# Comparing Room Temperature and Cryogenic Cesium Fountains

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***Abstract*—We have compared the frequency of a room-temperature cesium-fountain primary frequency standard with that of a cryogenic (~80K) cesium fountain. This comparison yields a measurement of the blackbody frequency shift of the room-temperature fountain.**

## I. Introduction

NIST-F1 is a well characterized cesium-fountain primary fractional frequency standard with frequency inaccuracy at the $\delta f/f \sim 4\times10^{-16}$ level. This inaccuracy is dominated by the uncertainty in the blackbody correction of about $\delta f/f \sim 3\times10^{-16}$. NIST-F2 and IT-CsF2 are cryogenic (80K) cesium-fountain frequency standards coming into operation at the National Institute of Standards and Technology (NIST) in Boulder, CO and at Istituto Nazionale di Ricerca Metrologica (INRIM) in Torino, Italy. Frequency comparisons among these fountains yield a measurement of the blackbody shift

## II. Room Temperature Fountains

### A. NIST-F1

NIST-F1 is the US primary frequency standard and has been previously described in great detail [1],[2],[3]. Thus we will give only a cursory overview of the salient points regarding its performance and uncertainties.



### B. Error Budget

An abbreviated error budget for NIST-F1 is shown in Table 1. It can be seen that the overall uncertainty of the standard is dominated by the $\delta f/f \sim 2.8\times10^{-16}$ fractional uncertainty in the blackbody shift. This uncertainty corresponds to a 1 K uncertainty in the effective radiation temperature of the standard, and is the uncertainty that the cryogenic fountains are designed to effectively eliminate. A comparison of the room temperature fountains with the cryogenic fountains combines the systematic errors in the fountains in ways that require individual treatment of these systematic uncertainties: an obvious example is the gravitational shift that largely cancels for both clocks with the uncertainty in the shift dropping from $\delta f/f \sim 3\times10^{-17}$ to $\delta f/f \sim 1\times10^{-18}$.

## III. Cryogenic Fountains

### A. NIST-F2 and INRIM CsF-2

The NIST and INRIM cryogenic fountains are similar in that the design of the Physics package is essentially identical. Details of the optical systems and control electronics are however idiosyncratic to each particular fountain. The physics package has been described previously and only a short review is given here [4],[5].

The fountains operate on a pure optical-molasses atom-loading scheme (no MOT), with the beam geometry being (1,1,1) (crystallographic notation that defines the beam geometry). The atoms are launched upwards at about 4.5 m/s and post-cooled in the moving frame to temperatures around 500 nK. The atoms fly upward through the room-temperature vacuum system before entering the magnetically shielded cryogenic region. In the cryogenic region the atoms are state-selected and Ramsey interrogation takes place. The microwave structure is essentially identical to that of NIST-F1 [1],[2],[3] with the exception that the microwave cavities are tuned to resonance at 80 K instead of 318 K (NIST-F1) or 340 K (IT CsF-1). Detection takes place at room temperature after the atoms have left the magnetically shielded cryogenic region. The detection region is very similar to that used in NIST-F1, and was specifically designed to minimize vignetting, with the modeled detection efficiency being uniform over the entire cloud and vignetting being less than 10 %.

TABLE I. NIST-F1 ERROR BUDGET – BIASES AND UNCERTAINTIES ARE GIVEN IN UNITS OF $\delta f/f = 10^{-15}$. THIS IS CURRENT AS OF MARCH 2011.

| Physical Effect | Bias | Type B Uncertainty |
|---|---|---|
| **Gravitational Red shift** | +179.95 | 0.03 |
| **Second-Order Zeeman** | +180.25 | 0.01 |
| **Blackbody** | -22.98 | 0.28 |
| **Microwave Effects** | -0.026 | 0.12 |
| **Spin Exchange (density =8)** | 0.0 (-0.56) | 0.06 (0.16) |
| **AC Zeeman (heaters)** | 0.05 | 0.05 |
| **Cavity Pulling** | 0.02 | 0.02 |
| **Rabi Pulling** | $10^{-4}$ | $10^{-4}$ |
| **Ramsey Pulling** | $10^{-4}$ | $10^{-4}$ |
| **Majorana Transitions** | 0.02 | 0.02 |
| **Fluorescence Light Shift** | $10^{-5}$ | $10^{-5}$ |
| **Second-Order Doppler** | 0.02 | 0.02 |
| **DC Stark Effect** | 0.02 | 0.02 |
| **Background Gas Collisions** | $10^{-3}$ | $10^{-3}$ |
| **Bloch-Siegert** | $10^{-4}$ | $10^{-4}$ |
| **RF Spectral purity** | $3x10^{-3}$ | $3x10^{-3}$ |
| **Integrator offset** | 0 | 0.01 |
| Total Type B Standard Uncertainty (including Spin Exchange) | | 0.30 (0.34) |

## B. *Error Budget – NIST-F2 & IT CSF-2*

An abbreviated error budget for NIST-F2 is shown in Table 2. This is a preliminary error budget and several systematic shifts, notably systematic frequency shifts associated with microwave effects (eg. microwave leakage, distributed cavity phase, microwave spurious signals etc) are not yet completely evaluated. The entries in the error budgets generally reflect our most pessimistic measurements and estimates and are usually limited by statistical uncertainties in those measurements. At this time the error budget for INRIM IT-CsF-2 is similar to that for NIST-F2.

TABLE II. NIST-F2 ERROR BUDGET – BIASES AND UNCERTAINTIES ARE GIVEN IN UNITS OF $\delta f/f = 10^{-15}$. THIS IS CURRENT AS OF MARCH 2011.

| Physical Effect | Bias | Type B Uncertainty |
|---|---|---|
| **Gravitational Red shift** | +179.15 | 0.03 |
| **Second-Order Zeeman** | +287.178 | 0.03 |
| **Blackbody** | -0.096 | 0.005 |
| **Microwave Effects** | -0.0025 | 0.27 |
| **Spin Exchange (density =10)** | 0.0 (0.07) | 0.01 (0 .24) |
| **Cavity Pulling** | 0.02 | 0.02 |
| **Rabi Pulling** | $10^{-4}$ | $10^{-4}$ |
| **Ramsey Pulling** | $10^{-4}$ | $10^{-4}$ |
| **Majorana Transitions** | 0.02 | 0.02 |
| **Fluorescence Light Shift** | $10^{-5}$ | $10^{-5}$ |
| **Second-Order Doppler** | 0.00 | 0.01 |
| **DC Stark Effect** | 0.02 | 0.02 |
| **Background Gas Collisions** | $10^{-3}$ | $10^{-3}$ |
| **Bloch-Siegert** | $10^{-4}$ | $10^{-4}$ |
| **RF Spectral purity** | $3x10^{-3}$ | $3x10^{-3}$ |
| **Integrator offset** | 0 | 0.01 |
| Total Type B Standard Uncertainty (Including Spin Exchange) | | 0.28 0.36 |

## IV. BLACKBODY SHIFT MEASUREMENT

Three measurement campaigns using NIST-F1 and NIST-F2 have been completed. These campaigns (in Sept 2010, Dec 2010 and March 2011) after appropriate data processing yield a measurement of the blackbody shift in NIST-F1. In the course of a measurement, NIST-F1 and NIST-F2 are run concurrently. Each fountain is corrected for systematic frequency shifts associated with the Zeeman effect, spin-exchange collisions, and differential gravitational effects. The frequency difference between the two fountains is then compared to the frequency difference calculated for the differing blackbody shifts in NIST-F1 and NIST-

F2. That comparison yields a measurement of the blackbody shift in NIST-F1.

Preliminary results from comparison of the NIST fountains suggests that the difference between the blackbody shift as predicted by theoretical calculations [6] and the measured blackbody shift is well within the experimental uncertainties ($\delta f/f \sim 5\text{-}7*10^{-16}$) of the comparison.

Further measurements are underway and full results will be published in a forthcoming paper.

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