PRELIMINARY ACCURACY EVALUATION OF A CESIUM FOUNTAIN PRIMARY FREQUENCY STANDARD AT NIST

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ABSTRACT

Since November of 1998, we have performed four uncertainty evaluations on NIST F-1, our laser-cooled cesium fountain. The results from the latest evaluation have a statistical uncertainty of 2.6×10^{-15} and an uncorrected bias of 1.1×10^{-15}. This paper presents a brief 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 0.6s. 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 mechanical design of the fountain is shown in Figure 1.

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, a TE_{011} OFHC copper cavity has been previously described [2]. 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.

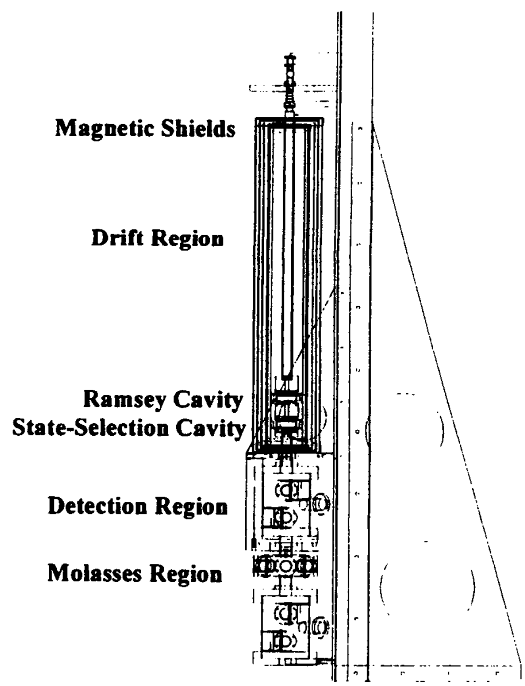

Figure 1- A schematic diagram of NIST F-1 showing major subcomponents.

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 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 four frequency evaluations since November of 1998. The results, shown on Figure 2, are compared to various other primary frequency standards as reported to the Bureau International des Poids et Mesures[3].

A complete description of the fountain and the evaluation process is in preparation and will be submitted for publication later this year.

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. These shifts will not be discussed further here.

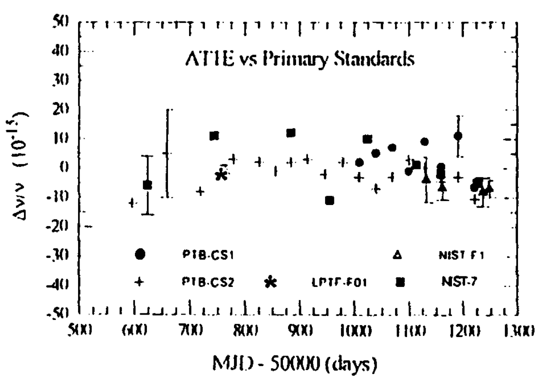

Figure 2 - NIST F-1 as compared to other National Primary Frequency Standards through the NIST AT-1E postprocessed time scale.

<u>Second-Order Zeeman Shift</u>

The C-field used in NIST F-1 is about 0.1 μT (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 $|4,0\rangle-|3,0\rangle$ transition. To sufficient of 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 $|4,0\rangle-|3,0\rangle$ and the $|4,1\rangle-|3,1\rangle$ transitions. There are several ways this approach can fail to yield the required accuracy in the fountain. First, due to the large number of Ramsey fringes, there is an uncertainty in identifying the central fringe on the magnetically-sensitive transitions. A magnetic field inhomogeneity will shift the Ramsey fringes with respect to the underlying Rabi pedestal. We identify the central fringe in two ways. First, a magnetic field map is constructed by launching the atoms to various heights and applying a Rabi pulse on a magnetically sensitive transition at apogee using an antenna in the drift region. This technique, described in some detail by the LPTF group [4]. A better method uses repeated measurements of the Ramsey fringe pattern around the central fringe for the m=1 transition while launching to various heights. The peaks of the Ramsey fringes constructively interfere on the central fringe and lose coherence away from it. A mis-assignment of even 1 full fringe (which we consider unlikely) would only produce a fractional frequency error of about 3×10^{-16}.

The stability of NIST F-1 when locked to a field-sensitive line shows a flicker floor at $\sigma_y(\tau)=10^{-12}$ which indicates that magnetic field fluctuations of about 10^{-12} T are present inside the C-Field region. Field fluctuations of this size cause a frequency shift in the m=0 clock transition of order 10^{-18} and are ignored here.

Measurement of the m=1 line determines the temporal average of the magnetic field B over the flight time. However, we need the temporal average of B^2 to correct the second-order Zeeman shift. If we model the magnetic field as seen by the atoms as H(t) $=H_0(1-\epsilon f(t))$, where f(t) is a function with $|f(t)|\leq 1$, and ϵ is a scaling factor, then the difference between the mean square and the square of the mean leads to a frequency shift given by

$$\frac{\Delta f}{f} = \frac{(427*10^8\ H_0^2)\epsilon^2}{f_0}[<f(t)>^2\ -\ <f(t)^2>]\ .$$

In our case ϵ is of order 0.1 and $<f(t)>^2 - <f(t)^2> \leq 0.01$. The maximum inhomogeneity frequency shift is therefore less than $\Delta f/f = 10^{-17}$.

The uncertainty associated with the quadratic Zeeman shift is therefore dominated by problems associated with location of the central fringe and is conservatively assigned a value equivalent to the mis-assignment of one whole fringe in the m=1 manifold, that is, 3×10^{-16}.

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. We use 2 mm high by 20 mm wide (1/e) detection beams which have an intensity well above the D_2 saturation intensity. The solid angle for the collection of photons has been modeled to be $1.2\pi(\pm10\ \%)$ with 10 % vignetting at 0.5 cm from the center of the optical system.

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 [5], to infer the total spin-exchange frequency shift. The process is complicated by the use of a pure molasses source, since the initial cloud size is uncertain and this propagates into the final result both directly and as an uncertainty on the atom temperature. We are presently attempting to do simulations of the atom trajectories through the fountain and to derive a rigorous analytic solution to the density as a function of time. The atomic density derived above is next used to predict the total spin-exchange frequency shift as

$$\frac{\Delta f}{f} = (-2\times10^{-21})[(\frac{ht}{T})(\frac{\rho_1+\rho_3}{2}-\overline{\rho_2})+\overline{\rho_2}]$$

where h is a factor of order unity which depends on the excitation power, t is the Rabi time, T the Ramsey time, ρ_1 and ρ_3 the atomic density on the first and second pass through the microwave cavity respectively, and $\overline{\rho_2}$ the average density over the entire Ramsey time. This formula, originally derived by Shirley [6] for Zeeman shifts over the length of a beam tube has been modified for the case at hand.

As a consistency check we compare the frequency of the fountain when using state selection to the frequency measured with no state selection. Without state selection the density is much higher, although the spin-exchange cross section is smaller by a factor of 2. We see no spin-exchange frequency shift at 3×10^{-15} when we make this test, limited by statistics. The total calculated spin-exchange shift in our fountain is typically 1×10^{-15} and as a result of the difficulties associated with the density determination mentioned above, we assign a conservative uncertainty of 0.8×10^{-15}. We expect that with continued work on the density model the uncertainty associated with the spin-exchange shift will be considerably reduced.

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. Sensors on the microwave cavities and the drift tube of the fountain monitor the temperature. Unfortunately there is a temperature gradient of about 3 °C between the drift tube and the cavities, which if unmodeled could cause an uncorrected frequency bias as large as 1×10^{-15}. We use a simple temperature profile model which allows correction of the blackbody radiation temperature to less than 1 °C, so that the uncorrected blackbody frequency bias is less than 5×10^{-16}.

NIST F-1 Error Budget

Physical Effect	Magnitude	Uncertainty	Correction?
First Order Doppler	$<10^{-16}$	$<10^{-16}$	No
Blackbody Radiation	2×10^{-14}	5×10^{-16}	Yes
Magnetic Field Inhomogeneity	$<10^{-16}$	$<10^{-16}$	No
Spin Exchange Collisions	1×10^{-15}	8×10^{-16}	Yes
Second order Zeeman	4×10^{-14}	3×10^{-16}	Yes
Ramsey Pulling	$<10^{-16}$	$<10^{-16}$	No
Rabi Pulling	$<10^{-16}$	$<10^{-16}$	No
Majorana Transitions	$<10^{-16}$	$<10^{-16}$	No
Microwave Leakage	$<10^{-16}$	$<10^{-16}$	No
Spectral Impurities	$<10^{-16}$	$<10^{-16}$	No
Gravitational Redshift	2×10^{-13}	5×10^{-16}	Yes
TOTAL UNCERTAINTY		1.1×10^{-15}	

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 5×10^{-16}[7].

The systematic frequency biases in NIST F-1 can be seen in Table 1. The overall type B uncertainty (systematic effects) is 1.1×10^{-15}, dominated by the spin-exchange shift.

STABILITY

As can be seen in Table 1, the statistical uncertainty (type A) is greater than the type B uncertainty. Our fountain presently has a stability of $\sigma_y(\tau)=1\times10^{-12}\tau^{-1/2}$ when operating as a primary frequency standard. This stability is much worse than predicted by the number of detected atoms. We think that excess optical noise, both amplitude and pointing noise is the major source of this excess noise. Work is underway to correct these noise sources and, presumably, improve the short-term stability.

ACKNOWLEDGMENTS

The authors acknowledge significant help from D. Lee, T. P. Heavner, C. Nelson, F. L. Walls, R.E. Drullinger, L.W. Hollberg, and A. DeMarchi. We are also glad to acknowledge M. Young, D.B. Sullivan, T.P. Heavner and S. Römisch for their helpful suggestions regarding the manuscript.

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