise timekeeping. Though the level of precise timekeeping for milsatcom may not be as stringent as that required for satellite navigation, milsatcom poses its own unique timekeeping problems. Specifically, milsatcom timekeeping must be precise without putting an undue burden on the ground station's workload. Additionally, milsatcom timekeeping must be robust, with the ability to autonomously detect and correct timekeeping problems during protracted periods when the ground control station is either unavailable or burdened with other pressing tasks.

Here, we investigate several different hardware and space-segment approaches to timekeeping as might be implemented in "next generation" milsatcom (e.g., Advanced EHF), with the specific objective of determining what, if any, impact these different options would have on a ground control station's workload. We compare the performance of three different space-segment timekeeping subsystems: a Master/Slave system similar to that of Milstar [1,2], a Kalman-Filter system similar to that implemented in GPS Block IIR [3,4], and an Ensembling system based on NIST's AT1 algorithm [5,6]. Additionally, we consider the impact on constellation timekeeping of satellite atomic clocks with differing levels of performance. The results of our simulations are assessed with two metrics. In order to quantify a ground station's "normal" workload, we set an arbitrary 2-µsec synchronization level for the constellation, and then determine the interval between ground–station updates needed to maintain this synchronization.[*] Further, to assess timekeeping during periods when the ground station is unavailable or overburdened, we determine the rate of the constellation's time-error buildup in the absence of ground control.

In the following sections, we present an overview of system timekeeping, brief descriptions of the satellite hardware options and space-segment timekeeping subsystems, our method of analysis, and our results. It will become apparent that, with a judicious choice of the space-segment timekeeping subsystem and the satellite timekeeping hardware, it should be possible to maintain accurate constellation time and frequency with a significantly reduced workload at the ground control station.

GENERAL TIMEKEEPING AND THE SPACE-SEGMENT

GENERAL TIMEKEEPING

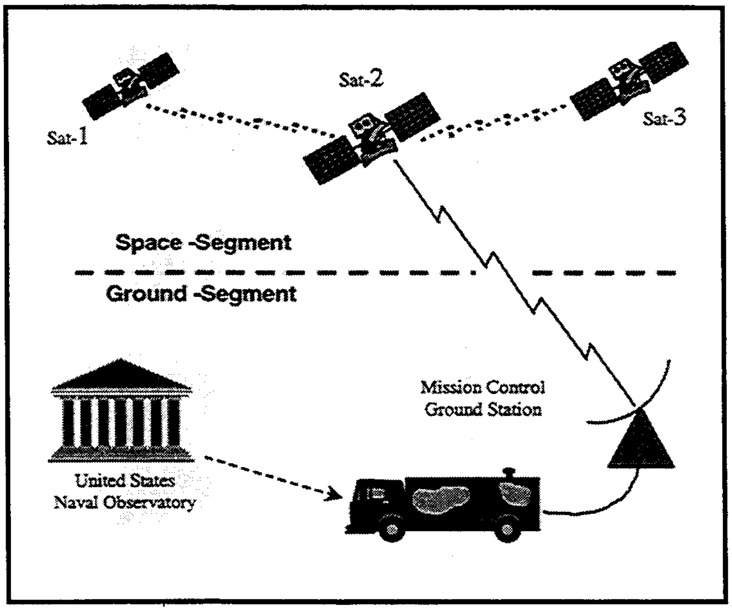

Figure 1: Division of space-system timekeeping into ground-and space-segment subsystems.

Figure 1 illustrates the generic elements associated with a satellite system's timekeeping. Spacecraft carry precision clocks and these need to be synchronized and syntonized [7] to some reference (e.g., Universal Coordinated Time, or UTC, as defined by the United States Naval Observatory, USNO [8]). Ground stations monitor the spacecraft clocks and typically mediate spacecraft synchronization and syntonization to the reference. As is clear in the figure, system timekeeping divides naturally into a space-segment and a ground-segment subsystem. The space segment consists of the satellite clocks and any hardware and/or algorithms employed on the spacecraft to synchronize and syntonize the constellation to the ground segment. The ground segment consists of the mission control ground station clocks, the algorithms that the ground stations use to synchronize and syntonize themselves to the reference (e.g., UTC), and the algorithms the ground stations use to monitor and periodically control the time and frequency of the spacecraft clocks. In the present work we focus attention on the space segment, specifically the spacecraft synchronization/syntonization procedures and algorithms, along with the spacecraft timekeeping hardware.

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[*] In order of magnitude, satellite navigation systems require nanosecond synchronization levels, while communications systems require microseconds. Hence, the choice of a 2 μsec synchronization level for our studies.

In order to simulate a complete system, it is of course necessary to include some elements of the ground-segment subsystem, specifically the hardware and algorithms the ground segment uses to synchronize and syntonize the constellation. Here, we consider a Milstar-like ground segment, where cesium (Cs) atomic clocks are employed at the ground control stations and a least-squares fit of ground-to-spacecraft time-offset readings is used to estimate appropriate corrections for a satellite clock's time and frequency [2]. Central to the Milstar-like estimation algorithm is its simple linear *model* for time-error buildup, $\Delta T(\tau)$:

$$\Delta T(\tau) = \Delta T(0) + y\tau + x(\tau). \tag{1}$$

Here, $\Delta T(0)$ is the residual time-error immediately after the last synchronization, y is a residual fractional frequency offset, and $x(\tau)$ is the clock's stochastic time variation at some time τ. Though the stochastic variations are attributed to the spacecraft clock, they result from the satellite clock *and* the ground-segment clock, and equal the integral of the two clocks' stochastic frequency fluctuations, $\delta y(t)$. The rms value of the stochastic time fluctuations may be written as $C\tau\sigma_y(\tau)$ [9], where $\sigma_y(\tau)$ is an aggregate Allan standard deviation [10] representative of the ground and space clocks' net frequency fluctuations and C is a constant on the order of unity. Typically, the ground station clock is much better than the spacecraft clock, and hence $\delta y(t)$ is dominated by the spacecraft clock's stochastic frequency fluctuations.

In order to assess the constellation's timekeeping, the ground segment periodically makes time-difference measurements between its clock and a satellite clock. The error associated with this "uplink/downlink time-transfer" is quantified in terms of a fixed bias and a random measurement error. These errors are presumed due to unaccounted-for delays in the transmitter/receiver hardware. While the fixed bias is a constant time offset for any given satellite, its specific value from satellite to satellite is a mean-zero normal random variable. The measurement errors for a specific ground-to-satellite link correspond to a mean-zero normal random process. For both the fixed bias and the measurement error, the standard deviations are somewhat arbitrary space-segment parameters in our simulations. In order to generalize our findings, we consider system performance for two sets of scenarios: 1) standard deviations that are relatively large compared to the 2 μsec constellation synchronization scale ("nominal time-transfer noise"), and 2) standard deviations that are relatively small on this scale ("minimal time-transfer noise").

When the ground station collects a minimum of 3 time-offset measurements, it fits these to Eq. (1) using a least squares procedure, and then estimates the current time offset. If the current time-offset exceeds the synchronization threshold, a time correction is uploaded to the constellation based on $\Delta T(0)$ and y. Additionally, if the estimated frequency correction is above a threshold value, $\Delta f_{\text{threshold}}$, a frequency correction is also uploaded to the satellite. As more time-offset measurements are collected by the ground station, these procedures are repeated. Note that depending on the specific space-segment subsystem under consideration, the ground segment may independently monitor multiple clocks or only a single clock that is representative of the entire constellation.

In each of the 3 space-segment subsystems, the satellites form a ring so that only nearest neighbors communicate. Thus, time-offset information between non-nearest neighbor satellites must be passed sequentially around the ring. Just as the ground-to-satellite link is subject to time-transfer noise, so too is the satellite-to-satellite link, and again the noise is characterized by bias and random contributions.

SPACE-SEGMENT TIMEKEEPING

The first space-segment subsystem we consider is a Master/Slave system. Here, the space-segment is composed of a master satellite reference (MSR) whose time and frequency are controlled by the ground-segment. A constellation of slave satellites derive time and frequency information from the MSR via intersatellite crosslinks. Additionally, to guard against a possible failure of the MSR clock, the constellation contains two Monitor satellites (MON1 and MON2) also controlled by the ground. The Monitors along with the MSR continuously assess each others timekeeping performance via crosslink time transfer. If the time-difference information indicates an MSR or Monitor failure, the system undergoes "Succession." During Succession the satellites execute any or all of the following role changes in order to reconstruct a healthy Master-Monitor "Triplet": Slave → MON2, MON2 → MON1, MON1 → MSR. Since our present focus is on system operation in the absence of clock failure, the specific procedures dealing with failure identification and role changing will not be considered further. These form the content of a companion study [11]. However, as the ground must control three independent clocks, the presence of the monitor satellites has an influence on the ground station's workload.

In the Master/Slave system, the ground-segment follows the time offsets of each of the Triplet members. Should any one of these exceed the synchronization threshold, a time or time/frequency correction is uploaded to *all* Triplet members. In this way, the synchronization error among the MSR and monitor clocks is reduced to near zero every time the constellation is updated. In order for the ground segment to follow the time offsets of Triplet members that are not directly in view, timing information is passed via crosslinks to the in-view satellite. Specifically, the ground segment measures the time offset of the in-view satellite and each satellite in the constellation determines its time offset to its nearest neighbors. The intersatellite time offsets are downloaded, and the ground segment manipulates these to determine the time-offset of each Triplet member to the in-view satellite. With this information, the ground segment can determine the time offset of any Triplet member relative to the ground station clock. The time required for the ground station to assemble all the relevant is referred to as "latency." As a reasonable upper bound, we limit latency to 24 hours, so that as a worst case the ground segment estimates space-segment timekeeping one day in the past.

As one possible alternate to the Master/Slave system, we consider the application of a Kalman-filter estimator to Milsatcom space-segment timekeeping. In this case, each satellite clock periodically obtains time-difference information between itself and all clocks that contribute to an aggregate timescale. Based on this information, each clock employs a Kalman filter [12] to estimate its state with respect to the aggregate or "composite" clock [4]. In order to estimate a clock state, the Kalman filter requires a model of time-error accumulation. Since crystal oscillator clocks and rubidium (Rb) atomic clocks have advantages for milsatcom applications [13], and since the output frequency of these devices changes slowly in time [14, 15], we employ a three-state model for time-error accumulation. This model is similar to Eq. (1), but with an additional clock state element D, the fractional frequency aging rate:

$$\Delta T(\tau) = \Delta T(0) + y\tau + \tfrac{1}{2}D\tau^2 + x(\tau). \tag{2}$$

The third space-segment timekeeping system we consider employs a direct clock-averaging algorithm, as distinct from the filtering process associated with the Kalman filter. Again, timekeeping information from a number of independent satellite clocks is combined to produce an aggregate timescale. The NIST AT1 ensembling algorithm [16, 17] forms the basis for our implementation of this "Ensembling" system. The AT1 algorithm is attractive for milsatcom applications, as it produces time- and frequency-offset information in real time. Similar to the Kalman-filter system, the timescale's construction requires periodic time-offset determinations among all contributing clocks, and these are obtained via crosslink time comparisons. Using this information, AT1 determines time and frequency offsets for each clock from the Ensemble timescale, and makes a prediction for the time and frequency offset of each clock the next time the clocks exchange timing information. The closer the actual time offset is to its prediction, the greater the weight given to that spacecraft clock in the formulation of the Ensemble timescale. So as to keep any single clock from dominating the Ensemble, we limit the weight of any one clock: as a rule of thumb it's assumed that 2/3 of all possible ensemble members, N, are "good," and therefore should contribute to the timescale with near equal weight. This gives a nominal weight of 3/2N for any clock, and we limit the clock weights to 110% of this value. Additionally, while the Ensemble updates the time of various satellites every hour, we limit the interval of frequency updates to once a day so that diurnal temperature effects don't introduce oscillations into the timescale.

A key requirement of an ensembling algorithm is the statistical independence of the contributing clocks. Consequently, in a straightforward application of AT1 the time and frequency corrections would be recorded, but not actually applied; otherwise, the clocks would lose their statistical independence. However, in a milsatcom application time and frequency corrections should be applied to the frequency standards and the timing counters so that proper communications is maintained. To employ AT1 in a milsatcom setting, we therefore correct the satellite clocks with Ensemble information, but maintain a record of the corrections so that uncorrected time and frequency information can be reconstructed [6].

HARDWARE OPTIONS

In addition to the 3 space-segment subsystems discussed above, there are options associated with the spacecraft's timekeeping hardware. While we anticipate that atomic clocks will be used onboard the satellites due to their inherent radiation insensitivity [18], the timekeeping characteristics of such devices can vary widely. The primary parameters defining the timekeeping performance of an atomic clock are its frequency stability, frequency aging rate, frequency setability, and temperature sensitivity. For an atomic clock the Allan standard deviation takes the general form,

$$\sigma_y(\tau) = \frac{A}{\sqrt{\tau}} + B + C\sqrt{\tau}, \tag{3}$$

where τ represents the frequency averaging time. For the cesium clocks used in the ground-segment A, B, and C have non-zero values and these are held constant in all of our studies. In the case of the Rb clocks, their frequency stabilities are better described in terms of just A and C (i.e., B = 0). In our studies, we consider 3 different types of Rb atomic clock: a clock that meets the nominal Advanced EHF specifications (i.e., Nominal Rb); a clock with somewhat better performance, similar to the Milstar FLT-2 Rb clock (i.e., FTL-2 Rb) [19]; and finally a very high quality Rb clock similar to that onboard the GPS Block IIR satellites (i.e., GPS IIR Rb) [20].

In addition to the Allan variance of a clock, the clock's frequency setability has important implications for spacecraft timekeeping. This parameter concerns the precision with which a clock's frequency may be changed, and in Rb clocks the frequency change may be affected in a variety of ways. For example, in many compact commercial devices the clock frequency is altered by changing a solenoid's current, which in turn controls the strength of a static magnetic field within the clock; the Rb atoms that form the heart of the clock sense the change in magnetic field and adjust their internal atomic frequency accordingly [21]. With this "analog" approach, it is impractical to accurately implement fractional frequency changes smaller than about 2×10^{-12} due to limitations associated with the solenoid current changes. An alternate approach, with a smaller frequency uncertainty, incorporates a digital frequency synthesizer into the timekeeping device [22]. In this case, the frequency of the Rb atoms is never adjusted. Rather, the Rb atoms' internal atomic frequency serves as a reference for a frequency synthesizer whose output is adjusted. Corrections to the output frequency of the digital synthesizer can be made with a precision of approximately 5×10^{-14}. The frequency control uncertainty (FCU) associated with the clock's frequency setability is modeled as a zero-mean, normally distributed random variable with a standard deviation of 2×10^{-12} for analog control and 5×10^{-14} for digital control. In terms of space-segment timekeeping, these uncertainties affect the level at which a ground-commanded frequency correction is realized on the spacecraft. There is, therefore, a space-segment threshold for frequency corrections, which is close to the FCU, and below this threshold no corrections are made.

Finally, though atomic clocks are much less sensitive to environmental perturbations than crystal oscillator clocks, the output frequencies of our three Rb atomic clock types will display a dependence on temperature (albeit small) [21]. While each unit will likely have its own temperature sensitivity, here we treat them as all having the same sensitivity. This is a realistic assumption for our simulations, as a baseplate temperature controller is often employed with an atomic clock (i.e., thermostatic plates placed between the satellite structure and the clock). While satellite temperature fluctuations will propagate through the baseplate controller to the clock, they will be highly attenuated, and the use of appropriate controllers should result in similar temperature sensitivities for all three types of Rb clock. In the following, we take the clock/controller temperature sensitivity to be $5\times10^{-13}/\,^{o}F$, and we model all satellite clocks as subject to a nearly sinusoidal diurnal temperature variation of approximately 9 ^{o}F amplitude.

"TRADE SPACE" CONSIDERATIONS

The various options with respect to space-segment subsystem, type of atomic clock, and parameter noise value are shown in Table I; and these provide a broad "trade space" for milsatcom designers. To investigate this trade space, we employ a Monte Carlo simulation of system timekeeping that includes both the ground and space segments. In the simulation all relevant processes are modeled, including: random and deterministic frequency variations of satellite and ground station clocks, diurnal temperature variations, uplink/downlink and crosslink time-transfer noise, and the specific algorithms associated with the different space-segment subsystems.

Table I: Trade Space Addressed in Current Studies

Options	Values		
Spacecraft Rb Clock	Nominal	FLT-2	GPS IIR
Rb Clock Frequency Control	Analog	Digital	
Uplink/Downlink Noise	Nominal	Minimal	
Space-segment Subsystem	Master/Slave	Kalman	Ensemble

From the trade space outlined in Table I, it is apparent that exploration of every potential combination would require an extremely large number of simulations. Therefore, we judiciously selected key combinations for detailed investigation. We perform Monte Carlo simulations to determine the satellite clock timekeeping errors and, most importantly for this study, the rate at which the ground must update the constellation in order to maintain the constellation's 2 μsec synchronization. A single simulation comprises a sequence of 5 update intervals. The first four are conducted with the ground-segment monitoring the satellite clocks and correcting their times and frequencies as needed. During these intervals, the ground measures spacecraft time offsets every eight hours. Our studies show that by the 4th update interval any numerical transients due to the simulation's initiation have died out, and the distributions of update times we report are based on results from the 4th and 5th update intervals. The 5th update interval simulates system operation in the absence of ground-segment control, and we record the rate at which time-error accumulates during this period. The five-update-interval scenario is repeated 10,000 times for each set of trade space parameters. To put this in perspective, each trade space investigation represents the simulation of roughly 1,000 years of a milsatcom system's operation. In all simulations, we assume the space segment is composed of four satellites with essentially identical characteristics, except for the frequency aging rate, D. Each time a scenario is repeated, we add a random component to the average aging rate, ⟨D⟩, of a Rb clock. This random variation corresponds to a zero mean, normally distributed random variable with a standard deviation of ⟨D⟩/2. In this way, we account for some variability among clock quality, even for the same type of clock. As a final point, we consider spacecraft in a ring at geosynchronous altitude, evenly spaced every 90^{o}; this gives each satellite a different phase with respect to the diurnal temperature cycle. We further assume, conservatively, that satellite-to-satellite time transfer requires 3 crosslinks. Tables II and III show the simulation parameters.

Table II. Satellite Rb Clock Parameters: $\sigma_y(t) = A\tau^{-1/2} + C\tau^{1/2}$

Rb Clock Parameter	Rb Clock Type		
	Nominal	**FLT-2**	**GPS IIR**
Rb Clock A:	1.5×10^{-11}	1.5×10^{-11}	2.8×10^{-12}
Rb Clock C:	8.0×10^{-15}	1.0×10^{-15}	1.9×10^{-17}
Average Frequency Aging, $\langle D \rangle$	3×10^{-13}/day	7×10^{-14}/day	-2.4×10^{-14}/day

Table III. General Simulation Parameters for Milsatcom Calculations: $\sigma_y(t) = A\tau^{-1/2} + B + C\tau^{1/2}$

Parameter	Value	Parameter	Value
Ground station Cs clock A:	8.5×10^{-12}	Number of satellites in constellation	4
Ground station Cs clock B:	2.0×10^{-14}	Spacecraft diurnal phase angles	0, $\pi/2$, π, $3\pi/2$ radians
Ground station Cs clock C:	1.2×10^{-17}	Ground-to-Satellite measurement: σ_{bias}	750 nsec
Satellite σ_{Drift}	$0.5 \langle D \rangle$	Ground-to-Satellite measurement: σ_{random} - Nominal	750 nsec
Analog FCU	2×10^{-12}	Ground-to-Satellite measurement: σ_{random} - Minimal	125 nsec
Space-segment $\Delta f_{threshold}$: Analog frequency control	3×10^{-12}	Simulation time step	600 seconds
Ground-segment $\Delta f_{threshold}$: Analog frequency control	1×10^{-11}	Satellite-to-Satellite measurement: σ_{bias}	75 nsec
Digital FCU	5×10^{-14}	Satellite-to-Satellite measurement: σ_{random}	75 nsec
Space-segment $\Delta f_{threshold}$ Digital frequency control	3×10^{-13}	Ground-to-Constellation synchronization level	2 μsec
Ground-segment $\Delta f_{threshold}$ Digital frequency control	1×10^{-12}	Maximum length of 5th update interval	20 days
Quantization level of satellite frequency corrections	Satellite $\Delta f_{threshold}$	Kalman/Ensemble period between intersatellite timing comparisons	1 hour
Satellite clock temperature coefficient	5×10^{-13}/°F	Satellite temperature profile	Nearly Sinusoidal

Simulation Results

Table IV is a summary of our results, and unless otherwise indicated these are based on the parameter values given in Tables II and III. Specifically, in Table IV we show the median time between ground-station updates of the constellation's timekeeping for various milsatcom situations. We note that in our studies the ground-station's data latency had very little effect on space-segment timekeeping, and will not be discussed further. However, as illustrated by the results of Table IV, the space-segment subsystem in combination with the type of spacecraft clock did have a significant influence on the results. The following series of figures clearly demonstrates this point.

Table IV: Simulation Results

Trade Space Parameters			**Median Update Intervals [days][1]**		
Rb Clock Type	**Uplink/Downlink Noise**	**Frequency Control**	**Master/Slave**	**Kalman**	**Ensemble**
Nominal	Nominal	Analog	0.7	2.5	2.2
Nominal	Minimal	Analog	1.8	3.2	3.0
Nominal	Minimal	Digital	2.7	5.0	4.7
FLT-2	Minimal	Analog	3.9	7.6	2.9 [7.7 2), 4.6 3)]
FLT-2	Minimal	Digital	6.7	11.9	5.9 [8.8 2)]
GPS IIR	Nominal	Analog	4.3	12.1	19.6
GPS IIR	Minimal	Analog	10.4	12.2	21.7
GPS IIR	Minimal	Digital	15.0	20.5	15.6 [>30 4)]

1) Update interval length corresponding to a cumulative probability of 50%
2) Time between intersatellite time comparisons = 8 hours
3) Space-segment $\Delta f_{threshold} = 9.0 \times 10^{-12}$
4) Space-segment $\Delta f_{threshold} = 3.0 \times 10^{-12}$

Figure 2 shows the cumulative probability for updates less than "X" number of days in the case of an Ensemble space-segment subsystem. The median update interval corresponds to a 50% cumulative probability. The figure illustrates how the performance of a given space-segment subsystem will depend on the particular hardware parameter values, specifically the type of clock flown on the satellite and the magnitude of the uplink/downlink random time-transfer noise. Consequently, in assessing the performance of a specific space-segment subsystem, it is essential to have accurate knowledge of the various timekeeping parameters.

Given a standard Master/Slave space-segment subsystem, Fig. 3 illustrates the improvements in timekeeping that would result from purely space-segment hardware modifications. Adding a frequency synthesizer to a FLT-2 type Rb clock for fine frequency control extends the median update interval from roughly 1 day to 7 days. Introduction of the high performance,GPS IIR-type Rb clock yields a median update interval of 15 days. Figure 4 demonstrates the timekeeping improvements that could be gained exclusively through modification of the space-segment subsystem. Specifically, compared to a Master/Slave system the median update interval could be extended from roughly 4 days to 7.5 days by employing an Ensemble system. (A similar conclusion was reached regarding the Kalman-filter system.

Moreover, we note that these results are only illustrative, as we did not do an exhaustive search for optimum algorithm settings in the case of Ensemble and Kalman-filter systems.)

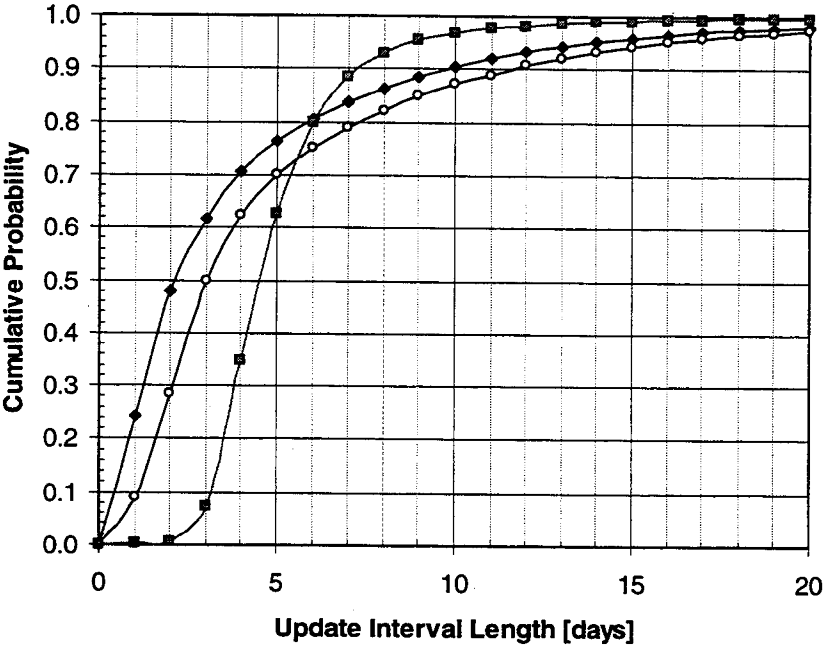

Figure 2: Cumulative probability for update less than "X" days in the case of an Ensemble system: diamonds imply nominal Rb clock with nominal uplink/downlink time-transfer noise, circles imply nominal clock with minimal uplink/downlink noise, and squares correspond to the FLT-2 Rb clock with minimal uplink/downlink noise. In case of the FLT-2 $\Delta f_{threshold}$ for space-segment was 9×10^{-12}. We simulated analog frequency control of Rb clock.

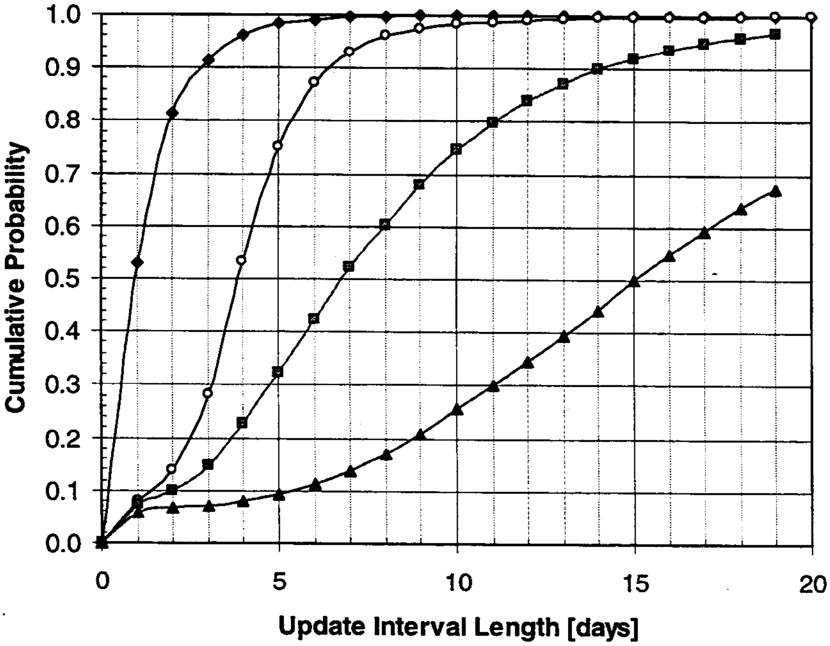

Figure 3: Cumulative probability for update illustrating improvement in space-segment timekeeping as a result of hardware variations for Master/Slave system. Diamonds ⇒ nominal Rb clock with nominal uplink/downlink noise and analog frequency control; circles ⇒ FLT-2 clock with minimal time-transfer noise and analog control; squares are similar to circles except digital control; and, finally, triangles correspond to a GPS IIR Rb clock with minimal time-transfer noise and digital control.

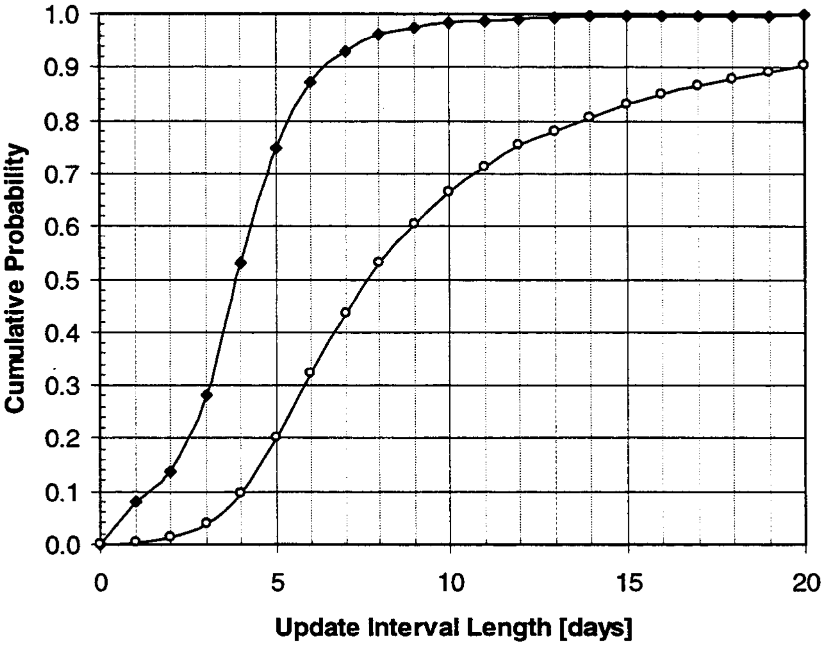

Figure 4: Cumulative probability for an update less than "X" number of days, illustrating improvements in space-segment timekeeping resulting from the space-segment subsystem: diamonds ⇒ Master/Slave while circles ⇒ Ensemble. In each case we simulate a FLT-2 Rb clock, minimal time-transfer noise and analog frequency control.

Finally, Fig. 5 shows the performance that can be achieved when both hardware and the space-segment subsystem are judiciously chosen. Here, the maximum time period for our 5th update interval was limited to 30 days, and even with that the computations indicated that for the GPS IIR Clock in an Ensemble system the median update interval had not yet been reached. Clearly, should one desire, the update interval in a next generation milsatcom system like Advanced EHF could be made extremely long, significantly reducing the timekeeping workload at a ground control station. While Fig. 5 corresponds to the Ensemble system, we believe that similar performance could be achieved with the Kalman-filter system given some care in the choice of the Kalman-filter algorithm's parameters.

SUMMARY

The principal conclusion to be drawn from our investigations is that modifications to spacecraft timekeeping hardware and/or the space-segment timekeeping subsystem have the potential to significantly improve the timekeeping performance of next generation milsatcom. A significant consequence of improved timekeeping is the reduction of the ground control station's workload, which not only impacts the ground segment during normal operation, but also during periods when the ground control station is either not present or overburdened. While improving hardware and the space-segment system independently provides two paths to a reduced ground station workload, it is clear that simultaneously pursuing improvements in both areas has the greatest potential for improved milsatcom timekeeping. Even in our simulations, in which optimization of the space-segment subsystem's algorithm was not considered, the combination of a high quality Rb clock and a sophisticated space-segment subsystem yielded a 700% increase in the median time between ground station updates of the constellation.

Though the Kalman and Ensemble systems may be viewed as "sophisticated" compared to the Master/Slave system, it must be noted that their use could lead to simplifications of ground operations. In particular, in the case of the Ensemble and Kalman-filter subsystems, the ground station "steers" the entire constellation when it steers the in-view satellite clock. Moreover, *any* in-view satellite provides full constellation timekeeping for the ground segment. There is no need for the ground segment to assemble and individually process the timing information of three satellite clocks as in the Master/Slave system. Of course, a complication associated with the Kalman and Ensemble systems is their need for time-difference information among constellation clocks (i.e., all contributing members to the aggregate timescale). However, when the constellation is relatively small (i.e., four to eight satellites) the communications demands placed on the various crosslinks is likely minimal.

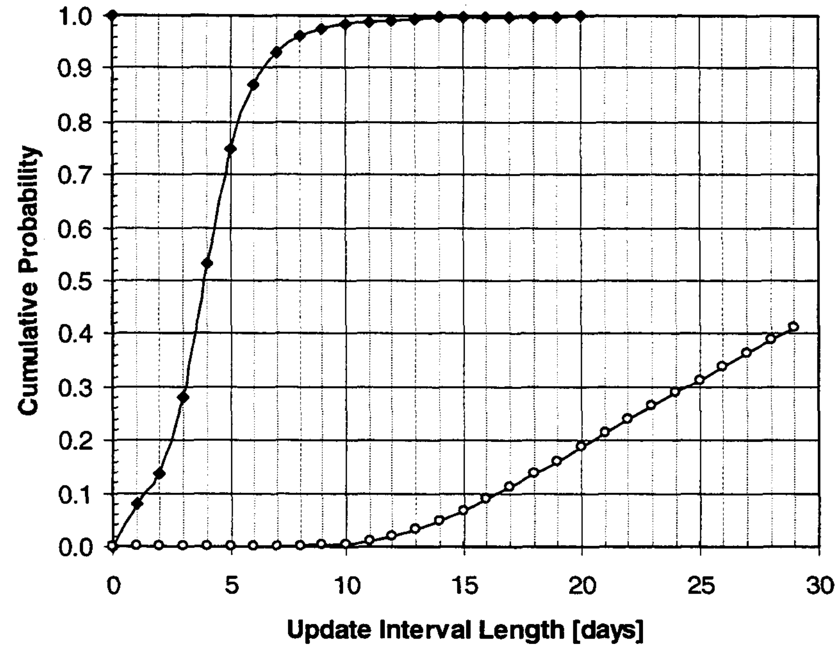

Figure 5: Cumulative probability for an update less than "X" number of days, illustrating improvement in system timekeeping when both hardware and the space-segment subsystem are chosen judiciously. In the figure, diamonds correspond to a FLT-2 Rb clock with minimal time-transfer noise and analog frequency control operating in a Master/Slave system; circles correspond to a GPS IIR Rb clock with minimal time-transfer noise and digital frequency control operating in an Ensemble system.

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