Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

Second Generation Cesium Fountain Primary Frequency Standards at NIST*

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INTRODUCTION

NIST is currently investigating the design of a second-generation cesium-fountain primary frequency standard. The design goals of this standard include an ultimate frequency inaccuracy of $\delta f/f < 10^{-16}$ and achievable stability better than $\sigma_y(\tau) < 10^{-13}/\tau^{1/2}$. This standard is expected to eventually replace NIST-F1, the current U.S. primary frequency standard [1].

In the context of reaching frequency uncertainties of $\delta f/f < 10^{-16}$ it is necessary to review the current limitations of cesium fountain primary standards, as well as limitations imposed by reporting such standards to the Bureau International des Poids et Mesures (BIPM), by comparing standards between national metrology laboratories and by internal uses of the fountain output frequency.

TIME TRANSFER, STABILITY AND ACCURACY

We take here a systems approach to the analysis of the required stability of a cesium fountain to realize its ultimate accuracy. A first glance at the problems would lead one to the conclusion that "the higher the stability the better". While it is true that high stability facilitates the evaluation of systematic frequency shifts in a fountain, a primary frequency standard is expected to report accuracy evaluations to the BIPM by comparison to TAI. This comparison presently requires that the standard be compared via GPS. Common-view time-transfer techniques with a frequency inaccuracy of around $\delta f/f = 10^{-15}$ at 30 days decreasing like $1/\tau$. This time-transfer technique would then require 300 days to transfer a fountain at the $\delta f/f = 10^{-16}$ level. In the narrow context of reporting a standard to the BIPM using present time-transfer techniques a short-term stability of better than $\sigma_y(\tau) = 5\times10^{-13}/\tau^{1/2}$ is unnecessary.

If we assume that GPS carrier phase techniques will replace GPS common view over the life of the standard, the situation is somewhat changed. Figure 1 shows some of the highest stability GPS carrier phase data available over a long baseline [2], and it is clear that using this system the task of successfully reporting a $\delta f/f = 10^{-16}$ frequency to TAI has been greatly eased, but still requiring some 50 days to complete the time transfer. The required short term fountain stability for this time transfer is $\sigma_y(\tau) = 2\times10^{-13}/\tau^{1/2}$.

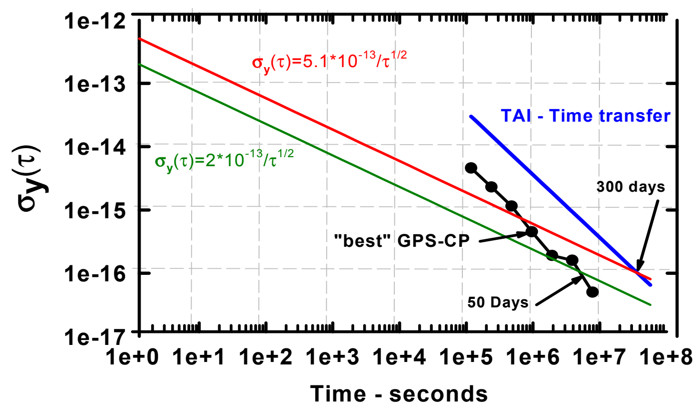

Figure 1 – A comparison of the time-transfer performances and the resulting requirements on the cesium fountain short term stability. The line labeled TAI time transfer is the existing GPS common-view time-transfer system, which would require some 300 days to effect a time-transfer with $\delta f/f = 10^{-16}$. The commensurate short-term stability of the cesium fountain is $\sigma_y(\tau) = 5\times10^{-13}/\tau^{1/2}$. The line labeled "best" GPS-CP is the data reported in [2] on time transfer over a 2000+ km path using GPS carrier phase. This system would take 50 days to transfer $\delta f/f = 10^{-16}$, requiring a corresponding fountain short term stability of $\sigma_y(\tau) = 2\times10^{-13}/\tau^{1/2}$.

NIST is fortunate to have a local time scale consisting of several commercial cesium clocks and 5 active hydrogen masers. This time scale provides the flywheel for the fountain and has a short term stability of around $\sigma_y(\tau) = 1\times10^{-13}/\tau^{1/2}$[3]. Since we are presently unaware of another continuously operating flywheel with greater short term stability (with the possible exception of the JPL Hg^+ microwave standard [4]) we find it disadvantageous to require higher short term stability in our proposed fountain while simultaneously meeting the accuracy goal of $\delta f/f<10^{-16}$. With a short term stability of $\sigma_y(\tau) = 1\times10^{-13}/\tau^{1/2}$ and an accuracy of $\delta f/f < 10^{-16}$ we can evaluate the fountain internally with 12 days of continuous operation.

Given the present state of the art in both our local time scale and in time transfer methods it seems unnecessary to require higher stability of the cesium fountain with the exception of the requirement to "calibrate" the internal NIST optical frequency standards based on neutral calcium and trapped Hg^+ ions[5,6].

EXISTING FOUNTAINS – ACCURACY BUDGET

Cesium-fountain primary frequency standards presently reporting to BIPM have delivered (to TAI) accuracies in the range of $\delta f/f = 10^{-15}$. All of the reporting fountains are compromised by several systematic frequency offsets as well as time transfer noise. Table I shows a typical accuracy budget for NIST-F1 as reported to the BIPM. While the accuracy budgets of other standards reporting to BIPM differ in the details certain general conclusions can be drawn.

The dominant uncertainty in the accuracy budget is the spin-exchange uncertainty at $\delta f/f = 5\times10^{-16}$. We will review in the next section a system that we believe will reduce the spin-exchange uncertainty to somewhat less than $\delta f/f = 10^{-16}$.

At a somewhat (but not greatly) lower level come a host of uncertainties such as the blackbody radiation shift, light shifts and so on. Some of these uncertainties may very well be limited simply by lack of effort; it is somewhat unfruitful to expend effort on uncertainties that are not dominant in the budget. Others, however, are not so simple to reduce. In particular, the blackbody shift is extremely difficult to correct at the $\delta f/f = 10^{-17}$ level in a room temperature device. It should be noticed that these sorts of shifts are generic to microwave frequency standards and are at the same level (or worse) in rubidium fountains as compared to cesium fountains. It is only the lack of a large spin-exchange shift which makes rubidium an attractive candidate for microwave frequency standards, in most other respects it is equivalent or inferior to cesium.

Table 1 – An abbreviated uncertainty budget from an evaluation of NIST-F1. This table is representative of the current state of the art of cesium-fountain uncertainties.

Physical Effect	**Size $*10^{-15}$**	**Uncertainty $*10^{-15}$**
Spin Exchange	-1.14	0.48
Zeeman	72.9	0.1
Blackbody	-20.6	0.3
Gravitational	+180.54	0.1
Cavity Phase & Leakage	0.0	0.2
Background Gas	<0.1	0.1
Light Shift	0.0	0.2

SPIN-EXCHANGE AND STABILITY

Since the development of the first laser-cooled cesium fountains the spin exchange frequency shift has been known to be extraordinarily large [7,8]. Considerable work over the past few years has gone into controlling and evaluating the spin exchange shift and it is now not unreasonable to expect that ultimately this shift in cesium primary standards will be controlled in the mid $\delta f/f = 10^{-17}$ range[9,10,11]. Because of the spin-exchange shift there is typically a trade-off between short term stability and ultimate accuracy. The spin exchange shift scales as the atomic density, therefore as the number of cesium atoms, N.A. The short term stability, however, scales as $1/\sqrt{N.A.}$. NIST-F1 shows quantum projection noise limited operation at detected atoms numbers greater than ~1000 atoms, corresponding to a short term stability of around $\sigma_y(\tau) = 6\times10^{-13}/\tau^{1/2}$ with a spin-exchange shift of less than $\delta f/f = 10^{-15}$. This mode of operation could probably be extended to an uncertainty in the spin exchange frequency shift of 10^{-16}, but only at these rather poor levels of short term stability. Under the same circumstances we would have to detect on the order of 3×10^4 atoms per ball with a resulting spin exchange shift on the order of 10^{-14} to obtain a short term stability of $\sigma_y(\tau) = 1\times10^{-13}/\tau^{1/2}$. It is unlikely that extrapolation of this shift to an uncertainty of $\delta f/f = 10^{-16}$ is possible.

Our proposed solution is based on the proposal by Godone and Levi [12] to use multiple balls of cesium atoms on non-intersecting trajectories. The multi-toss solution relies on launching multiple balls of cesium atoms quickly in such a way that the trajectories don't overlap in the Ramsey region of the fountain but rather overlap in the detection region. This approach allows the average atom density to be much lower than in the single ball case (roughly divided by the number of balls) but maintains the high signal to noise ratio afforded by large atom fluxes. Modeled trajectories are illustrated in Figure 2. An additional advantage of the multi-toss arrangement is that the first ball in the second launch sequence can be prepared before the Ramsey interrogation and detection of the last group of balls has been completed, thus sharply lowering the dead time associated with pulsed operation. The greatly reduced dead time of this operation reduces the Dick effect [13] to much more manageable levels than in traditional fountains. Additionally, the use of phase modulation interrogation of the Ramsey fringe also reduces the distortion and possible line pulling effects caused by the large spread in Ramsey times associated with this scheme [14].

In NIST-F1 we currently operate with atom "temperatures" (the velocity distribution is not Gaussian) below 1μK. Under these conditions, approximately 25% of the launched atoms are returned to the detection region. Transverse cooling would allow essentially 100% of the launched atoms to return yielding a further order of magnitude reduction in the spin exchange frequency shift at constant detected atom number [15]. This technique will be implemented if the spin-exchange proves to still be the limiting systematic frequency shift of the fountain.

Figure 3 shows the results of an experimental version of the multi-toss arrangement in which seven balls (rather than the planned 10) were launched. The data in Fig. 3 suffers from the low load rate of the optical molasses coupled with the short load times imposed by the multi-toss technique, together these represent serious drawbacks of the multi-toss scheme. We are presently testing a slow atomic beam (LVIS) [16] which should allow loading 2×10^{7} m = 0 atoms into the molasses every 25 ms. Assuming that the LVIS loading arrangement works as planned, achievable stabilities of $\sigma_y(\tau)\approx10^{-14}/\sqrt{\tau}$ should be achieved. At these stabilities the spin exchange shift is expected to be in the mid 10^{-14} range! A serious disadvantage of the multi-toss system is the requirement for in vacuum light-tight shutters. Our present plan is to use PARCS type shutters as described in [17].

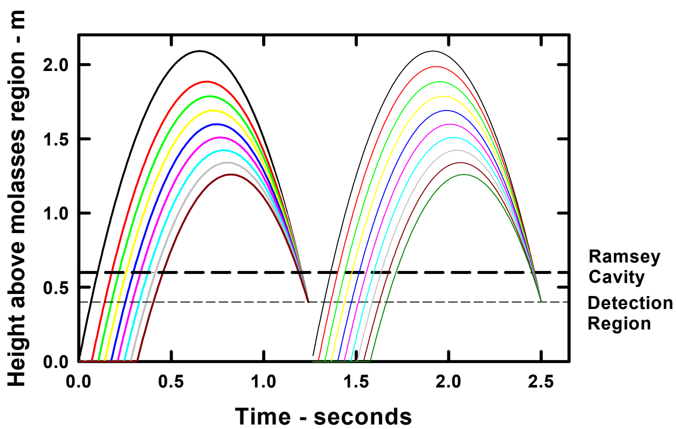

Figure 2 – Atom ball trajectories in the multi-toss case of Godone and Levi. Notice that the trajectories overlap in the detection region allowing high signal-to-noise ratios without major modification of the detection process. Notice also the large duty cycle (fraction of time atoms are above the Ramsey cavity) allowed in this arrangement.

OTHER SYSTEMATIC FREQUENCY SHIFTS

As shown in Table I, the next most important systematic frequency bias after the cesium spin-exchange shift is the blackbody frequency shift. The present ability to correct for the blackbody shift is limited by a variety of factors. First, the shift is large at room temperature, $\delta f/f = 2\times10^{-14}$ and the correction therefore has to be made at the 10^{-3} level to support an accuracy of $\delta f/f = 10^{-16}$. This requires knowledge of the effective temperature of the radiation over the flight path of the atoms at the 0.1K level, not a simple task. Further, in spite of an elegant experimental campaign to measure the polarizability coefficients to the required precision, the achieved accuracy is just barely adequate to support fountain uncertainties in the $\delta f/f = 10^{-16}$ range [18]. We are therefore investigating the feasibility of a 50K cooled Ramsey cavity and drift tube structure in our next fountain. This has the effect of reducing the blackbody shift by a factor of 10^{3} so that the total effect is at the $\delta f/f = 10^{-17}$ level and could presumably remain uncorrected. Cryogenic operation should also significantly lower the pressure above the Ramsey cavity, thus lowering the shift due to background gasses to the 10^{-18} level.

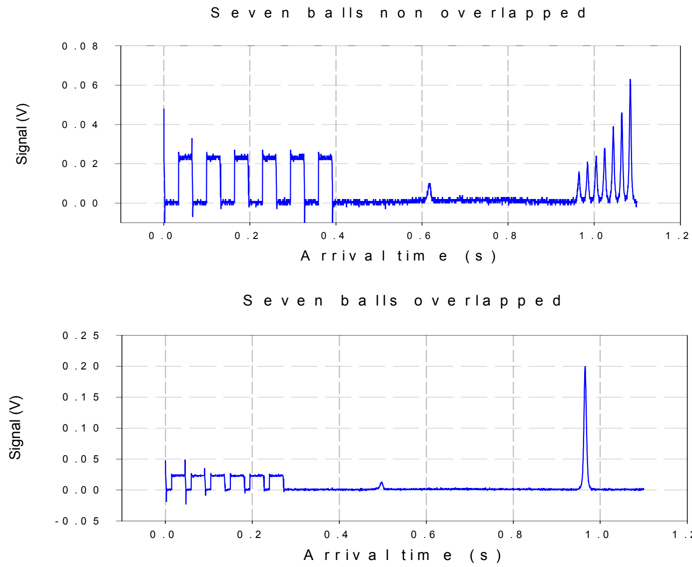

Figure 3 – Experimental multi-toss data. The upper figure shows seven individual launched balls. The square-wave like structure to the left is the atom-detection system responding to the molasses beams. The small peak at about 0.6 s is the fraction of "dropped" atoms (the detection system is below the molasses region in this experiment) and the seven spikes to the right edge of the figure are the seven balls returning to the detection region. In the lower figure the launch velocities have been adjusted to overlap the balls in the detection region with the resulting improvement in signal to noise.

The uncertainty in the second-order Zeeman shift is shown in Table I as 10^{-16}, but this is presently limited only by the lack of a servo on a field sensitive line. This could be implemented relatively easily at which point the uncertainty associated with this systematic shift should drop into the low 10^{-17} range.

Systematic frequency shifts associated with the microwave cavity and feed structure are presently limited at $\delta f/f = 2\times10^{-16}$, with the uncertainty being statistical in nature. We believe that this shift can be brought below 10^{-16} through a combination of appropriate design of the microwave structure and extrapolation. This remains to be demonstrated.

Controlling the resonant light shift in this fountain will be quite challenging as a result of the multiple shutters in vacuum. The PARCS project faces exactly the same challenges, and we plan to adapt their shutter design to control this shift[17].

Frequency shifts associated with adjacent atomic transitions, in particular the Majorana frequency shift, are a more serious problem in this proposed standard than in NIST-F1. This is a result of the need for an in-vacuum shutter between the state-selection microwave cavity and the Ramsey microwave cavity. In order that no Zeeman coherences develop between the two cavities the static magnetic field must be well controlled. Microwave leakage between the two cavities can also lead to frequency shifts and must be suppressed.

The remaining systematic frequency shifts also present hard targets. Electronic shifts in particular are well known to be difficult to control when "splitting' a line to the 10^6 level as we are planning here. However, line-splitting to well beyond what is contemplated here is relatively routine in the operation of thermal beam primary frequency standards and the same techniques discussed in [19] are applicable here.

CONCLUSIONS

We have presented a rationale for the design and construction of a second-generation cesium-fountain primary frequency standard at NIST. The proposed design should support a frequency inaccuracy of $\delta f/f = 10^{-16}$ and a short-term stability of $\sigma_y(\tau)\approx 10^{-14}/\sqrt{\tau}$, albeit not simultaneously! During operation as a $\delta f/f = 10^{-16}$ frequency standard the short term stability would be $\sigma_y(\tau)\approx 10^{-13}/\sqrt{\tau}$ commensurate with the NIST maser derived time scale. These stabilities are also more than adequate to support frequency transfer systems currently in use as well as reported experimental systems at the full $\delta f/f = 10^{-16}$ accuracy of the primary standard. Higher stabilities would come at the expense of decreased accuracy unless transverse atomic cooling was employed. With transverse cooling, simultaneous frequency accuracy of $\delta f/f = 10^{-16}$, and stability of $\sigma_y(\tau) \approx 3\times 10^{-14}/\sqrt{\tau}$ should be achievable, albeit at the expense of a much more complicated laser system. This may ultimately be required to support the calibration of optical frequency standards.

ACKNOWLEDGEMENTS

The authors have benefited enormously from collaborations with Aldo Godone and Filippo Levi of IEN G. Ferraris. This project has also benefited from the close cooperation of the PARCS team, in particular Neil Ashby, Eric Burt, John Dick, Leo Hollberg, Bill Klipstein, and Don Sullivan.

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