

INVESTIGATIONS INTO THE RB CLOCK'S 2ND HARMONIC SIGNAL: A STATUS REPORT

Gilda Fathi and James Camparo
Physical Sciences Laboratories
The Aerospace Corporation
2350 E. El Segundo Blvd., El Segundo, CA 90245, USA
E-mail: *Gilda.Fathi@aero.org*

Abstract

As commercial and military systems become ever more dependent on GNSS, it becomes vitally important to ensure the health of the system's spacecraft atomic clocks. Though a number of methodologies for monitoring clock integrity are now under study/discussion, all have particular strengths and weaknesses; no one methodology achieves the ideal. More than likely, future GNSS will ensure clock integrity through a hybrid of techniques, and one component of that hybrid will certainly focus on the clock's status-of-health monitors: rf-signal level, lock-monitor voltage (and for Rb clocks) cell temperature, lamp monitor voltage, and 2nd harmonic signal level. In the present work, we detail our preliminary investigations into the parameters that affect the 2nd harmonic signal.

INTRODUCTION

The rubidium (Rb) atomic clock has the potential for a number of status-of-health indicators. These include (but are not limited to) the rf-signal level, the resonance and filter cell temperatures, the lamp monitor voltage, and the 2nd harmonic signal level. In all cases except the 2nd harmonic signal, the interpretation of healthy and unhealthy is straightforward. For example, a cell temperature change of many degrees is a strong indication of a problem. Unfortunately, the situation is not always so clear with regard to the 2nd harmonic signal level, though it is a direct measure of the error signal's quality. To address this issue, we have begun a series of researches into the Rb clock's 2nd harmonic signal and how it depends on optical pumping rate, microwave power, resonance cell temperature, modulation parameters, etc. This is a non-trivial problem, since a clock's atomic dynamics occur at the onset of saturation for the 0-0 hyperfine transition [1], and the microwave frequency modulation rate is neither slow enough to be considered adiabatic nor fast enough to justify the term "sudden" [2].

Here, we describe our experimental approach to the problem, and the characterization of our "clock" signal. Specifically, in place of an rf-discharge lamp, we employ a VCSEL diode laser whose polarization is oriented relative to a fixed magnetic field so as to mimic the unpolarized light from a Rb discharge lamp. The advantage of the VCSEL is that we can tune the optical wavelength, and thereby consider filter-cell effects on the 2nd harmonic.

PHYSICAL BASIS OF THE 2ND HARMONIC SIGNAL

In the Rb clock, the atomic signal is generated by modulating the frequency of a microwave field (at modulation frequency f_m), which resonantly excites a vapor of rubidium atoms [3]. The atom's response to the modulated microwave signal is detected synchronously, producing a correction signal having a dispersion-like shape. This correction signal is the heart of the clock, producing a voltage that ties the output frequency of a crystal oscillator to the atomic resonance. Due to the nonlinear interaction between the atoms and the microwaves, the atoms also produce a modulated signal at $2f_m$, the 2nd harmonic signal. The 2nd harmonic is a measure of the correction signal's quality, and consequently is a good status-of-health indicator for the clock. Unfortunately, the 2nd harmonic signal's sensitivity to various atomic clock parameters is not well known, so that if a change in the 2nd harmonic is detected, it is often unclear as to what this may mean beyond a gross notion of health-status change.

Figure 1 shows the several basic atomic signals of interest. On the left, we show the change in lamplight transmitted by the vapor of Rb atoms as the microwave signal is scanned across the 0-0 hyperfine resonance (i.e., 6834.7 MHz). In the middle is the correction signal, which provides the signal that locks the output of a voltage-controlled-crystal oscillator (VCXO) to the atoms' ground state hyperfine transition. On the far right, we show the 2nd harmonic. This signal has an extremum when the microwaves are tuned to the atomic resonance, and the strength of this extremum should be a measure of the 1st harmonic signal's slope on resonance. Since the slope of the 1st harmonic signal is a measure of the correction signal's ability to discriminate against small frequency variations of the microwaves, the 2nd harmonic signal is a measure of the correction signal's quality.

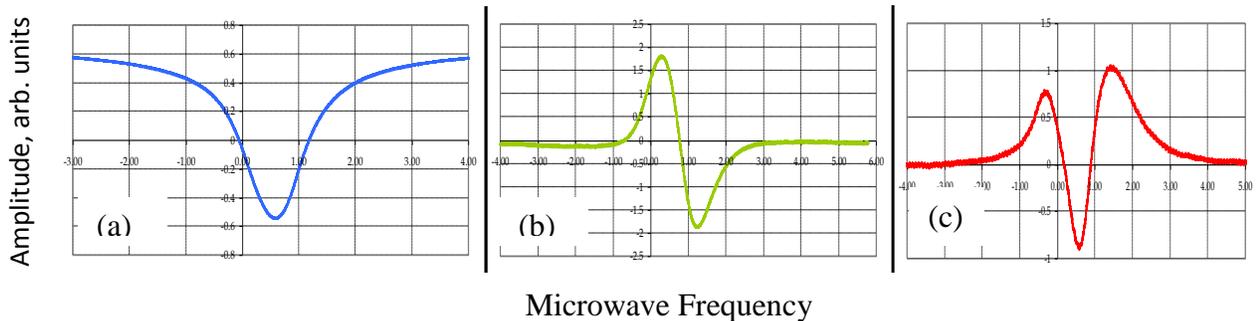


Figure 1. (a) Rubidium absorption signal, (b) first harmonic signal, (c) 2nd harmonic signal. We believe that the asymmetry in the 2nd harmonic signal is due to inhomogeneous broadening, and this is under investigation.

EXPERIMENTAL SETUP

Our experimental arrangement is illustrated in Fig. 2. Though a Rb atomic clock employs an rf-discharge lamp to generate its atomic clock signal [4], our experimental arrangement employs a VCSEL diode laser (i.e., vertical-cavity surface-emitting laser). Use of the diode laser gives us greater flexibility to study the 2nd harmonic signal, since we can easily adjust the output wavelength of the laser and investigate potential effects of wavelength drift in the lamplight. The laser optically pumps a vapor of Rb atoms contained in a glass cell with a buffer gas of 10 torr N_2 . Resonant microwaves impinge on the vapor via a 15 dB gain horn, and we modulate the microwave frequency at ~ 53 Hz. Using a lock-in amplifier, we phase-sensitively detect the atoms' 2nd harmonic response to the microwave modulation, both the inphase (I) and quadrature (Q) response, and record the lock-in's output on an averaging oscilloscope.

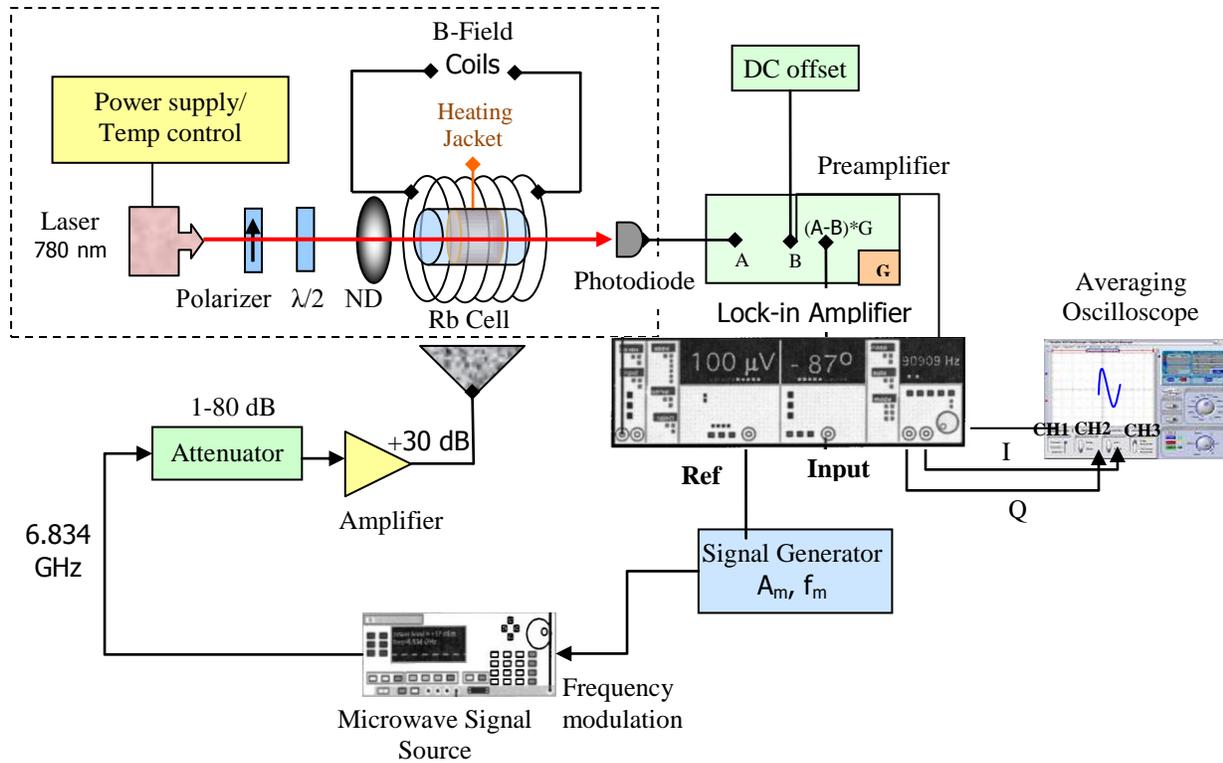


Figure 2. Experimental arrangement.

A unique aspect of our experimental setup concerns the orientation of the laser polarization relative to the atom's quantization axis. Briefly, considering Fig. 3, if the atom's quantization axis (as defined by an externally imposed magnetic field) is oriented parallel to the laser's propagation direction (i.e., z-axis), then the linearly polarized light will induce $\Delta m_F = \pm 1$ transitions in the atom. The same is true if the atom's quantization axis is oriented perpendicular to both the laser's propagation and polarization directions (i.e., the y-axis). If, however, the atom's quantization axis is oriented parallel to the laser's polarization direction (i.e., the x-axis), then only $\Delta m_F = 0$ transitions will be excited. Thus, by placing the atom's quantization axis in the x-y plane, and orienting the laser polarization at a critical angle relative to the magnetic field (i.e., 54.75°), $\Delta m_F = \pm 1$, and $\Delta m_F = 0$ transitions can be excited with equal probability, thereby allowing the laser to mimic atomic excitation by unpolarized lamplight.

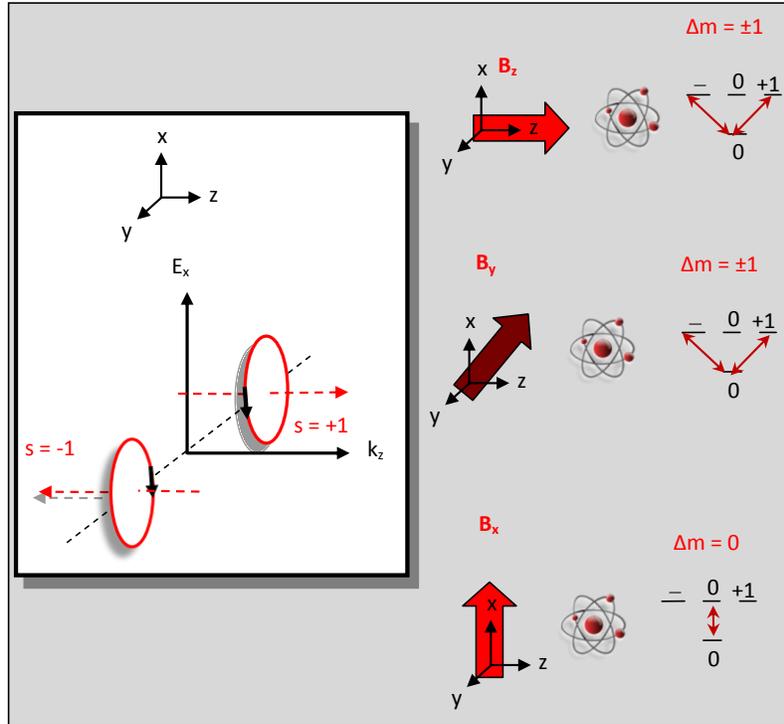


Figure 3. Atomic transitions' dependence on magnetic field orientation.

EXPERIMENTAL CLOCK SIGNAL

Figure 4 shows an example of our nominal clock signal, which has a linewidth (FWHM) of 487 Hz, and corresponds to a fractional change in transmitted light intensity of 2.1%; both of these values are consistent with standard rubidium atomic clock parameters. We do note, however, that our clock signal is somewhat larger than that of a lamp-pumped rubidium clock [5], due to the more efficient laser optical pumping. As shown in the two plots below our clock signal, we have characterized our nominal clock signal parameters by measuring the signal's amplitude and linewidth as a function of microwave power. Through these measurements we have determined that our nominal microwave Rabi frequency is 155 Hz, and that our inherent clock signal linewidth is 199 Hz.

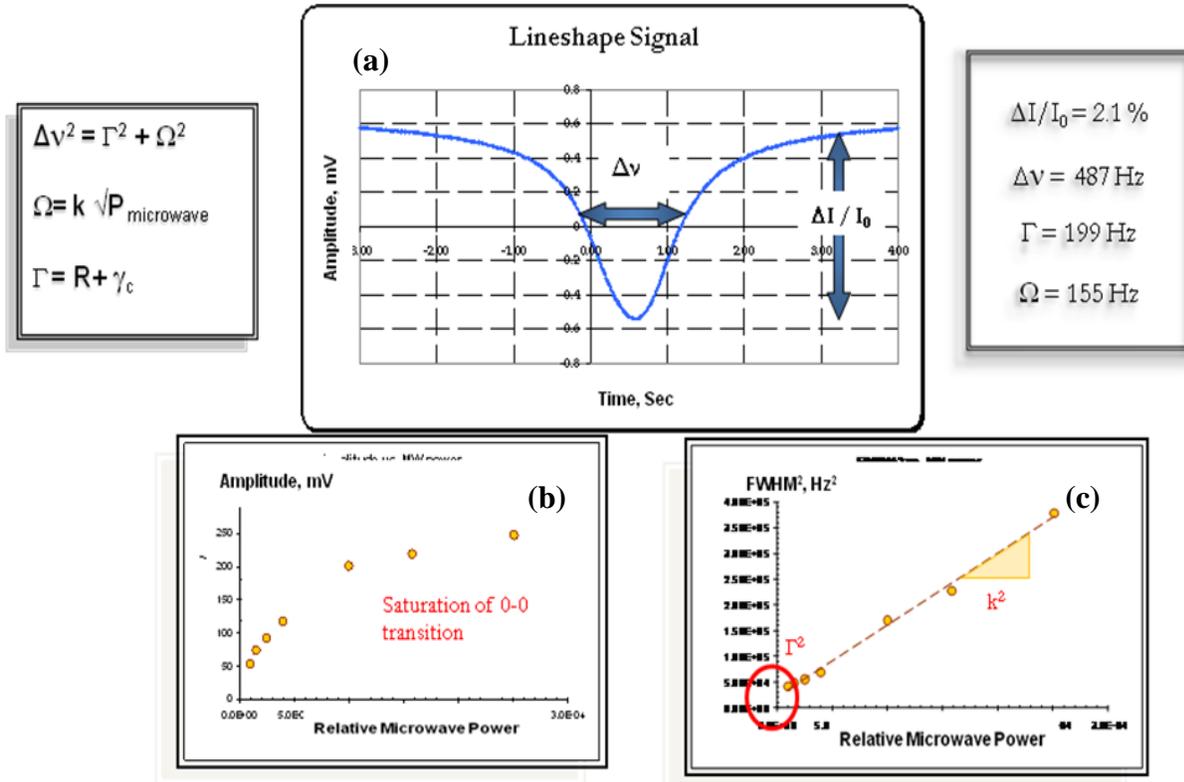


Figure 4. (a) Shows the Rb absorption lineshape. (b) shows our lineshape amplitude as a function of relative microwave; the nonlinearity demonstrates that our experimental arrangement can saturate the 0-0 hyperfine transition. (c) Shows the FWHM vs. relative microwave power; the intercept corresponds to the “intrinsic” linewidth of the clock transition (i.e., 199 Hz), and the slope calibrates the system’s Rabi frequency (Ω) in terms of microwave power.

One of our first investigations will be to carefully examine the 2nd harmonic signal as a function of the system’s *adiabaticity parameter*. In quantum mechanics, time-varying perturbations are often classified as either “sudden” or adiabatic [2]. As their name suggests, sudden perturbations occur on short time scales, and their hallmark is that they cause transitions between atomic states. Alternatively, adiabatic transitions are relatively slow, and they do not lead to state changes in the atom. Considering the Rabi frequency, Ω , the frequency modulation amplitude, $\delta\nu$, and frequency modulation rate, f_m , it is possible to derive a nondimensional adiabaticity parameter [6,7], η :

$$\eta = \Omega^2 / (f_m \delta\nu) \quad (1)$$

To the extent that $\eta \gg 1$, the modulation is adiabatic, and the atom easily follows the frequency oscillations of the modulated microwave field. Conversely, when $\eta \ll 1$, the modulation is non-adiabatic (i.e. sudden). In the sudden case, the atom cannot respond to the field, so that in some sense it is as if the modulated field was not present. (The “state changing” nature that we associate with sudden perturbations in the modulation case comes from changes between what are termed dressed energy levels [7].) In preliminary experiments, we have examined the 2nd harmonic signal as a function of the adiabaticity parameter η ; this is shown in Fig. 5. The first thing to note is that the functional relationship between the 2nd harmonic amplitude and η appears to have a universal shape. Additionally, the 2nd harmonic signal appears to have its maximum value well in the adiabatic regime.

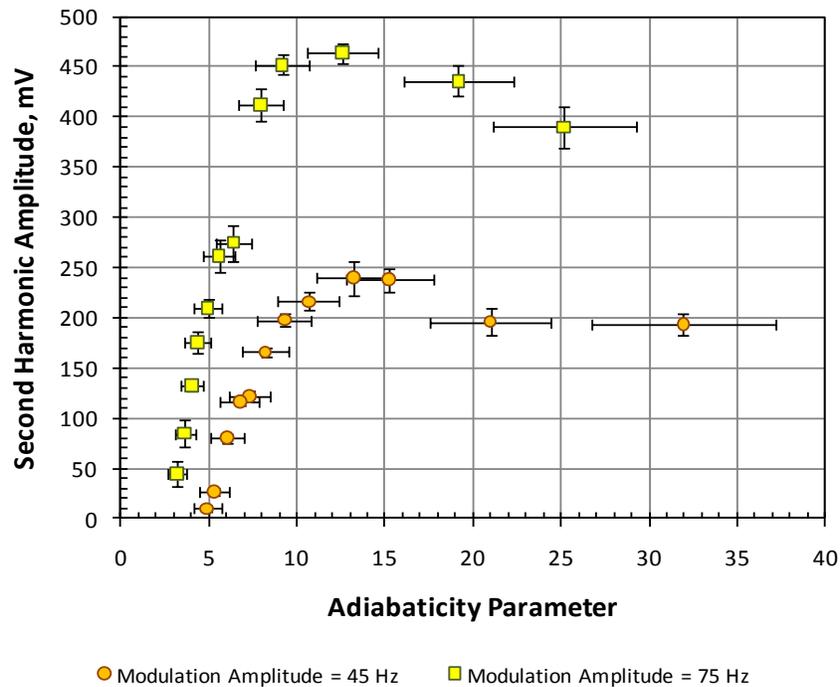


Figure 5. Variation of the 2nd harmonic amplitude as a function of the adiabaticity parameter, η .

CONCLUSION

The 2nd harmonic signal in Rb atomic clocks can be used as a status-of-health indicator, since it generally provides a measure of the correction signal's slope on resonance. However, at the present time the atomic dynamics of the 2nd harmonic signal's generation are not well understood. We have begun a series of studies to better understand the 2nd harmonic signal and its dependence on diverse clock parameters. In the present work, we have discussed our experimental approach and some very preliminary results regarding the 2nd harmonic signal's dependence on the adiabaticity parameter. These studies are continuing.

REFERENCES

- [1] J. C. Camparo and R. P. Frueholz, 1989, "A three-dimensional model of the gas cell atomic frequency standard," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **36**, 185-190.
- [2] D. Bohm, 1951, *Quantum Theory* (Prentice Hall, Englewood Cliffs, New Jersey).
- [3] J. C. Camparo, 2007, "The rubidium atomic clock and basic research," *Physics Today*, **60**, No. 11, 33-39.

- [4] J. C. Camparo and R. Mackay, 2007, “*Spectral mode changes in an alkali rf discharge,*” **Journal of Applied Physics**, **101**, 053303.
- [5] J. C. Camparo and R. P. Frueholz, 1986, “*A nonempirical model of the gas-cell atomic frequency standard,*” **Journal of Applied Physics**, **59**, 301-312.
- [6] J. C. Camparo and R. P. Frueholz, 1984, “*Parameters of adiabatic rapid passage in the 0-0 hyperfine transition of ⁸⁷Rb,*” **Physical Review, A**, **30**, 803-811.
- [7] J. C. Camparo and R. P. Frueholz, 1984, “*A dressed atom interpretation of adiabatic rapid passage,*” **Journal of Physics B: Atmospheric Molecular Physics**, **17**, 4169-4178.

