Rubidium clock lamplight variations and long-term frequency instability: First analyses of multiyear GPS data

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Rubidium Clock Lamplight Variations and Long-Term Frequency Instability: *First Analyses of Multiyear GPS Data*

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ABSTRACT

In the rubidium atomic frequency standard (RAFS), an rf-discharge lamp produces the device's atomic signal. As a consequence of the light-shift effect, variations in the lamplight's intensity result in variations in the RAFS' output frequency. While the basic physics of the light-shift is reasonably well understood, its operational implications for global navigation satellite system (GNSS) performance is only beginning to be fully appreciated. Here, we describe first results examining decade-long histories of on-orbit GPS RAFS lamplight variations and GPS RAFS frequency variations. Our preliminary analyses have focused on one space vehicle's RAFS, and our conclusions are tempered by that present limitation. Nevertheless, our

analyses suggest that a RAFS' long-term frequency stability (*i.e.*, $\tau \sim 10^6$ sec) is likely lower-bounded by the lamp's intensity fluctuations. Moreover, considering the light-shift coefficient for this one particular RAFS over 12 years, we find that the data do not support Camparo's hypothesis regarding RAFS frequency aging and a time-varying light-shift coefficient.

INTRODUCTION

Overview of the Rubidium Clock

The rubidium (Rb) atomic frequency standard (RAFS) is the workhorse of precise atomic timekeeping in space due to its low weight, small volume, and low power consumption [1]. Moreover, the device has excellent frequency stability out to (and beyond) 10^4 seconds averaging time, rivaling the performance of passive hydrogen masers [2,3]. As illustrated in Fig. 1, the physics package of the prototypical Rb clock is composed of a lamp, a filter cell, a resonance cell, and a photodetector, with the resonance cell inside a microwave cavity that is tuned to the ^{87}Rb atom's hyperfine-resonance frequency of 6834.7 MHz. The lamplight passes through the filter cell, and in so doing has its optical spectrum "shaped" so that it can efficiently produce an atomic signal via the process known as optical pumping [4,5]. As a consequence of optical pumping, the steady-state population of atoms in the absorbing hyperfine level (*i.e.*, F=1) is reduced, and so the Rb vapor in the resonance cell becomes (to some degree) transparent to the lamplight. With the Rb vapor absorbing little lamplight, more light passes through to the photodiode which registers a high signal.

If microwaves are applied to the vapor at the hyperfine-resonance frequency, atoms are forced by the microwave signal to return to the absorbing hyperfine state. Consequently, more lamplight gets absorbed by the vapor, and less passes through to the photodiode. The change in transmitted light corresponds to the amplitude of the atomic clock signal, and can be used in a feedback loop to lock the source of the microwave signal (*e.g.*, a voltage-controlled crystal oscillator, VCXO, at 10 MHz) to the atomic hyperfine-resonance frequency. In this way, the stability of atomic structure is transferred to the VCXO, creating an atomic frequency standard or atomic clock.

Clearly, the RAFS' lamplight is crucial to the device's operation: the lamplight not only generates the atomic signal via optical pumping, it monitors the atoms' absorption of the microwaves. Unfortunately, the lamplight can also alter the energy structure of the Rb atoms through a process known as the "light shift," and as a consequence of this phenomenon variations in the lamplight intensity get transformed to variations in the RAFS' output frequency. In this report we present first results examining the relationship between lamplight variations and long-term RAFS frequency variations for the RAFS flying on GPS Block–IIR satellites.

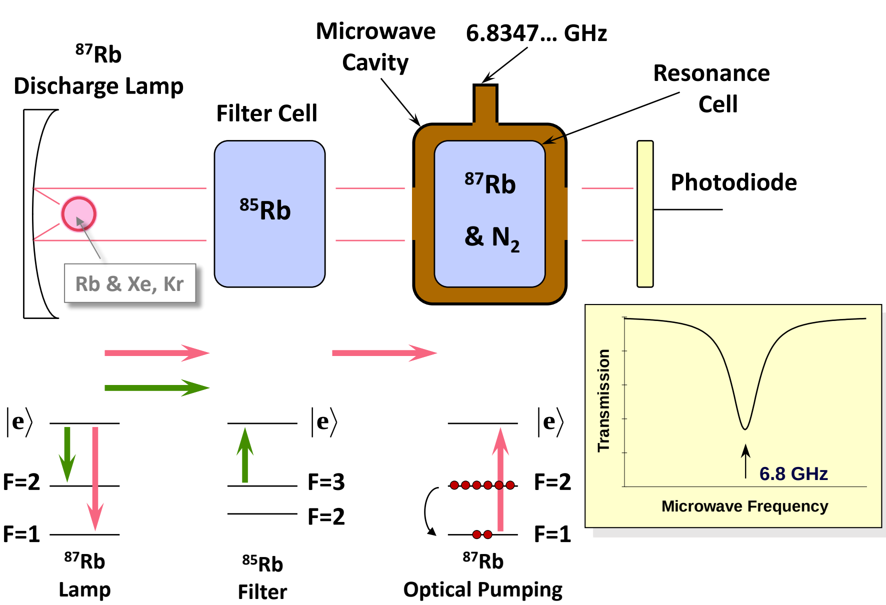

Figure 1: Block diagram of the prototypical RAFS. The ^{87}Rb rf-discharge lamp emits spectral lines that originate in a rubidium excited state and terminate on one of the two ground-state hyperfine levels of the atom (*i.e.*, F=2 and F=1 in the figure). Due to a coincidence of nature, one of these spectral lines is absorbed by the ^{85}Rb atoms in the resonance cell, allowing the other spectral line to pass through, where it can create a population imbalance between the ground-state hyperfine levels via optical pumping.

The Light Shift

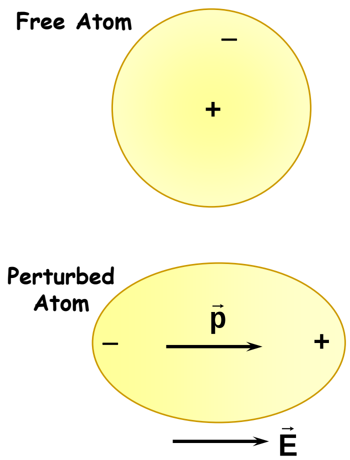

Figure 2: Illustration of an atom as a polarizable medium. In the presence of an electric field a dipole moment is induced in the atom, which can then interact with the electric field to produce a perturbation of the atom's energy level structure.

In a semiclassical formalism [6,7], the light shift arises as a second-order interaction between an atom's induced dipole moment and the light's perturbing electrical field. If we imagine the atom as a polarizable medium as illustrated in Fig. 2, with a (frequency dependent) polarizability $\alpha(\omega)$, then the perturbing electric field of the light, $\vec{E}(\omega)$, will induce a dipole moment $\vec{p}(\omega)$ in the atom:

$$\vec{p}(\omega) = \alpha(\omega)\vec{E}(\omega). \tag{1}$$

This dipole will interact with the electric field that produced it, so that to *second-order* in the electric field strength there is an interaction energy between the atom and the light, $\Delta\varepsilon$:

$$\Delta\varepsilon = -\tfrac{1}{2}\vec{p}(\omega)\cdot\vec{E}(\omega). \tag{2}$$

This interaction perturbs the atom's energy level structure, giving rise to a shift in the atom's ground-state hyperfine splitting, $h\nu_{hfs} = (E_{F=2} - E_{F=1})$:

$$\frac{\delta f}{f_o} = \frac{\Delta\varepsilon}{h\nu_{hfs}} = -\frac{\vec{p}(\omega)\cdot\vec{E}(\omega)}{2h\nu_{hfs}} = -\left(\frac{1}{2h\nu_{hfs}}\right)\alpha(\omega)\left|\vec{E}(\omega)\right|^2. \tag{3}$$

The light-shift as expressed by Eq. (3) is valid for a monochromatic light wave. However, as is well known the lamplight's spectrum after filtering can be fairly broadband and complex [8,9], and each spectral component of the lamplight will contribute to the overall light-shift, Δy_{LS}, via Eq. (3). Consequently, if we represent the normalized intensity spectrum of the lamplight (after filtering) in the frequency range ω to ω+dω, by S(ω)dω:

$$\int_0^\infty S(\omega)d\omega = 1, \tag{4}$$

and take I_o as the total Rb light reaching the ^{87}Rb atoms in the atomic-signal generating region of the clock's physics package, then

$$y_{LS} = \beta_{LS} I_o \sim I_o \int_0^\infty \alpha(\omega) S(\omega) d\omega_o, \tag{5}$$

where β_{LS} is the light-shift coefficient of the clock. Clearly, β_{LS} will depend on the emission spectrum of the rf-discharge lamp as well as the operation of the filter cell.

Equation (5) is valid for the clock's full light shift. However, we are typically not interested in the full light shift, but rather variations in the light shift about its average value: $\delta[y_{LS}]$, which for convenience we will write simply as δ_{LS}. Therefore, defining $\langle I_o\rangle$ as the average light intensity emitted by the lamp we have

$$\delta_{LS}(t) \equiv \delta[y_{LS}] = \beta_{LS}\left(I_o(t) - \langle I_o\rangle\right) = \beta_{LS}\langle I_o\rangle\frac{\Delta I(t)}{\langle I_o\rangle}, \tag{6a}$$

$$\delta_{LS} = \kappa_{LS}\frac{\Delta I(t)}{\langle I_o\rangle}. \tag{6b}$$

κ_{LS} is the parameter routinely reported in the literature for a clock's light-shift coefficient, typically in units of %$^{-1}$. However, as can readily be seen from Eqs. (6), clock-to-clock comparisons among κ_{LS} values should be treated with caution [10], since κ_{LS} depends on $\langle I_o\rangle$. The parameter of real comparative value is β_{LS}.

LAMP DISCONTINUTIES

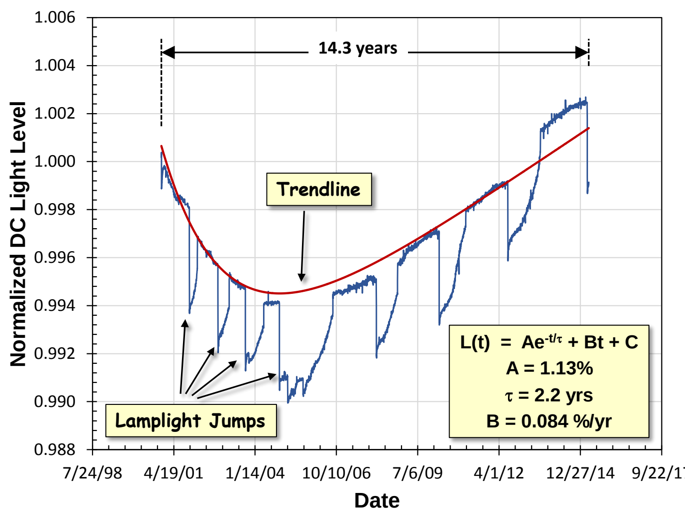

Figure 3: Example of long-term lamplight variations from one Block-IIR GPS RAFS. We model the deterministic change in lamplight, L(t), as $Ae^{-t/\tau} + Bt + C$.

Figure 3 shows long-term lamplight data from a Block-IIR GPS RAFS (SVN-41). In total, we have obtained similar data for 10 Block-IIR GPS satellite RAFS. The data span many years, in the case of Fig. 3 approximately 14.3 years, and it can be seen that the lamplight's trend line, L(t), is reasonably well approximated by an exponential sitting on a linear trend. Similar trend lines with similar magnitudes for the coefficients have been observed for the other RAFS in our sample, though the linear coefficient of the trend line, B, is typically negative.

Clearly, the most striking feature in the figure are the numerous jumps in light intensity corresponding to discontinuous light level changes of ~ 0.3%. For this particular RAFS, eight jumps occurred over the 14.3 years, yielding a (very rough) mean time between jumps of 1.8 years. All of the RAFS that we have examined over these long time intervals show lamplight jumps of one type or another, though the ones presented in Fig. 3 are the most striking.

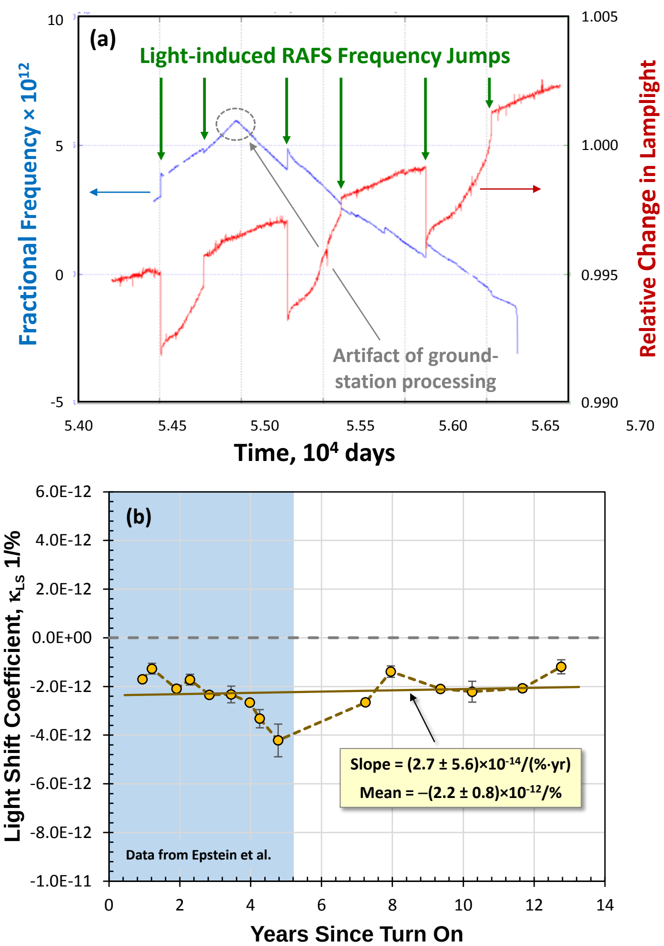

Figure 4: (a) Dual plot of the lamplight and fractional frequency for the RAFS on SVN-41; correlations between lamp jumps and frequency jumps are apparent. (b) Plot of the light-shift coefficient for the RAFS on SVN-41 as a function of time.

The lamplight jumps of Fig. 3 induced frequency jumps in the RAFS as a consequence of the light-shift effect. As illustrated in Fig. 4a, these frequency jumps were parts in 10^{13}, and as far as we are aware had no impact on GPS functioning. The correlation coefficient between lamplight jump and frequency jump is clearly the light-shift coefficient, κ_{LS}. Combining our data with that of Epstein *et al*. for SVN-41 [11] yields a 12-year history for this RAFS' light-shift coefficient, and as illustrated in Fig. 4b we find no evidence of a change in light-shift coefficient over this time period.

A MECHANISM OF RAFS FREQUENCY AGING

In 2005, Camparo hypothesized that changes in a RAFS' light-shift coefficient might be responsible for frequency aging [12]. Briefly, if we define the linear frequency aging rate of the RAFS as D: y(t) = Dt, then according to Camparo's hypothesis and Eq. (5) we should have

$$D = \frac{d}{dt}(\beta_{LS} I_o) = \dot{\kappa}_{LS}, \tag{7}$$

where we have taken $I_o(t)/\langle I_o \rangle \cong 1$ for all t. (Previous work cited in [12] indicates that changes in the lamplight intensity over time do not drive frequency aging.)

As noted by Camparo [12], $D_{SVN\text{-}41} = -3.75\times10^{-14}$/day, and from Eq. (7) this frequency aging rate would require $\dot{\kappa}_{LS} = -1.37\times10^{-13}/(\%\cdot yr)$. This, however is much larger than $\langle \dot{\kappa}_{LS} \rangle$ found in the data shown in Fig. 4b. More specifically, employing the standard error of the slope estimate given in Fig. 4b, the probability for this RAFS' frequency aging to be due to a temporal change of the light-shift coefficient is only 0.0017 (*i.e.*, the probability that $\dot{\kappa}_{LS} \le D_{SVN\text{-}41}$, remembering that $D_{SVN\text{-}41}$ is negative). Thus, the data from this one particular RAFS does <u>not</u> appear to support Camparo's hypothesis.

δ_{LS} AND THE RAFS ALLAN DEVIATION

As noted previously, the light shift is a fundamental atomic process; it is always operative converting light intensity changes into RAFS frequency changes. Consequently, *fluctuations* in lamplight (in addition and quite independent of jumps) must give rise, at some level, to fluctuations in the RAFS' frequency. As indicated in Fig. 4b, we have fairly good knowledge of the light-shift coefficient for the SVN-41 RAFS: $\langle \kappa_{LS}(\text{SVN-41}) \rangle = -2.2\times10^{-12}/\%$, and we have a very long continuous history of lamplight variations for this RAFS. Thus, we can generate an *inferred* history of RAFS frequency fluctuations. In essence, these are the frequency fluctuations that were produced by the lamplight in this RAFS, whether or not they were large enough to actually be observed and/or large enough to dominate other noise processes affecting the RAFS' frequency.

Figure 5a shows the time history of the SVN-41 RAFS' lamplight with the discrete lamp jumps labeled 'a' through 'n', while Fig. 5b shows the dynamic Allan deviation of the inferred frequency fluctuations with the lamp jumps similarly labeled [13]. Regarding Fig. 5b there are at least two intriguing observations:

1. The lamplight appears to act as a lower bound on the RAFS's frequency stability at long averaging times (*i.e.*, 20 days, or equivalently 10^6 sec), and this lower bound is something like 10^{-15}.
2. More interesting, perhaps, is the observation that the lamp noise appears to have increased noticeably in the weeks prior to a jump in the lamplight intensity.

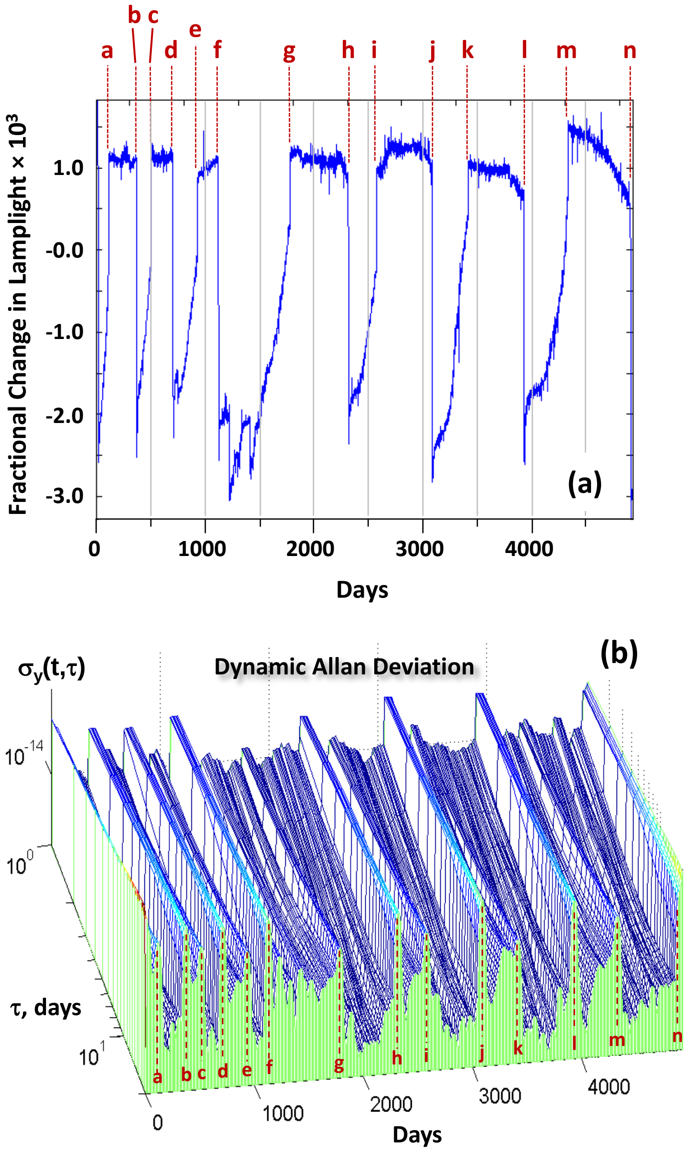

Figure 5: (a) Time history of the lamp's relative intensity variations with jumps labeled 'a' through 'n'. (b) Dynamic Allan deviation of the data from Fig. 5a after multiplying by the light-shift coefficient, turning the lamp's intensity variations into inferred RAFS frequency variations.

To help clarify these observations, Fig. 6 shows a blow-up of the dynamic Allan deviation between jumps 'g' and 'h'. Note that the minimum Allan deviation at τ = 20 days (just prior to t = day 2000) corresponds to 1×10^{-15}, and that this level of stability lasts for about a week or so. Consequently, our *intrinsic ability* to assess inferred frequency fluctuations from the on-orbit data could be smaller than 1×10^{-15}, but it cannot be materially larger. Saying this differently, our measurement "noise floor" at τ = 20 days is no larger than 1×10^{-15}.

The inferred Allan deviation at τ = 20 days from time t = day 2000 to t = day 2150 (*i.e.*, a period of five months) has a value clearly above the noise floor's upper bound. *Consequently, during this nearly half-year period the long-term stability of the RAFS had a lower bound that was set by the stability of the lamplight*. To our knowledge, this is the first time anyone has ever been able to ascribe a lower bound to a RAFS' long-term frequency stability, and simultaneously tie that lower bound to a clear physical mechanism.

Around day 2200 there is a relatively rapid increase in the RAFS inferred long-term frequency stability at τ = 20 days. From a level of about 2×10^{-15}, the Allan deviation transitions to a level of approximately 8×10^{-15}, and it maintains this level of stability for roughly a month before suffering the jump labeled 'h'. Though the present analysis is qualitative and correlational, it is suggestive of a stochastic resonance phenomenon [14].

One can imagine the lamp having two "stable modes" of operation [15], with a barrier of sorts separating these two regions of quasi-stability. As noise in the lamp increases, the probability of surmounting this barrier increases, so that at some point during the lamp's stochastic intensity fluctuations the barrier is crossed and the lamp jumps to a different average intensity level. Clearly, this thinking is extremely speculative and qualitative, and before any real effort is expended exploring the viability of the model further lamp data will need to be examined.

SUMMARY

The Aerospace Corporation and INRiM are collaborating to examine GNSS RAFS data, so as to better understand the long-term timekeeping behavior of these important space clocks. To date, we have collected multiyear RAFS lamplight data from 10 GPS-IIR satellites, and additionally we have collected (and are in the process of collecting) multiyear frequency data for these same satellites. Our initial work is aimed at understanding the role of the lamp in the RAFS' long-term timekeeping capabilities.

Our first, very preliminary, results have proven to be very enlightening and intriguing, and suggest that this research project holds considerable promise. We have been able to create a long time history of the light-shift coefficient for the SVN-41 RAFS, κ_{LS}, and over 12 years we find no evidence for a temporal variation in κ_{LS}. While more analysis is clearly required, this result would suggest that Camparo's hypothesis regarding a potential mechanism of RAFS frequency aging is untenable. Moreover, using κ_{LS} to create a series of inferred RAFS frequency fluctuations we were able to show that (at least for the RAFS onboard

SVN-41) the RAFS' long-term stability ($\tau \sim 10^6$ sec) has a lower bound that is determined by the lamplight fluctuations. Additionally, we have discovered suggestive evidence for increases in lamp noise preceding (by weeks) discrete jumps in the lamp's average light level. If this potential relationship between lamp noise and lamp jumps is confirmed by other RAFS data, it will not only be indicative of the mechanism causing lamp jumps, it might also be useful as a warning flag for GNSS operators of a potential on-orbit clock discontinuity. Clearly, there is much to be discovered in the long-term timekeeping and telemetry information from GNSS on-orbit clocks.

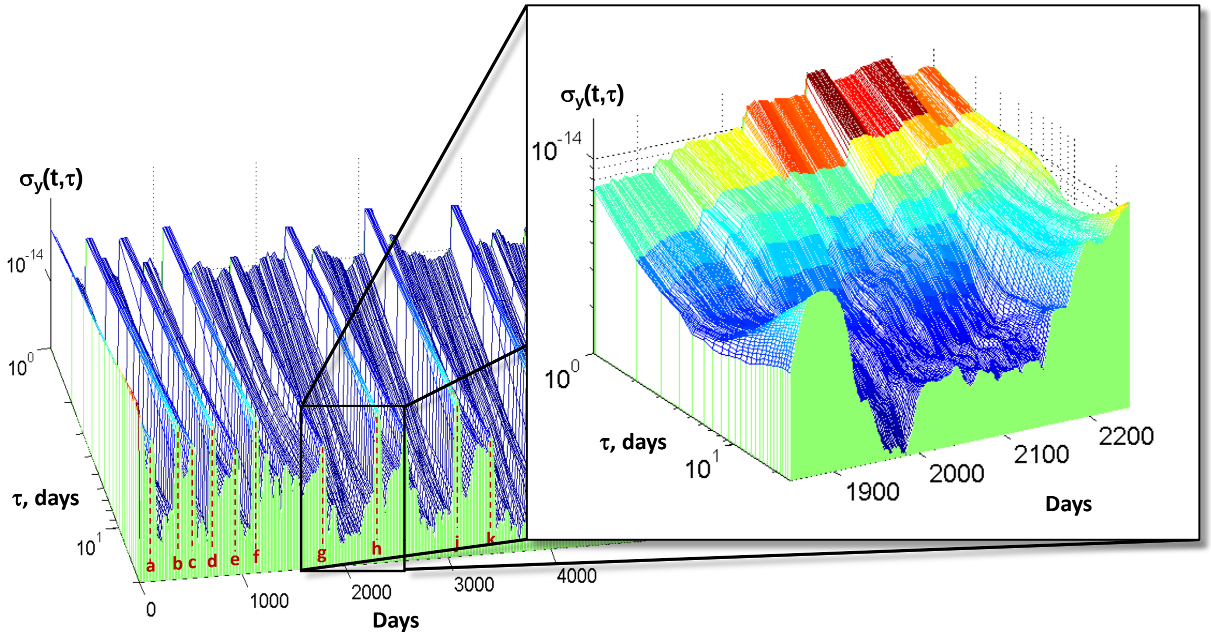

Figure 6: The dynamic Allan deviation for a portion of the full data set of inferred RAFS frequency variations: between lamp jumps 'g' and 'h'.

ACKNOWLEDGMENTS

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