COMMENT

Comment on ‘Accurate rubidium atomic fountain frequency standard’

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Abstract

We discuss the treatment of distributed cavity phase, microwave lensing and microwave leakage in the paper by Ovchinnikov and Marra (2011 Metrologia 48 87–100). The paper neglects the potential distributed cavity phase shifts from linear phase gradients and quadrupolar phase variations. Only azimuthally symmetric phase variations were analysed and an incorrect model was used for these. The paper also omits an uncertainty due to microwave lensing, which must be included. Finally, we describe additional measurements that could clarify the model used to analyse the frequency shifts due to microwave leakage.

A recent accuracy evaluation of the NPL Rb fountain reports a total uncertainty of 3.7 × 10^{-16} [1]. Here we comment on the evaluation of several of the leading systematic uncertainties: distributed cavity phase (DCP) [1–5], microwave lensing [5, 6] and microwave leakage [7, 8].

The DCP frequency shift is a first order Doppler shift that can occur when atoms in an atomic fountain clock do not experience the same time-dependent phase on their upward and downward traversals through the microwave clock cavity [1–5]. It was shown in [3], and more recently experimentally demonstrated in [4, 5], that DCP shifts can be evaluated by expanding the phase variations into Fourier components cos(mφ), where φ is the azimuthal angle coordinate in the cylindrical cavity. Fourier components with \( m \geq 3 \) are normally negligible, leaving the three lowest terms, \( m = 0, 1 \) and \( 2 \), to be evaluated [2, 3]. The \( m = 1 \) term can be particularly large, and the \( m = 2 \) term can be significant. These two terms are the leading contributions to the DCP uncertainty in recent evaluations [4, 5]. In [1], the \( m = 1 \) and \( 2 \) terms were not evaluated. Only the \( m = 0 \) term was analysed, using a phenomenological DCP model [9] that was previously shown to be incorrect [3, 10]. In figure 1, we illustrate the inconsistencies of this phenomenological DCP model (solid curve) with theory (dashed curve) and recent measurements (squares) [3, 4]. In [1], the phenomenological DCP model was also used to project a small future uncertainty for a Rb clock. We note that cavities proposed in [3] enable very small DCP uncertainties, less than \( 1 \times 10^{-17} \).

The discussion of DCP uncertainties in [1] also claims that high temperature clouds reduce DCP errors because the atoms uniformly illuminate the cavity apertures on both cavity traversals. Here, it is illustrative to consider a centred, very small, atomic cloud at launch. A high temperature will indeed give a uniform density distribution on both cavity passages, but all the atoms that are detected will have passed through the cavity very near the axis on the upward cavity traversal. For temperatures so high that the cloud is much larger at the upward cavity traversal than at launch, the correlations between the two passages cannot be neglected—the difference between equations (7) and (8) in [3] can be large. Thus, high temperatures are not particularly helpful for reducing DCP uncertainties. Moreover, there are significant drawbacks, including larger cavity pulling and potentially larger collision shifts [11].

Microwave lensing is a clock error caused by the dipole forces that are exerted on the atomic wavefunctions by the standing wave in the microwave clock cavity [5, 6]. The evaluation [1] did not include this systematic uncertainty. The frequency shift is of the order of the microwave recoil shift, \( 1.7 \times 10^{-16} \) for Rb. If this value was used as the uncertainty [12, 13], it would be the second largest systematic uncertainty contribution and a significant fraction of the clock’s total uncertainty of \( 3.7 \times 10^{-16} \) [1]. In addition, it would dominate the projected future Rb fountain accuracy of \( 5 \times 10^{-17} \) in [1], unless a reasonable limit of the microwave lensing bias was evaluated, as was recently completed in [5].
microwave lensing frequency shifts were not properly
cutoff waveguides [15]. The phenomenological model was scaled to match the data for 5π/2
pulses (b = 4.7). The grey circles indicate the theoretical δP’s for (1, 3, 5, 7, 9) π/2 pulses.

(Figure 1 is in colour only in the electronic version)

Frequency shifts from microwave leakage were observed in [1]. They exhibited an interesting dependence on the tilt of the fountain and a model based on travelling waves was
developed. We note that pure travelling waves are difficult to generate. While the interrogation region is not expected to have high-Q resonances, any travelling wave is likely to have significant reflections so that the phase of the field better resembles a standing wave with phase chirps at the field nodes than a pure travelling wave. Therefore, the frequency shift from the total field, the excited travelling wave and its reflection, has to be treated. The observed tilt dependence suggests that an m = 1 mode might be nearly resonant in the interrogation region, being excited by leakage from the cavity feeds. Information about the spatial profile of the mode and the polarization of the leakage field could constrain and test the model of the frequency shifts from the leakage. For example, a model based on a Doppler-shifted ac Zeeman effect between the clock states was developed in [1] but the coupling could as well to be 6m = ±1 transitions if the leakage mode is a TM instead of a TE mode. One way to probe the spatial profile and polarization of the leakage field mode is to inject strong sidebands and observe the ac Zeeman shifts as a function of detuning, and the time at which the sidebands are applied during the fountain trajectory [14]. Given that the fountain height is several microwave half-wavelengths, an oscillatory spatial dependence is expected from a standing wave. The field strength at the apogee, where the atoms spend the most time, is particularly important. Engineering the electromagnetic mode spectrum in the interrogation region can avoid unintended resonances, for example using cavities [11] or below cutoff waveguides [15].

In summary, the distributed cavity phase and the microwave lensing frequency shifts were not properly
evaluated in [1]. Measurements of the spatial mode and polarization of the leakage field may offer helpful insight into the origin of the observed frequency shifts from microwave leakage.

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