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ACCURACY RESULTS FROM NIST-F1 LASER-COOLED CESIUM PRIMARY FREQUENCY STANDARD

S.R. Jefferts, D.M. Meekhof, J.H. Shirley, M. Stepanovic, T.E. Parker
N.I.S.T. - Time and Frequency Division
Boulder, CO. USA

Introduction[1]

Since November of 1998, we have performed six frequency evaluations of NIST-F1. The results from the last two of these evaluations have been reported to the Bureau International des Poids et Mesures (BIPM) for inclusion in TAI. This fountain is presently one of two cesium fountains in the world used in the generation of TAI.

This paper presents an overview of the evaluation process and a brief description of the four systematic biases for which the fountain is corrected. These four biases, blackbody frequency shift, gravitational redshift, second-order Zeeman shift and spin-exchange shift, have reported associated uncertainties of $\delta\nu/\nu \approx 3\times10^{-16}$, 3×10^{-16}, 3×10^{-16}, and 5×10^{-16} respectively. A large list of other possible shifts which have been studied and found to be negligible are discussed in less detail.

Description of the Standard

The NIST fountain standard has been previously described and the reader is directed to [1,2] for further details. Cold cesium atoms are trapped in a pure optical-molasses source region and launched upwards through a detection region. Above the detection region atoms enter a magnetically shielded region in which the atoms are first state-selected so that only $|F,m_f\rangle = |4,0\rangle$ atoms enter the Ramsey microwave cavity. These atoms undergo a two-pulse Ramsey excitation and are then detected upon exiting the magnetically shielded region. The fountain measures the number of atoms in both F=3 and F=4 states, computes the transition probability and adjusts the frequency of the microwave synthesizer to the other side of the Ramsey fringe. The differential probability from the two sides of the central Ramsey fringe then determines the frequency of the central Ramsey fringe.

The microwaves are generated by a NIST-designed cesium microwave synthesizer [3]. The laser used in the trapping and detection is a tapered optical amplifier pumped by an extended cavity diode laser at 852 nm tuned to the $4\rightarrow5'$ transition. The repump radiation, tuned on the $F=3\rightarrow4'$ transition (also at 852nm), is generated by a 10 mW DBR laser.

Corrected Systematic Biases

The standard is corrected for four systematic biases, which are discussed below. A large list of other biases have been determined to be less than $\delta\nu/\nu = 10^{-16}$ and will not be extensively discussed. The interested reader is referred to [4]. These uncorrected biases are: first order Doppler shift, distributed cavity phase shift, Ramsey Pulling, Rabi Pulling, Majoranna transitions, microwave leakage, spectral impurities, and electronic biases and resonant light shift effects.

Blackbody Shift

This cesium fountain is temperature controlled at 41C. The temperature control is applied to the Ramsey cavity and flight-tube region which is an essentially monolithic structure constructed of oxygen-free high-conductivity copper. As a result of this method of construction and the careful temperature control, gradients are much less than 1 °C. An optical window at a temperature of about 33 °C subtends a small solid angle of the atoms surroundings at apogee of less than 5×10^{-5} sr. The window is anti-reflection coated for 852 nm and is relatively black in the deep IR. Radiation from this window represents the dominant uncertainty in the thermal radiation within the standard. This uncertainty is conservatively estimated at 1 °C resulting in an uncertainty of the blackbody shift of 3×10^{-16}.

Second Order Zeeman Frequency Shift

The C-field in NIST-F1 is typically set at about 0.1 μT, resulting in a fractional frequency shift of the clock ($|3,0\rangle\rightarrow|4,0\rangle$) transition of approximately 5×10^{-14}. Uncertainties in this transition can be considered to result from three main effects: uncertainty of the average value of the magnetic field, temporal instability of the field and an effect related to the magnetic field inhomogeneity.

The average value of the magnetic field over the atom trajectory is measured by first making a field map using the atoms as a magnetic field probe. This is done with a low frequency (~350 Hz) magnetic field transverse to the C-field which is imposed upon the atoms at apogee [5]. When the frequency of the field is correct, the atoms make a $\Delta m=1$ transition. The magnetic field at the location of the atoms is typically measured to less than 100 pT with this technique. The atom launch velocity is then varied so that the apogee position is a few cm higher and the measurement repeated. A field map constructed in this manner is then used to predict the location of the central fringe of the $|3,1\rangle \rightarrow |4,1\rangle$ Ramsey pattern. The agreement is typically excellent as shown in Fig.1. This measures the average of the magnetic field over the atomic trajectory.

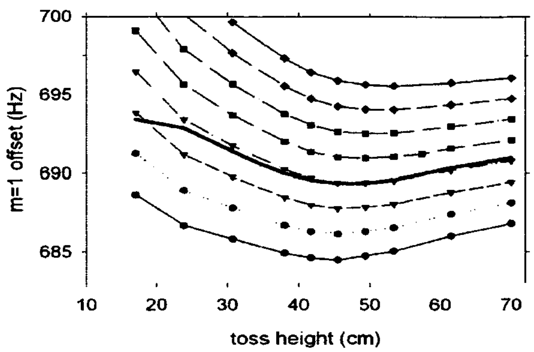

Figure 1 - The curves drawn through symbols are the positions of various Ramsey fringes in the m=1 Ramsey manifold as a function of height. The horizontal axis is distance above the Ramsey cavity. The dark line overlaying the 4th curve from the bottom of the graph is the location of the central Ramsey fringe as predicted from the magnetic field map. The disagreement at short distances above the Ramsey cavity is due to a lack of information about the magnetic field in the below-cutoff waveguide directly above the Ramsey cavity.

The temporal stability of the field can be addressed by locking the fountain to the $|3,1\rangle \rightarrow |4,1\rangle$ transition over an extended period and observing the measured frequency fluctuations. As can be seen in Fig. 2, there is a strong diurnal fluctuation of the magnetic field when this is done. This diurnal fluctuation causes a fractional frequency fluctuation of the clock transition of order 10^{-17} and is ignored at present, although this can be corrected with relative ease.

The C-field in NIST-F1 is only modestly homogenous as can be seen in Fig. 1. This inhomogeneity causes the average of the magnetic field squared to deviate from the square of the average with a small resulting frequency shift. Analysis of this effect for the present C-Field homogeneity shows that this effect is at most of order 10^{-17} and is uncorrected.

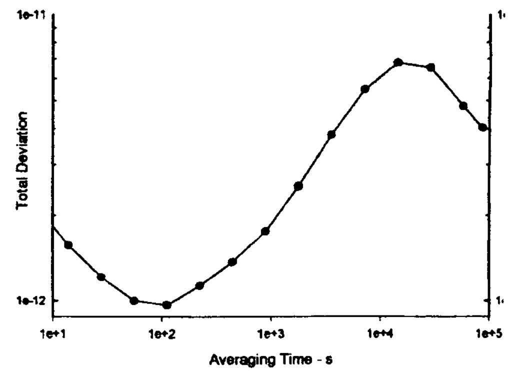

Figure 2 - The stability of NIST-F1 when locked to the m=1 magnetic field sensitive line. The "hump" at about ½ day is thought to be the sun magnetic cycle, although it could be another environmental effect

The uncertainty in the correction for the second-order Zeeman effect frequency bias is therefore dominated by the measurement of the magnetic field over the trajectory. The assigned uncertainty corresponds to one full fringe of mis-assignment (considered highly unlikely) and results in fractional frequency uncertainty of 3×10^{-16}.

Gravitational Redshift

The altitude in Boulder, Colorado makes the gravitational redshift the largest correction to NIST-F1. Work by Weiss et al.[6] has recently reduced the uncertainty in this frequency bias to $\delta\nu/\nu \approx 1\times10^{-16}$. This bias is simply a result of geography and not (properly speaking) a clock bias.

Spin-Exchange Frequency Shift

This frequency bias represents the largest contribution to the NIST-F1 uncertainty budget and dominates the uncertainty of all cesium fountains reported to date.

The evaluations described at the beginning of this paper rely on an *interpolation* of the atomic density over the flight time, as opposed to an extrapolation of the density such as that reported in [7].

The spin-exchange shift has been measured by two different groups[7,8] to be $\delta\nu \approx 2\times10^{-21}\rho$, where ρ is the average atomic density over the atomic flight time. The LPTF group has very recently repudiated their measurement of the above value [9]. As a result, we have recently begun an independent measurement of the above shift. Preliminary results indicate that our previous estimates of this shift were, in fact, correct within their stated uncertainties. This measurement is in progress at the moment and more complete results will be presented at a later date.

Measurement of the average atomic density requires knowledge of the absolute number of atoms, the spatial distribution of the atoms within the sample as well as the velocity distribution of those atoms. We measure the total number of launched atoms as well as the spatial distribution in the vertical direction by operating the atom detection region when the atom cloud passes through it on the way up. A measurement of the atomic sample on the way down ($\sim$1 s after launch), along with the measurement of the cloud on the way up, gives the velocity distribution along the vertical direction as well as the average radial speed of the atoms. The position distribution is assumed to be Gaussian in the horizontal plane (a direct measurement of the distribution along the vertical tends to support this). The measured velocity distribution along the vertical is reasonably Gaussian, and that velocity distribution is used in the radial direction as well, adjusting the Gaussian for the measured average radial speed. The LPTF group measured velocity distributions other than Gaussian, leading to relatively large errors in their density extrapolation when Gaussian velocity distributions were used[9]. We note here that our measurement is much less sensitive to this effect, as the density is interpolated rather than extrapolated.

Once the average density has been determined, the frequency shift of the measurement is obtained by multiplication of the average density (in cm^{-3}) by the measured coefficient of 2×10^{-21} (for atoms in m=0). As a result of the recent uncertainty in the previous measurements of this coefficient, we have now begun measurements of the frequency shift as a function of atomic density. Preliminary results are in rough agreement with frequency shifts estimated using the techniques just discussed.

Uncorrected Systematic Biases

As a result of the long Ramsey times in fountain standards as opposed to those in thermal beam standards (1s vs. 10 ms), many systematic biases which cause significant shifts in thermal beam standards are reduced to insignificant levels in fountain standards. The biases listed in this section all have frequency shifts of less than $\delta\nu/\nu = 1\times10^{-16}$.

Ramsey and Rabi pulling as well as Majoranna pulling are reduced well below this level in this standard as a result of state selection within the magnetic shield.

Distributed cavity phase shifts, both transverse and longitudinal, have been minimized by careful cavity design. Frequency shifts associated with these effects are predicted to be well below $\delta\nu/\nu\approx1\times10^{-16}$.

Microwave leakage is studied by simply running the standard at much higher than normal power, with Rabi frequencies up to 17 times the normal $\pi/2$ pulse. These tests reveal no microwave leakage with a sensitivity of less than $\delta\nu/\nu\approx3\times10^{-16}$. This measurement also tests for microwave synthesizer spectral impurities leading to frequency shifts.

Second-order cavity pulling, proportional to the square of the ratio of the cavity Q to the atomic Q is predicted to produce a worst-case frequency shift well below $\delta\nu/\nu\approx10^{-16}$. Frequency shifts associated with first order cavity pulling, caused by atomic back-reaction within the cavity is smaller than 10^{-17} at the atomic densities used for evaluations in this fountain.

Other possible frequency biases, including servo biases, second-order Doppler effects, resonant light shifts, etc, are discussed in reference [4].

Frequency Stability

The frequency stability in NIST-F1 is limited by the quartz crystal performance to about $\sigma_y(\tau) = 7\times10^{-13}\ \tau^{-1/2}$. This limit is much higher than the intrinsic limit set by the achievable atomic shot noise limit of about $1\times10^{-13}\ \tau^{-1/2}$. Lower noise quartz oscillators have been ordered and should allow us to improve stabilities to the 10^{-13} level. A byproduct of the relatively high Allan deviation is that we are able to lower the number of launched atoms dramatically with out an increase in the stability, when operating the standard, thus reducing the magnitude of the spin-exchange shift.

Conclusions

The error budget for NIST-F1, as reported to the B.I.P.M. is shown in Table 1. As a result of recent controversy regarding the magnitude of the spin-exchange frequency shift, we are presently re-determining the shift locally. This determination should be completed by September of 2000. The error budget presented in Table 1, while representative, is data from a single frequency evaluation cycle and it should be realized that the values reported in the table change from run to run.

Table 1 - A typical evaluation error budget

Physical Effect	Bias Magnitude $(\times 10^{-15})$	Type B Uncertainty $(\times 10^{-15})$
Second Order Zeeman	+45.0	0.3
Second Order Doppler	<0.1	<0.1
Cavity Pulling	<0.1	<0.1
Rabi Pulling	<0.1	<0.1
Ramsey Pulling	<0.1	<0.1
Cavity Phase (distributed)	<0.1	<0.1
Cavity Phase (end-to-end)	Not Applicable	
Fluorescent Light Shift	<0.1	<0.1
Adjacent Atomic Transitions	<0.1	<0.1
Spin Exchange	-0.9	0.5
Blackbody	-20.6	0.3
Gravitation	+180.54	0.3
Electronic Shifts		
R.F. Spectral Purity	0	<0.1
Integrator Offset	0	<0.1
A.M. on microwaves	0	<0.1
Microwave leakage	0	0.2
Total Type B Uncertainty		0.8

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