

INFLUENCE OF THE ATMOSPHERE ON A RUBIDIUM CLOCK'S FREQUENCY AGING

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Abstract

A number of mechanisms have been proposed to explain the phenomenon of frequency aging in the rubidium atomic clock. Helium permeation is one such mechanism. Briefly, the four millitorr of helium in the Earth's atmosphere can permeate into the resonance cell, changing the clock frequency via the pressure shift of the 0-0 hyperfine transition. On orbit, any He in the resonance cell would permeate out, again changing the buffer gas pressure in the resonance cell. Unfortunately, studies examining this hypothesis have not been particularly clear cut. Here, we report on a multi-year study comparing the frequency aging rates of three Rb clocks in vacuum and in air. Our findings indicate that the atmosphere does play a role in frequency aging, at least for one family of Rb clocks, and adds evidence to the helium permeation hypothesis. However, when combined with on-orbit data, it appears that frequency aging in vapor-cell clocks is likely driven by more than one mechanism.

INTRODUCTION

As illustrated in Fig. 1, all rubidium (Rb) atomic clocks appear to show two different long-term frequency variation behaviors: frequency equilibration [1] and frequency aging [2]. Frequency equilibration corresponds to what seems to be an exponential transient with a time constant on the order of hundreds of days, while frequency aging corresponds to a long-term linear frequency variation with time. The rate of frequency aging is on the order of $10^{-14}/\text{day}$ to $10^{-13}/\text{day}$ and can have either a positive or negative sign [1]. For both frequency equilibration and frequency aging, the mechanism(s) driving the process is unknown, and it is unclear if the two processes are driven by the same or different mechanisms.

Though frequency equilibration and frequency aging are both important for timekeeping, frequency aging will often have the greater significance, since one never has the option of simply waiting for it to disappear after "steady-state" has been achieved. Unfortunately, as is readily appreciated from Fig. 1, it can be difficult to distinguish between these two processes, and thereby attend to the mechanism(s) that solely affects frequency aging. It seems the only way to disentangle frequency equilibration and frequency aging without *a-priori* assumptions is to examine a vapor-cell clock's frequency over multiple years.

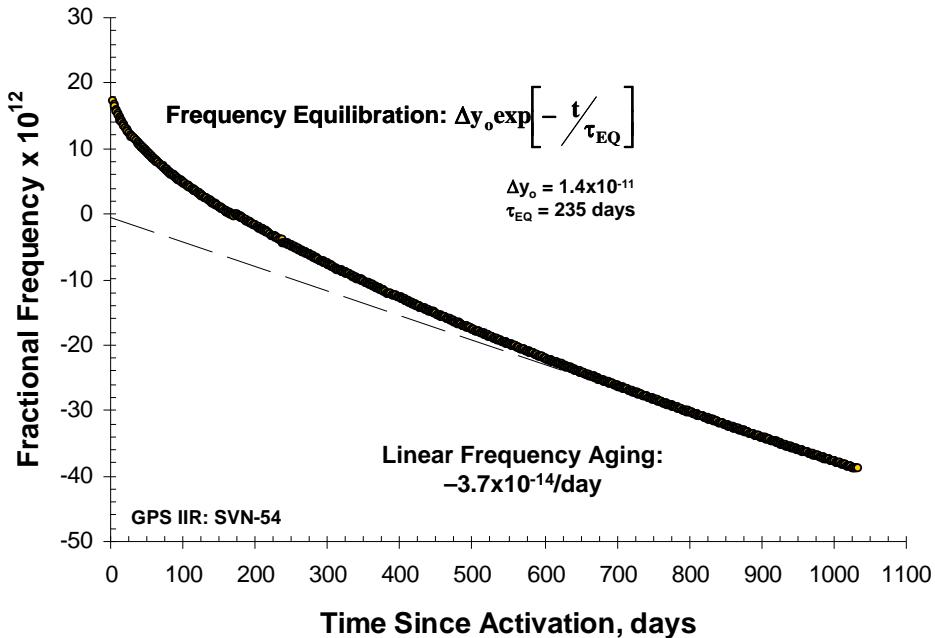


Figure 1. Deterministic frequency variations of a GPS Rb clock showing both frequency equilibration and linear frequency aging.

SOME POSSIBLE MECHANISMS OF FREQUENCY AGING

Though the mechanism(s) of frequency aging is unknown, there are a number of hypothesized mechanisms that continue to be suggested by various researchers in the timekeeping community. These include the intensity-dependent light shift, the spectrum-dependent light shift, the position shift, and helium permeation.

In the case of the intensity-dependent light shift mechanism, it is known that light intensity transmitted through the resonance cell changes slowly over time. Assuming that this change is due to the lamp (or filter-cell), and not the amount of light absorbed by the atoms in the resonance cell (i.e., a Rb density change), this could affect the clock frequency via the light shift mechanism. This hypothesized mechanism was recently tested for the Block IIR GPS Rb clocks, and the evidence indicated that for that family of Rb clocks frequency aging was *not* due to the intensity-dependent light shift [3]. However, that same analysis suggested that frequency aging might be caused by the spectrum-dependent light shift. The light shift of the clock's frequency depends on the lamp intensity and the details of its spectral emission. Slow changes in the lamp temperature, the lamp rf power, or the filter cell temperature could alter the lamplight's spectral profile in the resonance cell, giving rise to a slow change in clock frequency.

With regard to the position shift mechanism, it is well known that the clock signal is not generated uniformly in the resonance cell [4], and further that the light intensity and magnetic field strength vary across the resonance cell volume. If the microwave field strength in the cavity changes, the "special clock-signal-generating region" in the resonance cell will move and experience a slightly different light intensity and magnetic field strength. As a result, the clock frequency will change, and this is known as the position shift [5]. Additionally, if the cavity resonance is not tuned to the atomic hyperfine transition, then the microwave power will change as the field tunes across resonance. This gives rise to an

asymmetry in the clock lineshape, which will shift the clock frequency; this is referred to as the cavity-pulling shift in passive standards [6]. Data suggest that alkali film migration on the resonance cell's glass surface can change the microwave cavity Q, thereby giving rise to a slow change in clock frequency via the position shift and/or cavity-pulling shift [7].

Finally, it is known that glass resonance cells are (to varying degrees) permeable to the four millitorr of helium that exists in the Earth's atmosphere [1]. As the helium permeates into the resonance cell, the increased helium density alters the clock frequency; on orbit, any atmospheric helium that has permeated into the resonance cell will permeate out, again leading to a change in clock frequency [8]. Though researchers have shown that clocks operating in a high-pressure helium environment suffer a frequency shift, it remains unclear as to the extent to which atmospheric helium truly affects frequency aging. In the present work, we present what we believe is strong evidence that atmospheric helium does indeed play a role in frequency aging for at least one family of Rb clocks.

EXPERIMENT AND RESULTS

Our experiment is straightforward. For 2 years, we housed three COTS Rb clocks in a vacuum chamber that was kept at a pressure of one millitorr. While in vacuum, the clocks were not powered; they were simply stored in vacuum. Roughly once a month, we removed the clocks from the chamber, warmed them up for about 24 hours, and then measured their frequency relative to a cesium atomic clock. After 2 years of monitoring the clocks' frequency in this fashion, we removed the clocks from the vacuum chamber, but again kept them off; we stored them in air. Similar to the vacuum procedure, roughly once a month, we warmed the clocks up for 24 hours and then measured their frequency relative to a cesium atomic clock.

Figure 2 shows the basic results of our investigations over approximately 3½ years. In vacuum, all three rubidium clocks showed a negative frequency aging with time. Moreover, within the experimental uncertainty, all three clocks showed the same magnitude of frequency aging. Note that this frequency aging was without the clocks being powered for any appreciable period of time, so it is difficult to ascribe the frequency changes to any aging process that would be associated with long-term use (e.g., rubidium migration to a slowly evolving cold spot in the lamp, filter cell, or resonance cell). Once the clocks were returned to air, the frequency aging changed and now appears to be reversing sign. Taken as a whole, Fig. 2 argues that the atmosphere plays a role in frequency aging. In particular, it provides evidence for the helium permeation mechanism. Helium has a positive pressure shift coefficient [9], implying that increasing helium pressure within the resonance cell will increase the clock frequency. Prior to the start of these studies, the three COTS clocks were stored and operated in air for a number of years, so that atmospheric helium would have permeated into the clocks' resonance cells during this time. In vacuum, this helium would then permeate out of the resonance cell, giving rise to a negative frequency aging rate. After 2 years of helium permeating out of the resonance cell, returning the clocks to air would allow helium to again permeate into the resonance cell, thereby producing a positive frequency aging with time. Since we should expect helium permeation to give rise to an exponential change in clock frequency [1], the linear change in clock frequency we actually observe suggests that the time constant for helium permeation is much greater than 1000 days.

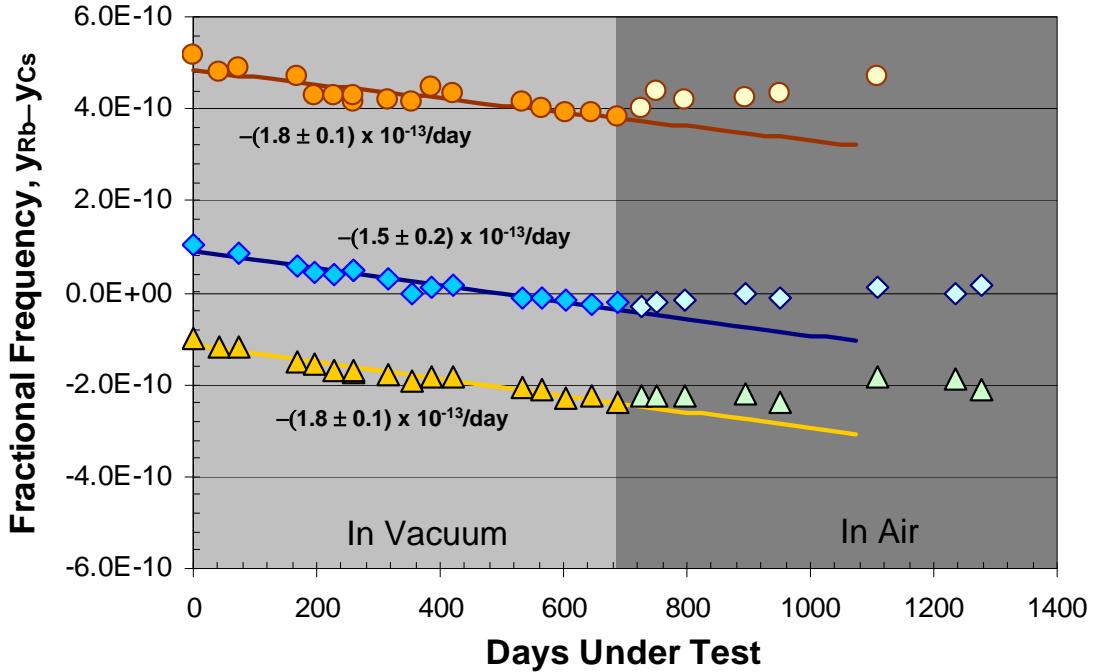


Figure 2. Frequency history of three COTS Rb clocks. For a portion of the test, these clocks were stored (unpowered) in vacuum. They were then removed from the vacuum chamber and stored in air. Roughly once a month, the clocks were turned on and, after warming up for 24 hours, their frequency was measured relative to a Cs clock.

DISCUSSION

Though the present work argues that helium permeation plays a role in frequency aging, it cannot be the sole cause of frequency aging in vapor-cell atomic clocks. Figure 3 shows on-orbit (i.e., vacuum) frequency aging rates for Milstar rubidium (Rb) clocks, GPS Block IIR Rb clocks, and GPS Block IIA Rb clocks. These clocks were produced by different manufacturers and correspond to different physics package designs: the Milstar and GPS Block IIR Rb clocks correspond to separated filter-cell designs, while the GPS Block IIA clocks correspond to an integrated filter-cell design [10]. (The COTS clocks used in the present study were separated filter-cell design.) Clearly, frequency aging rates can be either positive or negative. However, in space the helium permeation mechanism can only give rise to a *negative* frequency aging rate. Thus, the data in this figure taken with our results suggest that at least two different mechanisms must be responsible for frequency aging in vapor-cell clocks.

ACKNOWLEDGMENT

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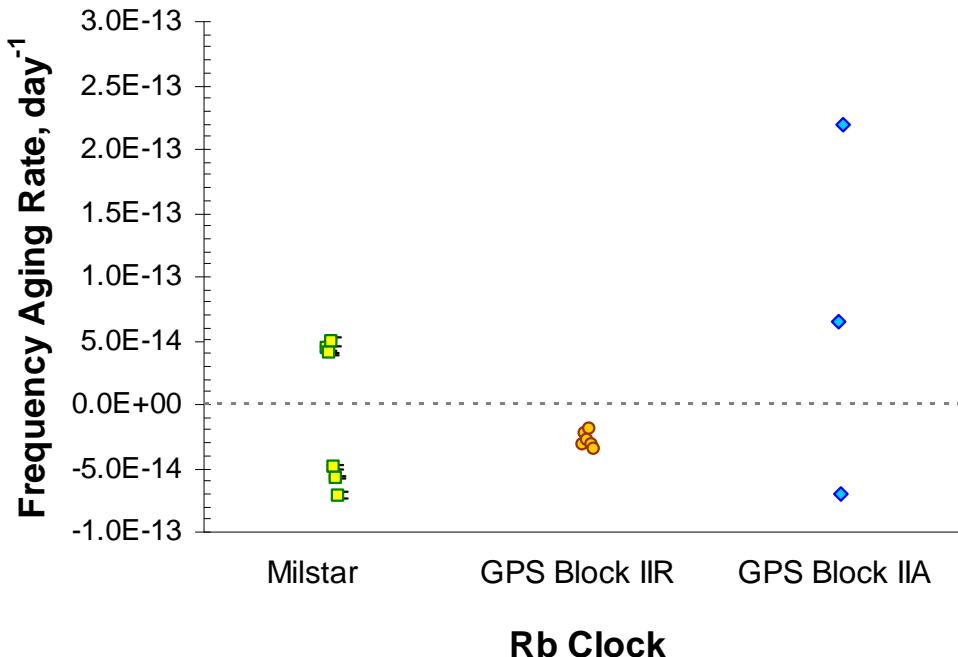


Figure 3. Frequency aging rates for Milstar, GPS Block IIR, and GPS Block IIA Rb clocks. In order to extract these frequency aging rates, the on-orbit data were non-linearly least-squares fit to the sum of an exponential equilibration term plus a linear frequency aging term. Thus, in complete fairness, we must note that some of our frequency aging estimates could have been influenced by the frequency equilibration term in the fit. We will be examining these data further in order to better untangle the two processes.

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