

NIST-7, THE U.S. PRIMARY FREQUENCY STANDARD: NEW EVALUATION TECHNIQUES*

R. E. Drullinger, J. H. Shirley, and W. D. Lee
National Institute of Standards and Technology
325 Broadway, Boulder, Colorado 80303, USA

Abstract

Primary frequency standards achieve their accuracy by direct reference to the definition of the second and evaluation of all known sources of systematic error that may perturb the measured resonance in the atom. NIST-7, the U.S. primary frequency standard, is a thermal, atomic-beam machine that uses optical pumping for atomic state preparation and detection, and digital frequency control. This technology enables the new evaluation techniques described here. All known systematic effects are determined by means of experiments not involving, or limited by, precision frequency measurements. This both speeds the evaluation and reduces the combined standard uncertainty. Its present value is $5 \cdot 10^{-15}$ for NIST-7.

INTRODUCTION

The second is defined to be "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom."^[1] It is left entirely to the individual primary standards laboratories to build and operate devices that realize this definition. Since it is impossible to build an apparatus without biases (there are electric and magnetic fields, relativistic effects, instrumental effects, etc.), standards laboratories must devise techniques to deal with them. They have been doing so throughout 45 years of advancing technology. Increasingly sophisticated techniques have been developed to evaluate these inevitable perturbations.

Past technology has been reviewed in [2]. The present U.S. primary frequency standard, NIST-7, uses a transitional technology. Like its predecessors, it uses a beam of atoms moving with thermal velocities, with all of the attendant shifts and limits associated with that motion. However, it differs from the conventional thermal beam standard in that it uses optical pumping for the required initial atomic state preparation and subsequent detection. (See [3,4] for reviews of this technology and its implementation in NIST-7.) It also uses a digital servo system for frequency agile synthesis of the microwave radiation. These changes have allowed the development of powerful tools for the evaluation of the biases to the measured atomic resonance. These tools have led to a reduced uncertainty in the operating frequency of the standard. The rest of this paper outlines this new evaluation and the results we have achieved to date.

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TRADITIONAL EVALUATION

Every conceivable frequency-biasing effect in a primary standard must be evaluated to a level that is small compared to the desired overall accuracy. The long list of biases that must be evaluated contains effects that cause shifts ranging from parts in 10^{10} down to parts in 10^{15} and less. In traditional evaluations, the comparatively large frequency bias from the second-order Zeeman effect is evaluated in a highly leveraged way by measuring the first-order Zeeman splittings and then calculating the much smaller second-order shift. Similarly, the second-order Doppler effect is evaluated by measuring the atomic velocity and then modeling the very small relativistic shift. However, the accepted technique for evaluating numerous small frequency bias terms has been to observe the dependence of the standard's frequency on some operating parameter.^[5] Examples are the magnetic field inhomogeneity, line overlap shifts, and various imperfections in the electronics.

This process involves measuring the frequency of the standard against a stable reference, then varying an operating parameter such as microwave power or magnetic field followed by another long, precise frequency measurement. The measured frequency difference F is given by

$$F = \nu_{cs} - \nu_{ref} + \sum_i b_i \pm \sigma_F, \quad (1)$$

where ν_{cs} is the frequency of the unperturbed cesium hyperfine resonance, ν_{ref} is the frequency of the reference, and b_i are all known frequency biases. The type A uncertainty^[6] in the measurement is σ_F , imposed by the averaged measurement noise. ν_{ref} is assumed to be constant over the measurement period. This representation reveals the limits to an evaluation that is based upon measuring the parametric dependence of the standard's frequency. First, the bias of interest may not vary strongly with the operating parameter. Second, many biases may change with the same operating parameter obscuring the significance of the measurement. Finally, the uncertainties of the biases are limited by the measurement uncertainty σ_F . There are also concerns regarding how best to combine the individual uncertainties for the overall error budget due to significant correlations between biases.

NEW EVALUATION TOOLS

Traditionally, second-order Zeeman and Doppler biases have been evaluated by measuring a different parameter (first-order Zeeman shift and atomic velocity) which is much more sensitive to the fundamental biasing mechanism. These measurements are then used to calculate the impact on the standard's frequency through a physical model. Using NIST-7, with its optical pumping and digital servo system, we have been able to extend this philosophy to all of the known sources of frequency bias. Some of the techniques have already been published and are cited here. The details of others are being prepared for future publication. For space reasons, we mention only briefly some of the frequency shifts and the techniques we use to evaluate them.

Shifts resulting from the magnetic field inhomogeneity, cavity pulling, and overlap of neighboring Zeeman lines are evaluated by measuring the offset of each Ramsey fringe from its corresponding Rabi pedestal in the Zeeman spectrum. These shifts are relatively large and are easily measured. ($\Delta y \approx 10^{-9}$ to 10^{-10} , where y is fractional frequency.) With suitable models, these measured frequency offsets enable us to calculate shifts in the clock transition that are very small ($\Delta y \approx 10^{-15}$ to 10^{-17} ^[7]). Fluorescence light shift is quantitatively amplified by changing the optical pumping

transition and laser geometry. Similarly, distributed cavity phase shift is investigated by using movable beam masks placed in front of the cavity beam windows to measure both the atomic beam illumination of the cavity as well as the frequency shift as a function of beam alignment.

To ensure control over microwave phase shifts, the atoms must experience the microwave field only within the microwave cavity. Microwave radiation leaking into the drift regions between the state preparation and detection zones must be low enough that its contribution to the transition probability is small compared to the degree to which the atomic line will be split. Radiation leaking from microwave components is located using a heterodyne detector^[9], much as helium and a mass spectrometer are used to search for leaks in a vacuum system.

Spectral impurities in the microwave radiation used to interrogate the clock transition can lead to line asymmetry and pulling effects.^[9] We have investigated the spectral purity of our RF source by heterodyning it against a similar source. We have analyzed it for correlated AM and PM that would introduce unbalanced sidebands.^[10] We find that frequency errors due to spectral impurities in our source are much less than one part in 10^{16} .

Other nonideal behavior in the electronics can lead to shifts in the measured line position. Electromagnetic interference in the servo electronics can result in biases to the main servo integrator. Most of the error-causing signal paths do not appear on a block diagram of the system and are very difficult to anticipate in paper studies of the servo system. As an example of this type of error, we find a bias equivalent to two parts in 10^{15} from the synchronous operation of the CRT monitor of the main servo computer. Errors of this type are investigated by using the digital demodulator and a modified software integrator in the absence of the actual clock signal. The averaged output of the demodulator then reveals any biases. The advantage in this class of experiments comes when the experiment is configured so the noise relative to the signal being investigated is reduced compared to normal operation. Amplitude modulation on the laser or microwave source that is synchronous with the main frequency servo is measured using a power detector driving the servo demodulator and integrator. Synchronous FM on the laser is studied by measuring laser-induced fluorescence just in front of the oven. Here, the atomic beam is much more intense and has lower relative shot noise. Various signal cross-talk pathways within the servo electronics are identified by simply blocking the atomic signal from the clock.

In addition to this set of evaluation tools for the known sources of bias, we do a number of additional experiments to verify our results. Our evaluation tools are model-dependent. Experimental verifications of the models have been performed. In addition, independent techniques have been used to evaluate several biases. Parametric tests like those done in traditional evaluations have been performed as a broad test of our methods. Examples are the frequency of the standard as a function of microwave power or magnetic field. These experiments involve modeling the simultaneous change of several biases. While not useful as direct evaluation tools, they are powerful search techniques for overlooked effects. A more detailed discussion of these experiments will be published soon.

DATA REDUCTION

Using the techniques just outlined, we are able to determine the known biases except end-to-end phase shift with uncertainties that are small compared to the normal type A uncertainty of the frequency measurements. Subtracting all these biases from the measured frequency, we are left with a reduced difference frequency:

$$f = \nu_{\text{cs}} - \nu_{\text{ref}} + V\phi + \delta f. \quad (2)$$

Here, $V\phi$ is the frequency bias resulting from the effective, end-to-end phase difference ϕ and δf is the measurement error due to noise. The coefficient V equals $1/2\pi T$ for a single atomic velocity, where T is the transit time for an atom to cross the drift region between the two excitation regions. For a distribution of velocities, V is the ratio of two velocity integrals whose integrands depend on microwave power and modulation amplitude. The effective phase difference ϕ is constant if atomic trajectories are stable (constant distributed cavity phases) and microwave leakage is eliminated.

When the atomic beam is reversed and we again remove the known biases from our measured frequency, we obtain a reduced difference frequency:

$$f' = \nu_{\text{cs}} - \nu_{\text{ref}} - V'\phi + \delta f'. \quad (3)$$

The sign of the phase difference has reversed and the measurement error $\delta f'$ is uncorrelated with δf . V and V' differ slightly because different oven temperatures and beam alignments in the two directions lead to differing velocity distributions. From Eqs. 2 and 3 we can extract the phase shift ϕ with an uncertainty limited by that of the difference:

$$f - f' = (V + V')\phi + \delta f - \delta f'. \quad (4)$$

We obtain values of ϕ with each evaluation, so we can test its stability over long times. No significant change has been observed in the last 3 years.

If we combine Eqs. 2 and 3 in a weighted average, we eliminate the end-to-end phase shift bias:

$$\bar{f} \equiv (V'f + Vf')/(V + V') = \nu_{\text{cs}} - \nu_{\text{ref}} + (V'\delta f + V\delta f')/(V + V'). \quad (5)$$

The cancelling of the phase-shift bias depends only on the accuracy of V and V' , not on the uncertainties δf and $\delta f'$. Further, the type A uncertainty in \bar{f} is less than the uncertainty of either f or f' alone. We have subtracted the known biases and weighted the combination using the known differences in velocity distribution and microwave power for the frequency measurements in two beam directions. We are then able to combine the measurements as if they had been a single run twice as long. This process can be extended to combine reduced frequency differences from several beam reversals.

RESULTS

Figure 1 is a plot of the frequency difference between NIST-7 and the hydrogen maser (M2) we have been using as our reference. The error bars represent the combined standard uncertainty. Independent comparisons between this maser and other masers, UTC(NIST), and TAI show it to be remarkably stable and characterized by a linear frequency drift. In this plot, all of the known systematic frequency shifts to the cesium resonance have been removed. Thus, the data represent the frequency difference between the unperturbed cesium resonance and the maser. The data indicate that the maser exhibits a linear fractional frequency drift rate of

$+7 \cdot 10^{-17}$ /day. A residual scatter of $2 \cdot 10^{-15}$ about the linear fit is consistent with the type A uncertainty of the individual frequency measurements.

The results of an evaluation are summarized in Table 1. We can now evaluate every known bias term with a fractional frequency uncertainty no more than $\approx 2 \cdot 10^{-15}$ and often much less. However, biases for fluorescence light shift and distributed cavity phase shift have not yet been experimentally verified to this level.

CONCLUSION

We have developed a set of evaluation tools and techniques that allow all known systematic effects to be evaluated through experiments that are not limited by precise frequency measurements. This speeds the overall evaluation process and leads to improved independence of the various bias terms and a smaller uncertainty in their value. The present combined standard uncertainty for NIST-7 is $5 \cdot 10^{-15}$.

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Table 1. Evaluation Results

Physical Effect	Bias ($\cdot 10^{-15}$)	Uncertainty ($\cdot 10^{-15}$)
Second-order Doppler	≈ -300	1
Second-order Zeeman	$+10^5$	0.1
Cavity pulling	-5	1
Rabi pulling	≤ 0.1	0.1
Cavity phase (end-to-end)	$\approx \pm 750$	0.7
Cavity phase (distributed)*	0	4
Fluorescence light*	-0.01	0.1
Blackbody	-20	1
Gravitation	+180	0.1
Electronics		
RF spectral purity	0	0.1
Integrator offsets, Signal feedthrough	0	1
Modulation induced AM on RF or laser	-2	2
Microwave leakage	0	0.1
Combined Standard Uncertainty		5

(* see text)

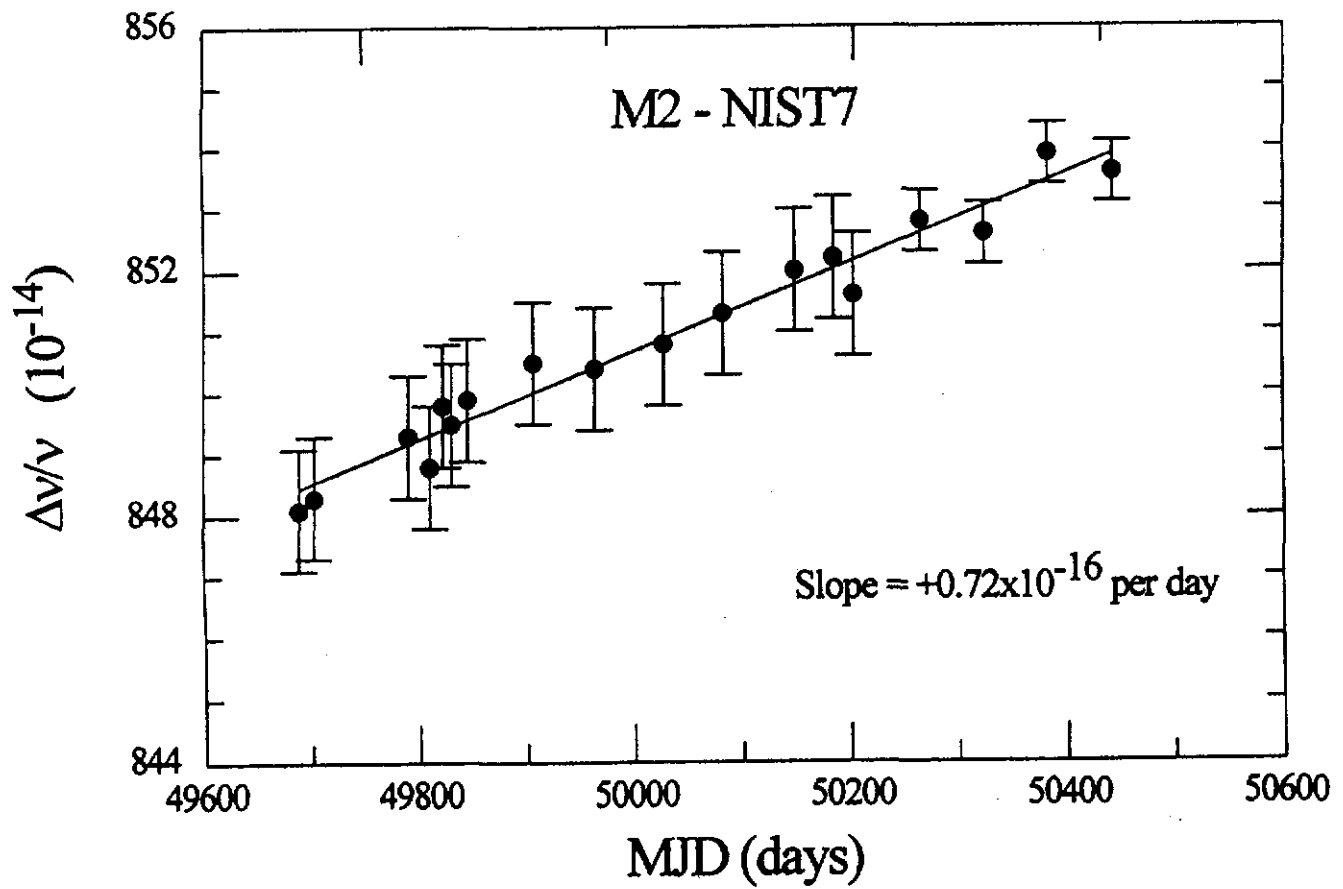


Figure 1. This plot shows the frequency difference between NIST-7 and our reference (M2) over a period of 2 years.

Questions and Answers

GERNOT WINKLER (INNOVATIVE SOLUTIONS INT'L): I have one question. You mentioned that, in your concept of the primary frequency standard, you have to switch not concepts but definitions when you come to the top. Wouldn't it be better to follow what I believe is the more generally adopted procedure or nomenclature to call a primary frequency standard a standard which can reproduce the undisturbed frequency of cesium within a given or specified tolerance? And the difference between yours and, for instance, Hewlett-Packard's is that you can do that to 5 parts in 10 to the 15th, compared to Hewlett-Packard's claim of 1 part in 10 to the 12th. I believe that's their latest number.

ROBERT DRULLINGER: I don't know how they would obtain the information of how close to the definition they approached without reference to some other standard. Whereas, this technology can do it internally without reference to a superior device.

GERNOT WINKLER: Well, for all standards, including yours, you have to allow that we have still some unknown effects. And the only way to get over that is compare independently constructed standards and have an internal measure of scatter which could serve as an estimate of your final obtainable accuracy.

ROBERT DRULLINGER: I'm sorry I didn't have time to go into all of the details. But in addition to this set of experiments that I do, I have a number of broad-brush things. For example, I revert to that old style of changing the microwave power. When I do, 15 parameters change; and the output frequency of the clock changes enormously. But I apply all of my known corrections and I look to see if they bring that back to normal. So that's a broad sweeping approach to look to see if I missed anything. And with half a dozen such cross-checks, I have found no exceptions yet.

So the appearance is, at the level we're claiming, we have a complete set.

DAVID ALLAN (ALLAN'S TIME): The root-sum-square assumes there's no correlation between any of the entries. Do you know that's the case?

ROBERT DRULLINGER: A valid question. The answer is in two parts. I reported this simply so that we're speaking apples and apples. All of the other primary standards have been using that as the way to report.

It happens that, with this evaluation technique, I believe I can prove a much greater degree of independence of the biases than with the typical one. And so I think I'm on solid ground to use the root-sum-square technique.