PROBING MAGNETIC FIELD EFFECTS IN 12-POLE LINEAR ION TRAP FREQUENCY STANDARDS

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Abstract – **The second-order Zeeman shift in a 12-pole buffer-gas-cooled linear ion trap frequency standard is characterized. Results for magnetic shielding effectiveness and long term stability against magnetic field perturbations are presented. The clock frequency is found to be stable against typical ambient magnetic field fluctuations to less than 2×10^{-16}. The frequency shift as a function of ion number is also studied and a plausibility argument is given relating this to magnetic field inhomogeneity.**
Keywords – **Linear ion trap frequency standard, 12-pole ion trap, Zeeman shift**

Introduction

Lamp-based mercury linear ion trap frequency standards (LITS) at the Jet Propulsion Laboratory have already achieved exceptional short-term stability below $3\times10^{-14}\tau^{-1/2}$ [1] and long-term stability below 10^{-15} [2]. Recently the design has been extended to include a 12-pole trap [3]. Ions are first collected in a conventional linear quadrupole trap and then shuttled from there to the spatially separate 12-pole trap where the microwave clock transition is probed. The primary advantage of the 12-pole geometry is the large reduction in this clock's main systematic effect: the second order Doppler shift [4]. Shuttling to a second trap makes it possible to spatially separate the loading and interrogation regions thereby making the standard far less sensitive to perturbations due to the loading process. In addition, magnetic shielding can be made more effective since it is smaller with fewer access ports.

Reducing the second-order Doppler shift increases the importance of characterizing the other systematic effects more carefully. One of these is the second-order Zeeman shift. Usually this effect is measured by using field-sensitive lines to determine the value of the average magnetic field that the ions "see". Since the microwave interrogation in this frequency standard does not take place in a cavity, the field-sensitive line is broadened to 10's of kHz. Instead of probing the field-sensitive lines directly we use a far more sensitive probe involving simultaneous interrogation by microwaves tuned to the clock transition and an rf field tuned to the $\Delta m=1$ Zeeman transition. This probe results in a field-sensitive spectroscopic line that is 15 times narrower than that achieved with the direct excitation. We will present data on this probe and how it has enabled us to improve the precision in our knowledge of the stability of this standard due to magnetic field effects to below 2×10^{-16}.

Characterization of the 12-Pole-based Linear Ion Trap Standard: Current Status

The primary systematic effects in the JPL 12-pole frequency standard are 1) the second order Doppler shift 2) the pressure shift (primarily helium since this is currently used as the buffer gas, but also hydrogen, nitrogen, mercury and others), and 3) the second order Zeeman shift. The first two shifts have been measured elsewhere [4, 5]. The black body fractional frequency shift for the mercury hyperfine transition is estimated to be -1×10^{-16} with a stability of $< 5\times10^{-20}$, and is not considered in detail here.

The second order Doppler fractional frequency shift in the 12-pole standard has been measured to be 2.4×10^{-13} with a stability of $< 1\times10^{-16}$ [4]. The helium fractional frequency shift in the 12-pole standard has been measured to be $(df/dP_{He})(1/f)=1.2\times10^{-10}$/Pascal [5] or about 1.6×10^{-13} at a typical operating helium pressure of about 1.3×10^{-3} Pascal. The helium pressure is stable at the 0.1% level making this shift stable at $< 2\times10^{-16}$. The nitrogen pressure shift has been measured to be $(df/dP_N)(1/f)=-8.7\times10^{-9}$/Pascal [5]. The pressure shift of nitrogen has been measured and is not significant for this device. The pressure shift due to other background gasses have not yet been measured, however measured stabilities place an upper bound on these of about 5×10^{-16}.

In this paper we characterize the second order Zeeman shift, completing the characterization of the largest systematic shifts in the 12-pole mercury LITS.

Characterization of Magnetic Field Effects

Figure 1 shows the $^{199}Hg^+$ level diagram. Operation of this standard is described elsewhere [4] and will only be summarized here. Initially about 10^6 Hg^+ ions are loaded into a quadrupole linear ion trap. After thermalization with the background helium buffer gas and optical pumping (using a mercury plasma discharge lamp) to the $S_{1/2}$, F=0 state, the ions are then transferred to the 12-pole trap in about 2 seconds. There they are interrogated with microwave radiation tuned to the 40.5 GHz clock transition between the $S_{1/2}$, F=0, m_F=0 state and the $S_{1/2}$, F=1, m_F=0 state using either separated Ramsey pulses or one Rabi pulse with a 6 second duration. When the microwave interrogation is complete, the ions are transferred back to the quadrupole trap for final state detection. This detection is performed with the same discharge lamp used for optical pumping. It is only resonant with the F=1 state so fluorescence due to this excitation is a precise indicator of how many ions made the transition from the F=0 to F=1 state. On the other hand the spectral width of the lamp does not permit resolution of the m_F Zeeman levels.

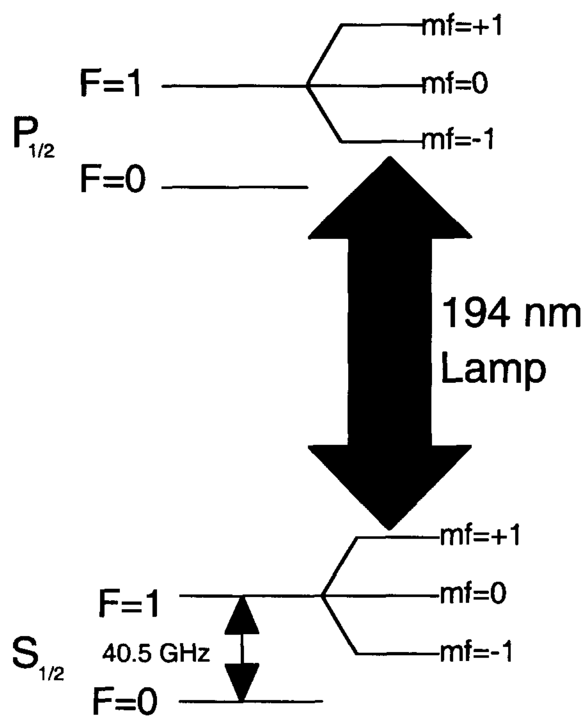

Figure 1. A level diagram for $^{199}Hg^+$ showing the clock transition at 40.5 GHz and the optical interrogation transition at 194 nm. The clock is typically operated with a bias field of 3-7 μT resulting in a shift between adjacent Zeeman m_f levels of approximately 50-100 kHz.

The microwave field used to interrogate the ions has a polarization aligned with the bias field so as to drive the $\Delta m=0$, $m_f=0 - m_f=0$ field-insensitive clock transition. The bias field is itself aligned with the axis of the trap so the microwaves propagate perpendicular to this axis. The ion motion in this direction is small compared to the microwave wavelength so to the extent that this polarization and propagation direction do not deviate from these initial values, the ions are Lamb-Dicke confined and the first order Doppler shift is suppressed. However the microwave radiation is emitted from a horn and its output approaches a spherical wave-front as the wave gets further from the horn. In the wings of the trap furthest away from the horn, there is some component of the microwave field with polarization perpendicular to the axis of the trap. This polarization can drive field-sensitive $\Delta m=\pm1$ transitions. In addition, at the edges of the trap the microwaves are propagating along the trap axis and ion motion in this direction is no longer small compared to the microwave wavelength. Therefore, field-sensitive lines excited in this way are also first-order Doppler broadened. For room temperature ions, this broadening is of order 20 kHz. To prevent "Zeeman de-coherence" of the clock transition, these lines must be shifted several 10's of kHz, hence the typical operating bias field mentioned above.

While these Zeeman lines must be avoided for proper clock operation, they can be used to determine clock magnetic field sensitivity. For the field-insensitive clock transition, the shift is second order:

$$\Delta f_{z2} = 9.7 \times B_0^2 \, mHz/\mu T^2,$$

where B_0 is the bias field. For the field-sensitive lines, the shift is first order:

$$\Delta f_{z1} = 14 \times B_0 kHz/\mu T.$$

A measurement on the field-sensitive line gives information about the average field as "seen" by the ions. To the extent that $\langle B_0\rangle^2 = \langle B_0^2\rangle$, shifts on the field-sensitive line can be used to determine the expected (much smaller) shift on the field-insensitive line. However, since there is no field-sensitive $\Delta m=0$ transition in $^{199}Hg^+$ the only field-sensitive lines available require transverse polarization, which is first-order Doppler broadened. With the Doppler broadening being of the same order as the Zeeman shift, this measurement method has poor resolution. This lack of resolution is made worse by the fact that only a small fraction of the microwave power has the right polarization to be resonant with the field-sensitive transition. Propagating the microwaves along the trap axis results in larger signal [6], but still suffers from a large Doppler broadening. Here we report results using a double-resonance technique [7] consisting of the normal clock transition microwave radiation super-imposed with an additional rf field tuned to the Zeeman separation.

Double Resonance Technique

Figure 2 shows the two transitions used in the double resonance technique. The microwave radiation is the normal 40.5 GHz polarized along the bias field. The ~100 kHz rf field is derived from a current loop placed on the trap electrodes whose axis is perpendicular to the trap and bias field axis. The 40.5 GHz is Doppler-free because it (primarily) propagates perpendicular to the trap axis. The 100 kHz rf field is not Doppler-free, but at this frequency, the Doppler shift is insignificant. If the readout probe (the discharge lamp) were able to resolve Zeeman sublevels, we could simply turn on these two frequencies sequentially and then tune the readout probe to the desired Zeeman sublevel. The frequency of the rf field at maximum signal would then give the desired (effectively Doppler-free) magnetic field information.

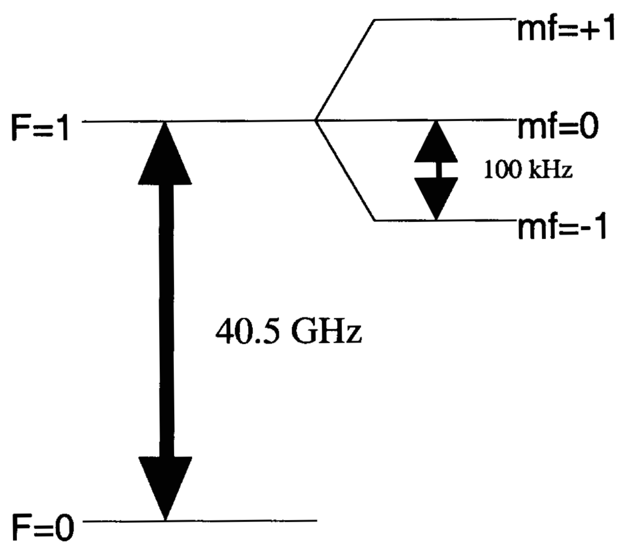

Figure 2. Detail of the ground state hyperfine level structure showing the two transitions used in the double-resonance probe.

However, since the lamp does not resolve Zeeman levels, we instead operate both frequencies simultaneously. The presence of the rf field causes a de-coherence in the precession of the ion spins (this is equivalent to a T2-relaxation of off-diagonal elements of the density matrix [8]). In order for the same number of ions to make the transition from the F=0 to F=1 state, the microwave power must be increased so that on average this transition happens before the m_f=0 to m_f=±1 transition. Equivalently, if the microwave power is held constant and its frequency is on resonance, as the rf frequency is scanned across the m_f=0 to m_f=±1 line, the signal measured by lamp-stimulated fluorescence will dip. This dip will be essentially Doppler-free making it a potentially far more precise probe of the magnetic fields. A simplified three-level Bloch equation analysis using only one of the two possible rf-induced Zeeman transitions gives this behavior

Results

Figure 3 shows a scan of the rf frequency across the Zeeman transition while holding the microwave frequency fixed on resonance and constant in power. The resultant dip in the fluorescence signal has a width of 1.4 kHz and a signal-to-noise ratio (SNR) of about 10. This should be compared to a width of 20 kHz and an SNR of about 1 for the single frequency microwave interrogation of the field-sensitive line. The result is a 100-fold improvement in resolution.

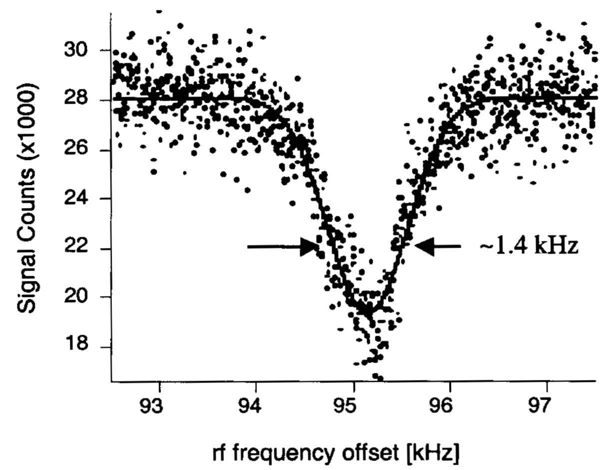

Figure 3. A scan of the rf frequency over the Zeeman transition with the microwave frequency on resonance and the microwave power held constant. The actual data are represented in dots with the line being a gaussian fit to the data. The full width at half maximum of the "dip" as determined by the fit is 1.4 kHz.

The magnetic shielding effectiveness in this device is measured by observing the rf frequency shift as a function of changing external field. A coil was placed outside of the magnetic shields and supplied with current to produce a 68 μT field at the location of the 12-pole trap and aligned with the trap axis. As a result of switching the polarity of this coil (a total field change of 136 μT) the shift in the center of the "dip" was 80(5) Hz or a field difference as seen by the ions of 5.7(3) nT. This implies a shielding effectiveness of 24,000 (1200). As a result, a 0.1 μT

fluctuation in the external field (typical ambient fluctuation) would result in a fractional frequency shift on the clock transition of less than 10^{-16}.

To observe the magnetic stability over time, we lock the rf synthesizer to the dip feature at approximately 95 kHz. Figure 4 shows the Allan deviation for this data. At 10^5 seconds the floor is seen to be < 1.5×10^{-11}. Since the clock transition is approximately 10^5 less sensitive to magnetic field fluctuations this means that the contribution to the overall clock systematic floor due to magnetic field effects (in this particular environment) is < 1.5×10^{-16}.

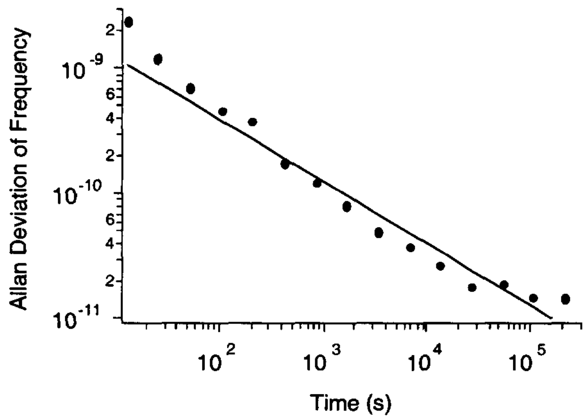

Figure 4. Allan deviation of rf frequency differences while the clock is locked to the field-sensitive Zeeman excitation feature. The straight line is for reference.

Anomalous Number Dependence

The first 12-pole standard results [4] showed dramatically improved insensitivity to the second order Doppler shift compared to the conventional quadrupole LITS. These measurements were accomplished by varying the number of ions in the trap and measuring the resultant frequency shift due to rf heating effects. While the 12-pole data is essentially flat, it does have a very small number dependence at low number (low end-pin voltage). It is referred to here as "anomalous" because it has an opposite sign from the second-order Doppler shift.

One possible explanation for the anomalous number-dependent effect is that as the number of ions change, the average magnetic field as seen by the ions varies. Such differences could be due to fringing non-uniformities at the bias solenoid ends or to the presence of shield endcaps near the ends of the 12-pole trap.

To further investigate the anomalous shift we first re-measured it with improved resolution. Figure 5 shows this data where the change in ion number is accomplished by changing the 12-pole trap end-pin voltage, effectively reducing the trap well depth. The full-scale change is seen to be 2.5 mHz or a fractional shift of 6×10^{-14}. Note that at the normal end-pin voltage of 8 V, this number dependence is insignificant.

To test the hypothesis that the effect is magnetic field related we performed the same experiment on the field sensitive line using the double resonance technique (Figure 6).

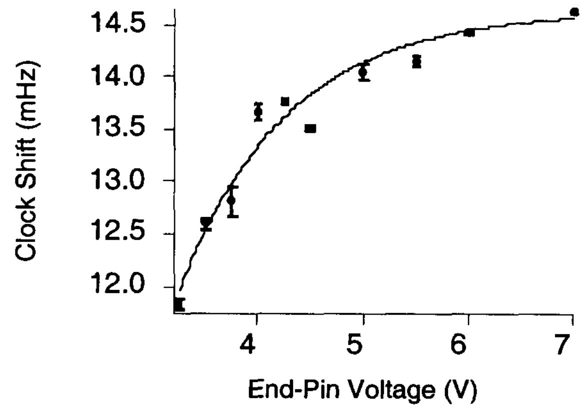

Figure 5. Data demonstrating the frequency shift as a function of ion number as determined by the 12-pole trap end-pin voltage. The continuous line is a fit to an exponential. The end-pin voltage range observed corresponds to a trap that is about 25% full to full and results in 2.5 mHz or a fractional shift of 6×10^{-14}.

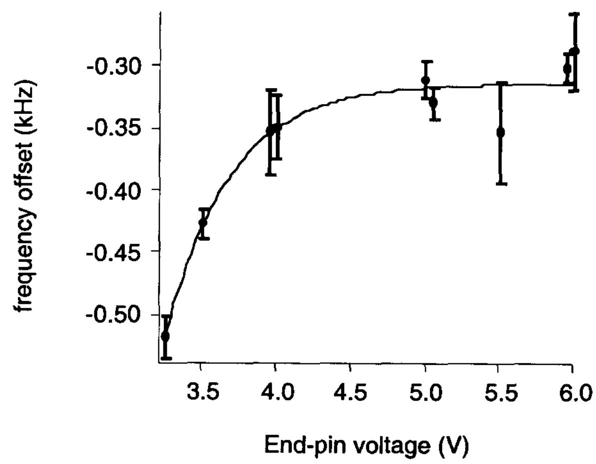

Figure 6. Data showing the frequency dependence of the field sensitive $F=1,m_f=0$ to $F=1,m_f=\pm1$ transition on ion number (end-pin voltage). The line is a fit to an exponential.

The data shows the same exponential behavior as the clock frequency data, however the magnitude of the shift is different. If the difference in sensitivity between the field-sensitive and field-insensitive lines is taken into account, the field-sensitive data would correspond to a full scale shift of 0.23 mHz on the clock transition. This must be compared to the 2.5 mHz shift in the actual clock data over the same range of end-pin voltages. So we have qualitative agreement, but the wrong magnitude.

Two possible explanations for this discrepancy are due to magnetic field non-uniformity. The first has to do with the fact that the field-sensitive data measures effects of $\langle B \rangle$, the spatially averaged field seen by the ions. Whereas, the clock transition is sensitive to $\langle B^2 \rangle$. To make comparisons we take $\langle B \rangle^2$ with the assumption that $\langle B \rangle^2 \cong \langle B^2 \rangle$. This assumption is false if the field has significant non-uniformity. A simplified model using a non-uniformity that changes quadratically along the trap axis indicates that the extent of the non-uniformity must reach 10% at the ends of the trap to account for the observed difference. While this could happen in a solenoid alone where fringing of the fields at the ends is expected, it is difficult (though not impossible) to imagine that a solenoid positioned inside of a cylindrical shield whose endcaps are forcing the field toward uniformity would have this behavior.

The second possibility is the magnetic inhomogeneity shift [9]. Here, inhomogeneities in the field in the transverse direction result in a time-varying field as seen by the ions. Some components of this time-varying field can exist at the Zeeman frequency. These have the right polarization and frequency to drive the F=1, m_f=0 to F=1, m_f=±1 transition. This is very similar to the double resonance that we apply. As with our externally applied double resonance, these ion-motion-induced Zeeman transitions represent a relaxation process. The relaxation process is a perturbation that leads to a shift in the clock frequency [10]. In the case of the shift introduced by the time-varying field that the ions see as part of the secular motion, the shift is proportional to $\langle B_t^2 \rangle$ where B_t is the transverse field. As the end-pin voltage is turned down the ion cloud occupies a smaller region of space with a smaller amount of inhomogeneity. Thus, one would expect to see the shift get smaller as the end-pin voltage is reduced. This is qualitatively what is observed on the clock transition data (Figure 5).

The double resonance technique that we use to probe the field-sensitive line introduces a shift as well that can be seen in figure 7. There several double resonance curves, each at different rf power, are shown. The center of each curve is observed to shift by a negative amount as power is increased. The total shift at our operating point is about 200 Hz. This is equivalent to 2 mHz on the clock transition. Thus the externally applied double resonance introduces an additional shift with the correct magnitude to possibly mask the effect we are trying to measure. This may explain why the effect is qualitatively the same, but different in magnitude between the clock and field-sensitive data. We are continuing to investigate this effect, though it does not currently impact the overall performance of the clock.

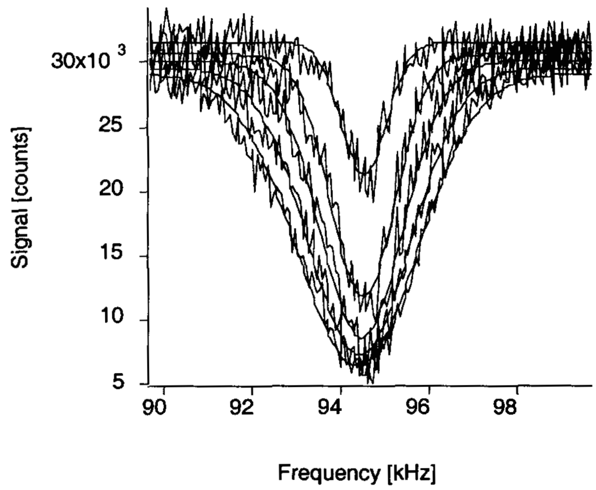

Figure 7. Data showing the behavior of the double resonance dip as a function of applied rf power. At highest power, the dip not only displays saturation behavior, but is also shifted by approximately 200 Hz.

Conclusion

We have demonstrated the use of double resonance as a way of increasing the resolution with which the magnetic field can be measured in a 12-pole mercury linear ion trap frequency standard. We have used the technique to verify that the magnetic shields provide sufficient shielding (~24,000) and that the contribution to the systematic floor of the standard from magnetic field effects is $< 2\times10^{-16}$. Finally we have also used the technique to gain insight into the anomalous number dependency observed previously and have given a plausible explanation for that dependency in terms of the magnetic inhomogeneity shift.

Acknowledgments

This work was carried out at the Jet Propulsion laboratory, California Institute of Technology, under a contract with the U.S. National Aeronautics and Space Administration.

References

1. G.J. Dick, R.T. Wang and R.L. Tjoelker, "Cryo-Cooled Sapphire Oscillator with Ultra-High Stability," in Proc. 1998 IEEE International Frequency Control Symposium, p. 528.
2. R.L. Tjoelker, J.D. Prestage, L. Maleki, "Record Frequency Stability with Mercury in a Linear Ion Trap," in Proc. Of the Fifth Symposium on Frequency

Standards and Metrology, Woods Hole, MA October 1995, p. 33.

3. J.D. Prestage, R.L. Tjoelker and L.Maleki, "Higher Pole Linear Traps for Atomic Clock Applications," in proc. 1999 Joint Meeting EFTF – IEEE IFCS, p. 121. See also, Prestage et al., "Stability Measurements Between Hg^+ LITE 12-Pole Clocks," in this proceeding.
4. J.D. Prestage, R.L. Tjoelker and L. Maleki, "Mercury-Ion Clock Based on Linear Multi-Pole Ion Trap," in Proc. 2000 IEEE International Frequency Control Symposium, p. 706.
5. R.L. Tjoelker, S. Chung, W. Diener, A. Kirk, L. Maleki, J.D. Prestage and B. Young, "Nitrogen Buffer Gas Experiments in Mercury Trapped Ion Frequency Standards," in Proc. 2000 IEEE International Frequency Control Symposium, p. 668.
6. J.D. Prestage, R.L. Tjoelker, G.J. Dick and L.Maleki, "Doppler Sideband Spectra for Ions in a Linear Trap," in Proc. 1993 IEEE International Frequency Control Symposium, p. 148.
7. A. Corney, "Atomic and Laser Spectroscopy,"Oxford Science Publications (1988), p. 534.
8. R. Loudon, "The Quantum Theory of Light," Oxford Science Publications, Second Edition (1984), p. 78.
9. V. S. Reinhardt and H. Peters, "An Improved Method of Measuring the Magnetic Inhomogeneity Shift in Hydrogen Masers," Proceedings of the 29th Frequency Control Symposium (ERADCOM, Atlantic City), 1975.
10. J. Vanier and C. Audoin, "The Qunatum Physics of Atomic Frequency Standards," IOP Publishing Ltd (1989), p. 82.