RECENT IMPROVEMENTS IN NIST-F1 AND RESULTING ACCURACIES OF $\delta f/f<7\times 10^{-16}$ †

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Abstract

Since our last publication describing the accuracy budget for NIST-F1 (a laser-cooled Cs fountain primary frequency standard) we have made many improvements resulting in nearly a factor of 2 reduction in the uncertainty in the realization of the SI second. Recently we reported a combined standard fractional uncertainty of 0.67×10^{-15}.

Introduction

In the last several years since the publication of Ref. [1], which described the physics package, evaluation procedure, and the accuracy budget for NIST-F1, we have made a number of improvements. These have resulted in uncertainties that are smaller by nearly a factor of 2 and greater reliability. We now routinely produce frequency evaluations of NIST-F1 with combined standard uncertainties below 1×10^{-15}. A review of the error budget in [1] shows the three major contributors to the final systematic type B uncertainties were the spin-exchange shift, the second-order Zeeman shift and the Blackbody shift. While the uncertainties due to these three have decreased, most notably the spin-exchange shift, they are still dominant. However, other shifts, once considered minor, are now significant contributors to the error budget.

Improvements in NIST-F1

We have incorporated a commercial laser system to generate the 852 nm light used for the optical molasses and detection. This system uses a 10 W green diode laser system to pump a Titanium:Sapphire ring laser which produces about 1 W of 852 nm light. The primary advantage of this commercial system over the previous in-house built system is reliability. Loss of laser lock is now a rare event, occurring approximately once a month. This has allowed us to run the Cs fountain essentially uninterrupted for long stretches thus increasing our "live time". Live time is a measure of fountain reliability and is the percentage of time during an evaluation that useful data is collected. Consequently, this has reduced the statistical uncertainty (Type A) due to total measurement time as well as reduced the dead time in the comparison with our hydrogen maser reference.

Laser light is now delivered to the physics package via optical fiber cables so there is no longer a source of resonant laser light which is on continuously near the physics package. This further reduces the possibility of light shifts. Also, use of fiber optic cables simplifies the alignment and maintenance of the optical table. This has also increased our live time.

The detection system as reported in Ref. [1] has been improved. The original vacuum windows that allow laser light into to the physics package for detection and re-pumping have been replaced with windows with superior optical coatings thus reducing the level of scattered light into the collection optics and detectors. NIST-F1 now reaches the quantum projection noise limit at ~500 atoms.

The detection light power is also now servo controlled which has reduced AM noise in the laser light probe and reduced long term drift. This servo controlled detection system allows us to closely monitor and control the total number of atoms returning to the detection system (since atom number is proportional to the fluorescence). A second servo controls the power of the microwaves entering the state-selection cavity to fix the total detected atom number to a set point. Potential drawbacks with this scheme were pointed out in Ref. [2]. Of concern is the possibility of variations in the atomic distribution due to changes in applied microwave power in the state-selection cavity. Measurements discussed in [1] show that we see no evidence of this in our fountain. This is partly due to the aspect ratio of the multi-feed microwave cavity design used in our fountain; it is relatively short in the axial dimension and has a large radius. This reduces field variations across the cavity apertures. We are able to control the atom number for long periods of time despite small changes in Cs vapor pressure, cooling beam power and polarization, etc.

The implementation of the new laser system with higher power allows for larger diameter horizontal cooling beams than described in [1]. (The size of the vertical beams is fixed by the aperture in the microwave cavities since we employ the (0,0,1) beam geometry.) Thus our optical molasses is physically larger and we operate at about half of the former atomic density using the same atom number for stability.

New monitor and alarm systems, while simple, have been important. An alarm system allows us to quickly detect problems and bring the fountain back on line thus increasing fractional run time.

Spin-Exchange Shift

We evaluate the spin-exchange shift by operating the fountain alternately between low and high atomic densities (a factor of ≈6 between low and high densities). The zero density intercept of a linear least-squares fit yields the unbiased clock frequency. The improvements outlined above have aided twofold. First, the reduction in the statistical uncertainty results in a better fit to the spin-exchange shift data. Second, since the optical molasses is larger, we can operate at the same clock stability with a smaller spin-exchange shift. We operate our fountain ~60% of the run time at low density where the spin-exchange shift is less than 0.5×10^{-15}.

Second-Order Zeeman Shift

Evaluation of the second order Zeeman shift involves mapping the magnetic field along the atomic trajectory within the fountain. As described in [1] the type B uncertainty was 0.3×10^{-15}. Since then, we have made improvements in the uniformity of the magnetic field using shim coils and have more thoroughly mapped the field. Additionally, we have investigated a new field mapping technique [3] using continuous Majorana excitation along the atomic trajectory. As a result of these improvements, the type B uncertainty in the second-order Zeeman shift has decreased to 0.10×10^{-15}.

Blackbody Shift

The blackbody shift uncertainty has been reduced slightly by the recent addition of more accurate temperature sensing instrumentation within the drift tube region of the physics package. The type B uncertainty in the Blackbody shift is now reported to be 0.26×10^{-15}, which represents a 1° C uncertainty in the temperature of the radiation field seen by the atoms in the interrogation region.

Error Budget

Table 1 compares the results of two typical formal evaluations of NIST-F1. The first occurred during June and July of 2001 and the results were used for the discussions in Ref. [1]. The second is from a recent formal evaluation during November and December of 2003. The combined type A and B uncertainty has been reduced by nearly a factor of 2. Generally, in the 2001 time frame, we managed live times of about 65%. Presently, we achieve about 85%-90%, limited mainly by scheduled shutdowns to change operating parameters. Less dramatic is the change in the final uncertainties in the number which is submitted to the BIPM. This is the result of uncertainties in the time transfer techniques.

Conclusion

While the three leading uncertainties (the spin-exchange shift, the second-order Zeeman shift, the Blackbody shift) have been reduced, there are many other shifts that are beginning to have similar weight. For example, during our formal evaluations we perform leverage measurements of microwave leakage. In the Nov.-Dec. 2003 evaluation, the type B uncertainty in the microwave power shift was 0.18×10^{-15} and is now a major item in the error budget.

Table 1: The Comparison of Two Formal Evaluations of NIST-F1.

FRACTIONAL UNCERTAINTIES	JUNE-JULY 2001 EVALUATION	NOV.-DEC. 2003 EVALUATION
Type A	0.86×10^{-15}	0.50×10^{-15}
Type B	0.99×10^{-15}	0.44×10^{-15}
Combined A and B	1.31×10^{-15}	0.67×10^{-15}
Time Transfer and Dead Time	1.03×10^{-15}	1.02×10^{-15}
Final Uncertainty Reported to BIPM	1.67×10^{-15}	1.22×10^{-15}

References

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