ACCURACY EVALUATION OF A CESIUM FOUNTAIN PRIMARY FREQUENCY STANDARD AT NIST

D.M. Meekhof, S.R. Jefferts, J.H. Shirley and T.E. Parker
Time and Frequency Division
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80303 U.S.A.

Abstract

Since November of 1998, we have performed five frequency uncertainty evaluations on NIST F-1, our laser-cooled cesium fountain. The results from the latest evaluation have a statistical uncertainty of 1.4×10^{-15} and an uncorrected bias of 0.7×10^{-15}. The results have been reported to the Bureau International des Poids et Mesures (B.I.P.M.) for inclusion in TAI, making this clock one of two cesium fountain clocks used as primary standards in the world. We will present an overview of the evaluations and their uncertainties.

Overview

The NIST cesium fountain has been previously described in detail [1] and only a short overview will be given here. NIST F-1 has a pure optical molasses source (no MOT) which gathers approximately 10^7 cesium atoms at 2 μK in about 0.4s. The ball of atoms is then launched by differential detuning of the two vertical laser beams to make a moving optical molasses. After the atoms have been accelerated to their launch velocity the molasses laser beams are all detuned to the red in frequency while simultaneously reducing the optical intensity to further cool the launched atom sample.

The atoms travel from the optical molasses source region through a region which is used to detect atoms later in the process, and into the magnetically shielded C-field section of the fountain. The launched ball of atoms is at this point all in the F=4 state and more or less evenly distributed over all possible m-state values. The atoms first encounter a microwave state selection cavity which moves the $|F=4,m=0\rangle$ atoms to the $|3,0\rangle$ state using a π-pulse at 9.192 GHz. The remaining F=4 atoms are then removed from the sample with an optical pulse.

The remaining atoms in the $|3,0\rangle$ state next encounter the Ramsey microwave cavity, where the microwave field prepares the atoms in a superposition state of F=4 and F=3. The Ramsey cavity is a TE_{011} OFHC copper cavity with a Q of 22,500. After the Ramsey cavity the atoms drift upward in the flight-tube, achieve apogee, accelerate downward, and re-enter the Ramsey cavity where the Ramsey-interrogation process is completed. After leaving the Ramsey cavity the atoms next fall through the state-selection cavity, in which the microwave drive has been both detuned by 12 MHZ and attenuated by more than 100 dB.

Finally, upon exiting the C-field region, the atoms enter the detection region. Here atoms in the F=4 state are first detected by fluorescence in an optical standing wave and then removed from the atomic sample by an optical traveling wave. The sample then traverses an optical re-pump beam which transfers F=3 atoms to the F=4 state. These F=4 atoms (formerly F=3) are then detected by optical fluorescence in a standing wave similar to the one described above.

One gather, launch, microwave interrogation, and then optical detection cycle is used to probe each side of the central Ramsey fringe. The microwave synthesizer is then tuned to the other side of the fringe and the cycle repeated. A single measurement of the cesium clock frequency consists of two measurement cycles, one on either side of the Ramsey fringe.

Systematic Frequency Biases

NIST F-1 has undergone five frequency evaluations since November of 1998. The results are compared to various other primary frequency standards as reported to the B.I.P.M. Unfortunately the L.P.T.F. fountain[2] which is the only other clock in the world with similar accuracy has not reported during this period, however the NIST F-1 results are consistent with other primary standards, albeit with much smaller uncertainty.

The following systematic effects have been calculated to have a worst case frequency bias $\Delta\upsilon/\upsilon$ of 10^{-16} or less in our fountain: cavity pulling, distributed cavity phase shift (first-order Doppler shift), Rabi pulling, Ramsey pulling, second-order Doppler shift, D.C. Stark shift and the Bloch-Siegert Shift.

Four frequency biases are corrected for: Second Order Zeeman Shift, Spin Exchange, Blackbody Radiation and Gravitational Redshift.

Second-Order Zeeman Shift

The C-field used in NIST F-1 is about $0.1\mu T$ (1 mG) and causes a 5×10^{-14} fractional frequency shift due to the second order Zeeman effect. This shift is evaluated by measuring the frequency of the $|4,1\rangle$ magnetic-field-sensitive transition and using the frequency of that transition to correct for the shift in the $|4,0\rangle\rightarrow|3,0\rangle$ transition. To sufficient accuracy the fractional Zeeman correction, $\delta\nu_z/\nu_{Cs}$, is then given by

$$\frac{\delta\nu_z}{\nu_{Cs}}=\frac{8\,\delta\nu_{1,0}^2}{\nu_{Cs}^2}\ ,$$

where $\delta\nu_{1,0}$ is the measured difference frequency between the $|4,0\rangle\rightarrow|3,0\rangle$ and the $|4,1\rangle\rightarrow|3,1\rangle$ transitions.

Spin-Exchange Frequency Shift

The spin-exchange frequency shift is evaluated using various techniques. The evaluation of the spin-exchange frequency shift requires a measurement of the atomic density. This involves a careful calibration of the entire detection system. The size of the detection beams and their intensity, the solid angle for collection of photons from the atomic sample, including vignetting, and finally a calibration of the photodiode and its associated amplifier.

The average density is determined from a measurement of the number of atoms launched by using the detection region to measure the number of atoms in the cloud on the way up and again on the way down. Assuming Maxwellian thermal distributions and extracting the physical dimensions of the launched atom ball from the data we can determine the atomic density as a function of time. This density is then used, along with a spin-exchange frequency shift coefficient for the m=0 state as measured by the LPTF group [3], to infer the total spin-exchange frequency shift.

The total calculated spin-exchange shift in our fountain is typically $\Delta\nu/\nu\approx 9\times10^{-16}$ and as a result of the difficulties associated with the density determination mentioned above, we assign a conservative uncertainty of 0.5×10^{-15}.

Blackbody Radiation Shift

The next significant systematic frequency bias is the blackbody radiation shift. The cavity and drift tube region of the fountain are temperature controlled at a temperature of 41 °C. Thermal gradients as well as environmental thermal radiation limit the knowledge of the radiation environment of the standard to 1C resulting in an uncorrected frequency bias of 3×10^{-16}.

Gravitational Redshift

The gravitational frequency shift (redshift) in Boulder is large, -1.8×10^{-13}. The gravitational potential in Boulder Colorado relative to the geoid has been reevaluated using the EGM-98 Earth potential model and the resulting claimed uncertainty on the frequency correction is less than 3×10^{-16}.

Stability

Our fountain presently has a stability of $\sigma_y(\tau)=6\times10^{-13}\tau^{-1/2}$ when operating as a primary frequency standard. This stability is much worse than predicted by the number of detected atoms, but is consistent with the stability predicted from measurements of the quartz local oscillator and a calculated Dick Effect factor.

References

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[3] S. Ghezali, Ph. Laurent, S.N. Lea, A. Clairon, "An Experimental Study of the spin-exchange frequency shift in a laser-cooled cesium fountain frequency standard," *Europhys. Lett.* **36**(1996) pp25.