NIST F1 AND F2

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Abstract

The National Institute of Standards and Technology operates a cesium fountain primary frequency standard, NIST-F1, which has been contributing to International Atomic Time (TAI) since 1999. During the intervening 11 years, we have improved NIST-F1 so that the uncertainty is currently $\delta f / f_0 \approx 3\times10^{-16}$, dominated by uncertainty in the blackbody-radiation-induced frequency shift. In order to circumvent the uncertainty associated with the blackbody shift, we have built a new fountain, NIST-F2, in which the microwave interrogation region is cryogenic (80 K), reducing the blackbody shift to negligible levels. We briefly describe here the series of improvements to NIST-F1 that have allowed its uncertainty to reach the low 10^{-16} level and present early results from NIST-F2.

1. NIST-F1

Table 1 shows the error budget of NIST-F1 as of the summer of 2001. The type B frequency uncertainty of 1×10^{-15} at that time was the smallest achieved by fountain standards. Table 1 also shows the error budget of NIST-F1 as of Sept 2010. The type B frequency uncertainty of 3.4×10^{-16} defines the 2010 state of the art for frequency uncertainty in fountain frequency standards.

1.1. SPIN EXCHANGE FREQUENCY BIAS

It is apparent, from Table 1, that the frequency uncertainty in 2001 was dominated by the spin exchange shift from collisions between cold cesium atoms. In fact, this shift was predicted to likely be the most "troublesome systematic effect of an atomic fountain" **[1]**. Since that time, several new techniques have been brought to bear on the problem of estimating the spin-exchange shift in fountain frequency standards **[2,3]**. The spin-exchange shift is no longer a dominant problem in the best fountain frequency standards in use today. In Table 1, we show the spin-exchange uncertainty as of 2010 reduced to $\delta f / f_0 = 1.5\times10^{-16}$, much smaller than the frequency uncertainty associated with the blackbody radiation shift and comparable to that associated with microwave effects. This trend is echoed in other cesium frequency standards in various laboratories.

In NIST-F1, we use a traditional extrapolation of the density to evaluate the spin exchange shift, along with a large optical molasses in order to make the density of the sample much smaller than that obtained with the use of a magneto-optic trap (MOT). In addition, we achieve temperatures of about 450 nK in the launched molasses. These low temperatures mean that approximately 80% of the atoms entering the Ramsey cavity for the initial microwave interaction eventually contribute to the signal. This allows significant reductions in the initial density (and, hence, spin-exchange shift) compared to returning atom fractions of 20% that are more typical with 1.5 μK atoms. As a result, we can achieve reasonable shortterm stability, $\sigma_y(\tau) \approx 2\times10^{-13}/\tau^{1/2}$, while keeping the uncertainty in the spin-exchange frequency shift around $\delta f/f_0 = 10^{-16}$.

Table 1. The Type B Uncertainties ($\delta f/f\times10^{-15}$) of NIST-F1 in 2001 and 2010.

Physical Effect	Magnitude	Uncertainty2001	Magnitude	Uncertainty 2010
Second Order Zeeman	44.76	0.3	180.60	0.013
Spin Exchange	0.0	0.84	-0.41	0.15
Blackbody	-20.6	0.3	-22.98	0.28
Gravitation	180.54	0.1	179.95	0.03
Cavity Pulling	<0.1	<0.1	0.02	0.02
Rabi/Ramsey Pulling	<0.1	<0.1	10^{-4}	10^{-4}
Microwave effects	0	0.2	0.026	0.12
Cavity Phase	<0.1	<0.1	0.02	0.02
Light Shift	<0.2	0.2	10^{-5}	10^{-5}
Adjacent Transition	<0.1	<0.1	0.02	0.02
Microwave Spectrum	0	<0.1	0.003	0.003
Integrator Offset	0	<0.1	0	0.01
AM on microwaves	0	<0.1	0	10^{-4}
AC Zeeman (heaters)			0.05	0.05
Total Uncertainty		0.99		0.34

1.2. Blackbody Frequency Bias

As pointed out by Itano **[4]**, the hyperfine splitting of the cesium atom is shifted by the ambient blackbody radiation field. This shift has recently been the subject of some controversy, with several measurements being in disagreement **[5-7]**. The experimental measurements apparently stimulated a great deal of theoretical interest culminating in very high quality calculations of the blackbody frequency bias **[8,9]**. At this point, it seems that the shift is well characterized by

$$\delta\nu/\nu_0 = \beta\left(T/300K\right)^4\left(1+\varepsilon\left(T/300K\right)^2\right),\ \beta = -\left(1.710\pm0.006\right)\times10^{-14},\ \varepsilon=0.014,$$

where T is the blackbody temperature of the environment experienced by the atoms in the fountain. NIST-F1 operates slightly above room temperature at about 47^{o} C and we estimate that the temperature uncertainty of the radiation field is, at most, 1 K, leading to an uncertainty in the frequency bias from this source of $\delta f/f_0 = 2.8\times10^{-16}$. As shown in Table 1, this bias currently dominates the frequency uncertainty of NIST-F1. We note that the calculations referred to above depend on a measured value for the D.C. stark shift and that there have been no direct measurements of the blackbody bias with uncertainties close to the $\delta f/f_0 = 10^{-16}$ level.

1.3. MICROWAVE INDUCED FREQUENCY BIASES

Ramsey interrogation using a TE_{011} cylindrical microwave cavity is universally used in cesium fountain primary frequency standards reporting to TAI. While this interrogation method is robust, it is still quite easy to introduce frequency biases as a result of various microwave effects. These include spurs in the microwave spectrum, microwave radiation leaking outside the microwave cavity, and position-dependent phase shifts within the microwave cavity itself. A glance at the current (in 2010) error budget in Table 1 shows that these microwave effects account for the third largest part of the uncertainty in the fountain. These effects are quite different from those in traditional thermal beam standards. Our group, as well as others, has investigated these effects in fountain-style frequency standards extensively over the past several years **[10-14]**. We briefly review some of the conclusions here.

1.3.1. Distributed Cavity Phase

The phase of the microwave field within the Ramsey cavity of a fountain was first investigated by De Marchi, *et al.* He developed a first-order model of the phase field and explicitly linked the phase variations to losses and power flows within the cavity **[15,16]**. Later, many groups expanded on these results with various full three-dimensional calculations of the phase gradients within the cavities and used these phase gradients to estimate the frequency bias. They assumed the microwave phase shift within the cavity caused a frequency bias given approximately by $\delta\nu/\nu \approx \delta\phi/\phi_{tot} = \delta\phi/2\pi\nu_0 T_R$, where $\delta\phi$ is the phase shift in the microwave field, $\nu_0 = 9.1926$ GHz is the frequency of the hyperfine splitting and T_R is the Ramsey period. This is, however, incorrect. What matters is not the phase variations of the microwave field within the cavity, but the effect on the cesium atom coherent superposition. As we first showed in **[13]** and was later reconfirmed in **[17]**, the frequency bias shows a large dependence on microwave amplitude.

1.3.2. Microwave Leakage

Microwave fields interacting with the cesium atoms outside of the Ramsey interaction zone are a major source of frequency uncertainty in NIST-F1. These interactions can happen in two distinct places: first, atoms can be subjected to a microwave interaction in the drift region above the Ramsey cavity and, second, the phase of the atomic superposition can be altered as well by interactions below the Ramsey cavity in the space between the Ramsey cavity and the detection zone. As detailed in **[12]**, interactions above the Ramsey cavity in NIST-F1 are doubly forbidden by the physical structure of the drift region. The 2.5 cm diameter drift tube is below cutoff for all microwave modes at 9.2 GHz except the dominant TE_{11} mode. The TE_{11} mode does not cause a frequency shift in first order because the azimuthal dependence of the mode averages to zero for a well-centered atomic sample. Also, the drift tube is terminated on both ends and the length is chosen so that the resulting cavity is anti-resonant at 9.2 GHz.

It has been pointed out in **[14]** that if the two Ramsey pulses are, on average, different, then second-order effects can be expected as well. This imbalance can be severe when a MOT is used in a fountain with a traditional "square" (diameter = height) microwave cavity. As a result of the tight MOT confinement and large thermal velocity of the sample, along with the ~20 % variation of the microwave field amplitude over the aperture, the atomic sample "sees" almost the maximum field in the microwave cavity on the way up with as much as a 10% average reduction on the way down. However, with the flattened cavity in NIST-F1, variation in the microwave field over the aperture is reduced by a factor of 2. Because the molasses is both cold ($V_{thermal}$~ 0.5 cm/s) and large (radius ~ 0.5 cm), the two Ramsey excitations differ by less than 1% on average.

These considerations also apply to the use of the cancellation of the spin exchange shift as described in **[3]**. This cancellation is effected by carefully adjusting the amplitude of the first Ramsey interaction so that the frequency shift of the $|3,0\rangle$ and $|4,0\rangle$ components of the wavefunction (which have different signs at sufficiently low interaction energies) cancel. The very low interaction energies required necessitate the use of a MOT with tight confinement in order to introduce position-velocity correlations in the cloud very quickly. The tightly confined atomic sample has a large intrinsic spin-exchange shift. If the cancellation is not perfect, a leakage field complicates the whole picture for two reasons. First, the two passages of the Ramsey cavity have unequal excitation for the reasons detailed above. Second, the leakage field changes the relative amplitude of the $|3,0\rangle$ and $|4,0\rangle$ components, thereby affecting the cancellation of the spin-exchange frequency shift. In this case, the frequency shift caused by a leakage field can be strongly "leveraged" by the spin-exchange shift, with the result that the two effects are difficult to disentangle.

Microwave leakage after the second Ramsey interaction causes a frequency shift that maximizes in a fountain operated at optimum power. The signature of the effect is quite similar to that from distributed cavity phase. In NIST-F1, we combine these two effects in the error budget when we search for evidence of microwave effects by operating above optimum power. These combined effects (distributed cavity phase and leakage after the Ramsey interaction) dominate the uncertainty in the microwave amplitude shift at $\delta\nu/\nu_0 = 1.2\times10^{-16}$.

1.3.3. Microwave Spectrum

As a result of the pulsed operation of fountain standards, along with the possibility of operating well above optimum microwave excitation, spurs reveal rich and complicated features affecting frequency accuracy. We refer here to both incoherent and coherent spurs. Incoherent spurs are those spurs introduced onto the microwave spectrum by, for example, the 60 Hz line frequency: this type of spur generally has random and evolving phase with respect to the fountain cycle time. Coherent spurs are those introduced onto the microwave spectrum by the pulsed operation of the fountain itself. An example is a spur on the microwave spectrum caused by turning off the MOT coils just before launching the atom cloud. Careful study of the microwave spectrum using a spectrum analyzer can provide sufficient knowledge of incoherent spur amplitudes to hopefully eliminate spurs large enough to cause significant frequency errors. As discussed in **[11]**, the magnitude of the frequency shift is difficult to estimate without detailed knowledge of the spur behavior at elevated microwave power. A full discussion of these effects is included in **[11,13]** and the references contained therein.

Coherent spurs can cause frequency shifts far in excess of those predicted by the classical theory of spurs in **[18]**. We have developed in **[13]** a complete theory which agrees well with the experimental results presented there.

2. NIST-F2

We are developing a new fountain standard, named (imaginatively!) NIST-F2. NIST-F2 is designed to incorporate several unique features: cryogenic operation of the Ramsey interrogation region, Low-Velocity Intense-Source (LVIS) loading of cold atomic samples, and multi-pulse operation. In its initial phase, NIST-F2 operates cryogenically. The cold atom loading and the multiple ball operation are not yet implemented.

NIST-F2 is shown schematically in Fig. 1. The source is a pure optical molasses operated in a (1,1,1) geometry. Directly above the source region is a state-selection cavity that is required for multiple ball operation. The detection region, also at room temperature, is between the source region and the cryogenic, magnetically shielded Ramsey interrogation region. The magnetically shielded interrogation region is enclosed in a liquid nitrogen dewar and operates at about 80 K. At these temperatures, the blackbody shift (which is large in NIST-F1) is reduced in magnitude by a factor of about 250. The microwave interrogation and flight-tube region is similar to that of NIST-F1, except the microwave cavities are tuned to be resonant at the cryogenic operating temperature and not at room temperature.

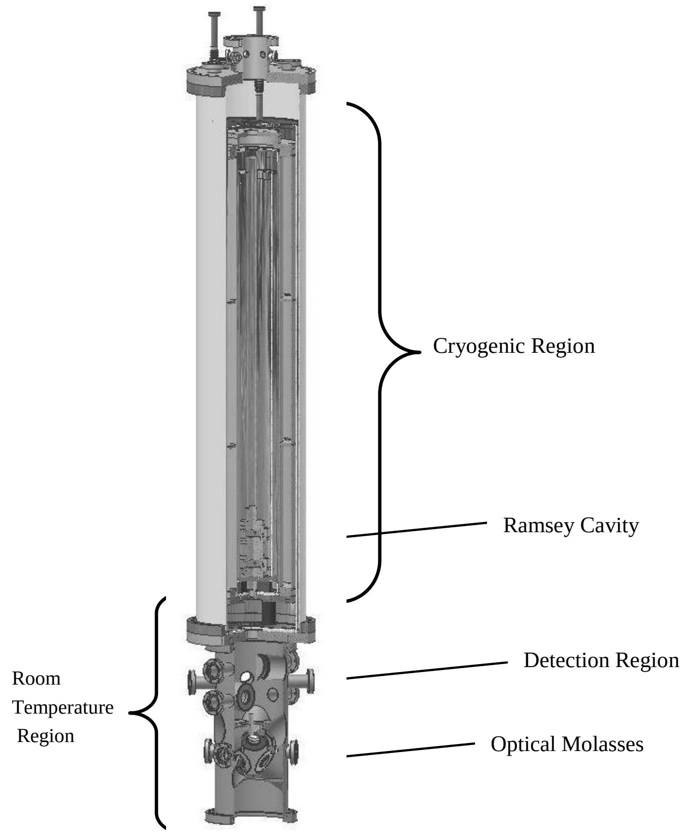

Figure 1. This is a cutaway drawing of NIST-F2 showing the 1,1,1 molasses region, the detection region, and the cryogenic microwave interrogation region. The overall height is about 2.5 m.

NIST-F2 has undergone several preliminary measurement campaigns that show agreement between NIST-F1 and NIST-F2 to better than $\delta\nu/\nu = 1\times10^{-15}$. The frequency of NIST-F2, after correction for the Zeeman shift, spin-exchange shift, microwave amplitude shift, and the Blackbody shift, was accurate at the $\delta\nu/\nu = 10^{-15}$ level, supported by the statistical uncertainty of the limited data set. We are currently embarking on a series of comparisons between NIST-F1 and NIST-F2 before placing NIST-F2 into routine operation.

3. CONCLUSIONS

NIST-F1 is a mature standard and is unlikely to evolve much further. Its total systematic uncertainty around $\delta\nu/\nu = 3\times10^{-16}$ is strongly limited by the $\delta\nu/\nu = 2.8\times10^{-16}$ blackbody uncertainty.

NIST-F2 a cryogenic fountain has recently begun initial operation. This fountain is eventually expected to significantly improve on the current best results (as typified by NIST-F1) with a total uncertainty below $\delta\nu/\nu = 10^{-16}$.

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