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Hydrogen Masers and Cesium Fountains at NRC

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Abstract

The NRC masers H-3 and H-4 have been operating since June/93 with cavity servo control. These low-flux active H masers are showing stabilities of about 10^{-15} *from 1 hour to several days. Stability results are presented, and the current and planned uses of the masers are discussed.*

A cesium fountain primary frequency standard project has been started at NRC. Trapping and launching experiments with the goal of 7 m/s launches are beginning. We discuss our plans for a local oscillator and servo that exploit the pulsed aspect of cesium-fountain standards, and meet the challenge of $10^{-14}\tau^{-1/2}$ *stability [1] without requiring masers.*

At best, we expect to run this frequency standard initially for periods of hours each working day rather than continuously for years, and so frequency transfer to outside laboratories has been carefully considered [2]. We conclude that masers (or other even better secondary clocks) are required to exploit this potential accuracy of the cesium fountain. We present and discuss our conclusion that it is feasible to transfer frequency in this way with a transfer-induced uncertainty of less than 10^{-15}*, even in the presence of maser frequency drift and random walk noise.*

Introduction

NRC has been building and operating frequency standards (Cesium beam tubes and hydrogen masers) for more than 25 years[3]. One NRC maser, H-1, has been operating since 1967, and is still in operation. Two newer masers, H-3 and H-4 began operation as clocks, with cavity servo contol, in June 1993. They have a better long term stability as well as a better short term stability, due to the improvements made to the design. Despite the inaccuracy inherent to the wall shift problems preventing their use as primary frequency standards, hydrogen masers are still the best widely used timekeepers in the range of hours to weeks.

In parallel with the development of hydrogen masers, cesium clocks were built at NRC[4][5]. Cs-V, a 2.1 metre primary cesium beam frequency standard, has been operating for more than twenty years and two of the three Cs-VI, one metre beam tubes built in 1978, are also in operation. The

[0] Retired

development of these cesium beam tubes had been facilitated by the availability of the hydrogen masers. By increasing the intensity of the cesium beam, the short term stability of these clocks from $3 \times 10^{-12}\tau^{-1/2}$ can be pushed to better than $8 \times 10^{-13}\tau^{-1/2}$. The good medium term stability of the hydrogen maser can then be used to measure various parameters of a cesium clock at 10^{-14} level of accuracy in several hours.

But these old laboratory cesium frequency standards are on the verge of being obsolete when compared to the possibilities of the cesium fountains due to the advance in magneto-optical trapping. We have started experiments aimed at building a cesium fountain frequency standard. We are planning to use the hydrogen masers in various ways to help develop, operate and use these new frequency standards, which should give an accuracy better than 10^{-15}. Our plans are to build a tall fountain, with a launch velocity of 7m/s or more. This can minimize the density shift[6] and allows enough room for magnetic focusing and adiabatic fast passage between Zeeman levels. The method of interrogation which was proposed in 1992[1] should allow us to use a one second cycle quasi-continuous fountain.

The main role of our hydrogen masers will be to allow intercomparison of frequency between cesium fountains at various sites and operating at different times. They will probably be our only reliable link between laboratories and BIPM at a level of accuracy of 10^{-15} until the fountains will be operating continuously for months at a time.

Hydrogen masers

The design of the two hydrogen masers, H-3 and H-4[7] [8], has been based partly on experience gained at NRC[3] and at Laval University[9] in Quebec City. In order to operate these masers as clocks, special attention has been paid to minimize the effects of external influences, such as vibration, magnetic field changes and changes in atmospheric pressure and ambient temperature. Five layers of magnetic shielding are used. Their design is the same as the one used in the Laval University masers[9], for which a magnetic shielding factor of 100 000 was measured. This means that a 10% fluctuation in the earth's field should cause a frequency change of less than 10^{-15}. Three concentric ovens are used outside the vacuum enclosure for active temperature stabilization. Two thermal shields have been added inside the vacuum housing, enclosing the resonant cavity. The supports of these shields also serve to decouple mechanically the resonant cavity from changes in atmospheric pressure. The resonant cavity is made of fused quartz, silvered internally. A reentrant aluminum disk is mounted in such a way to compensate the difference in dimensions due to relative thermal expansion of the quartz and aluminum. The loaded Q of the cavity is 38 000. A spherical storage bulb 18 cm in diameter is symmetrically located in the cavity. The bulb in H-3 has been coated internally with FEP-120 Teflon. Since April 1992, a bulb coated with the Russian Fluoroplast F-10 material has been used in H-4. All vacuum seals on the masers use metal rings or wires (either copper or indium). A thin-walled tube of palladium-silver alloy is temperature controlled to control the hydrogen pressure in the discharge tube. The masers are operated in low-flux mode.

The masers have been operated experimentally in different modes: free-running and with external spin-exchange auto-tuning. Now in clock operation, they operate with stand-alone cavity frequency servos employing injected square wave FM signals[10]. Figure 1 shows the relative stability of the two masers over a period of more than two months. Over the same period, the Allan deviation of Cs-VIC and HP234 (Hewlett-Packard cesium beam standard model 5071 with high stability option) against NRC ensemble (based on a Kalman filter algorithm[11]) are also shown. It is obvious that the hydrogen masers have a definite advantage in stability, making them the best candidates to keep memory of frequency calibrations by a cesium fountain running shortly (less than a day) from time to time. It is still too soon to see if there is really any improvement to the drift rate by using the Russian coating. Periods of one to two months without any relative drift between the masers are followed by periods with a relative drift of about 5×10^{-16}/day. It seems that most of the drift is due to H-3. The drift against the ensemble of Cesium clocks appears smaller for the bulb coated with Fluoroplast F-10. (The apparent degradation of stability of H-3 and H-4 against the ensemble (three hydrogen masers, four cesium clocks) in the range of 2×10^4 to 10^6 seconds, is due to the algorithm: no clock is allowed a weight greater than 50%. This puts too much weight on the cesium clocks in the considered range, where they start to compete with the hydrogen masers. It is also in this range where H-1, not shown here, suffers from changes in atmospheric pressure. It does degrade the ensemble, grabbing too much weight from the two better hydrogen masers.)

Cesium fountain

We are currently building a magneto-optical trap which will allow us to laser-trap, laser-cool and laser-accelerate cesium atoms to velocities greater than 7 m/s (see Figure 2). The basic characteristic of our trap is that no laser beam lies along the launch direction. This is done in order to allow preparation of an ensemble of cold atoms while another one is already on its ballistic trajectory. Two choppers acting synchronously let the ensemble of atoms go up along the tube and stop the diffusion light from the trap which could perturb the atoms in the fountain. The Ramsey phase discriminator[1] will be used to interrogate the atomic ensemble. It is a quasi-continuous phase measurement of the local oscillator (a quartz oscillator) with respect to the hyperfine phase of the ensemble of cold cesium atoms. Using the shortest possible dead time τ, relative to the Ramsey interrogation cycle t_a, or active time, we can expect to measure the phase of the local oscillator with an accuracy level of $10^{-14}\tau^{-1/2}$[1]. Post-processing of these measurements makes it possible to calculate a correction relative to the time-scale of the local oscillator. Such a correction can probably be done within a few seconds of the actual measurements.

Optics of the Magneto-Optical trap

The master laser, an extended-cavity diode laser is locked to the saturated absorption crossover resonance peak $6S_{1/2}, F = 4 \rightarrow 6P_{1/2}, F' = 4/5$, which is 125.7 MHz lower than the $6S_{1/2}, F = 4 \rightarrow 6P_{1/2}, F' = 5$ transition used to cool the cesium atoms. The locking is done through an acousto-optic modulator scanning the crossover transition, allowing a modulation free locking of the master laser. Third harmonic detection is used to remove the slope of the saturated absorption profile. A slave laser (>100 mW) is locked to the master laser by optical injection and is split in five beams to create the appropriate trap configuration. Acousto-optic modulators are used to shift the frequency of each beam to create the trapping, the cooling and the acceleration of the atoms. The power per beam is about 10 mW, with a diameter of 1.5 cm. The repumping laser, tuned to the transition $6S_{1/2}, F = 3 \rightarrow 6P_{1/2}, F' = 4$, is locked to the Doppler profile of Cesium absorption. Plans to lock it to the master laser by detection of the beat period at 9.1926 GHz are under development. The repumping laser is added to the horizontal pair of arms. It can also be added to the other four arms.

Vacuum System

The current system is built in two main parts: the trap and the 'clock'. The magneto-optical trap is stainless steel with six viewports on arms aligned in pairs for the three orthogonal laser beam axes. One axis is in the horizontal plane, and the other two are at 45° to the vertical launch axis. The anti-Helmholtz pair of coils are wound around the horizontal arms. The viewing ports are of the Housekeeper type, non-magnetic AR coated glass windows, with a clear aperture of over 2 cm. This allows quasi-continuous trapping. On a one second cycle, it is expected to trap at least 10^7 atoms with laser beams of 1.5 cm diameter, and 10 mW per beam. The preparation of the polarization of the atoms can be made at this level by laser pumping.

The 'clock' part is separated from the trap by a valve, allowing fast modification to the whole system, without having to destroy the vacuum of the trap. The lower section of the clock encloses the choppers to let the atoms get through, but not the light. The middle section contains the quadrupole magnets, and the adiabatic fast passage systems. These will allow us to switch atoms from one Zeeman state to the other allowing for a clock transition from the $F = 4$ to the $F = 3$ levels. The quadrupole magnets could be used to eliminate the atoms in states other than $F = 4, m_F = 0$. The first use of these magnets is to control the transversal dispersion of the moving ensemble of atoms. The upper section houses the detection region, the microwave cavity and the drift region with the C-field.

Microwave System

The microwave cavity is a section of wave guide in the mode TE_{01}. The magnetic and microwave fields will be perpendicular to the beam, as in our classical cesium beam tubes. To select only the clock resonance with a pulsed system, the Ramsey beat-period polarization might be used in addition to the C-field splitting and optical pumping depopulation of undesired levels. For large-diameter detected beams, since $\nabla \cdot B = 0$, transverse-field systems offer some important advantages over axial-field system, and we propose to use a transverse-field system in our initial experiments.The interrogation scheme[1] is a new type of servo: the phase of the atomic ensemble is the reference for evaluating the local oscillator phase. The local oscillator is not providing a reference frequency to evaluate the performance of the locking system to the center frequency of the clock transition. The transition is used to evaluate the phase difference accumulated over the time of flight of the atomic ensemble between the two Ramsey passages in the cavity. For this reason, it is important to minimize the dead time between two cycles. The overall stability does not depend[1] on the stability of the local oscillator over the time of a Ramsey cycle, as in a conventional

[1]To some extent only; the phase error accumulated during one cycle must still be less than $\pi/4$, i.e. a stability of about 10^{-11}.

servo. It depends only on the stability of the local oscillator during the dead time. Depending on the type of noise dominating such a time interval, the long term stability can be dramatically improved over a conventional servo using the same local oscillator.

Detection of the Atomic Polarization

The detection is one of the major problem for delivering the full accuracy of a cesium fountain. It is mandatory to evaluate the atomic polarization of the ensemble of atoms with the highest accuracy possible. We will need to measure the atomic polarization errors at the 10^{-5} level. Since the total number of atoms trapped is not a constant, the ratio of atoms which have undergone a transition to those not having done so is the real parameter to evaluate. We will use a double detection region, where atoms in the $F = 4$ state are first detected by the fluorescence of the cycling transition $6S_{1/2}, F = 4 \rightarrow .6P_{1/2}, F' = 5$, then a second region where atoms in the $F = 3$ state are pumped in the $F = 4$ and detected. The disadvantage of this method is the non-uniformity of detection over the probed volume of the returning atomic ensemble and the difficulties in evaluating perturbations of nearby atoms from the fluorescence.

Another technique we are considering for use is multi-step, multi-photon excitation to high Rydberg states where atoms can be ionized and counted. The advantage of this method is the possibility to have a more uniform detection region. It is also possible to put to use old techniques too. A magnetic detection, using dipole magnet to separate the various Zeeman states could allow direct measurement of the polarization of atoms.

Evaluation of the System

The main advantage of a fountain over a conventional thermal cesium beam tube is the long interrogation time which gives a much narrower line-width, roughly an improvement of 100. In order to get the most out of these new devices, each still has to be evaluated for all the parameters which can affect their potential accuracy. Some new effects, negligible or unheard of in the old standards, might arise. Here are the parameters important to evaluate, in order to reach an accuracy of 10^{-15} or better, and the solutions we intend to apply.

- The second-order Doppler effect can be estimated to much better than 10^{-16}. In the thermal-beam Cs clocks, it can be evaluated to 10^{-15}[12] and the velocity of the atomic ensemble is reduced by close to two orders of magnitude, the second order Doppler effect is reduced by about four orders of magnitude. Also, the velocity distribution is much easier to define than with a classical clock with magnets. This should give another order of magnitude in accuracy on the second order Doppler effect.
- Frequency pulling by neighboring transitions can be eliminated first by depleting the neighboring Zeeman states and second by careful alignment of the cavity microwave field and C-field. To study this last effect, we will use a transverse-field and a six-rod structure for the C-field generation. One pair of opposing rods will be used to controlled the rotation of the C-field. By rotating the C-field respect to the microwave field, Ramsey pulling can be

studied. The long travelling time between the two passages into the cavity will permit to rotate the C-field with constant amplitude and push further the study of this effect.

The easiest way to eliminate some of the frequency pulling is still to operate the frequency standard in the Ramsey phase discriminator mode. If the local oscillator's offset is kept small enough, it eliminates virtually all the pulling effects due to the distortion of the baseline.

- The C-field inhomogeneities can be studied in different ways. Since the atoms are spending most of their time above the cavity in the top part of their trajectory, by varying the height above the cavity, it is possible to sample the C-field effectively. Based on our experience with cesium beam tubes, with proper care, it is possible to build a transverse field with 0.02% uniformity[9], reducing the error associated to less than 10^{-15} for fields smaller than 10 mGauss. Using a cold, superconducting, drift region for the fountain part, it is also possible to have a calculable magnetic field.
- Spectral impurities, cavity pulling and microwave power effects can be reduced to less than 10^{-16} with proper electronics design and the mode of operation in phase modulation instead of frequency modulation.
- The spin-exchange effects are likely to be one of the dominant effect on the frequency pulling. Operating the clock at a low density of atoms is then very important to reduce the uncertainty due to this effect. Very careful measurements of the real density and polarization of each ensemble of cold atoms will probably be a necessity to break the 10^{-15} limit. First measurements made by Gibble and Chu[6] are already giving an order of the magnitude of the problem.
- The cavity phase shift due to different phase between two cavities in the Ramsey beam configuration may still be present in a different form. The power absorbed by the atoms is likely to be different on the going up trajectory than on the going down trajectory. The density of atoms will likely be lower on the second passage, loading the cavity at a lower level but for a longer time. Using a variable quadrupole focusing magnet, we will measure the effect of the ratio of densities between the two passages. There is still the problem of trajectories through the cavity, sampling different phases of the microwave field. A superconducting cavity would alleviate this problem.
- The black body radiation will have to be measured very accurately. Being of the order of 1.5×10^{-14} at room temperature, it needs to be measured at various temperature, including very low temperature, in order to get the required accuracy to compensate for any bias at room temperature. The best solution is to compare two fountains, one at liquid helium temperature[2], one at room temperature.

There is still a lot of work to be done before assessing an accuracy of 10^{-15} or better to the cesium fountains. For this reason alone, it is unlikely that such a device would be operated continuously in the near future. So many experiments need to be done that it is likely a cesium fountain would be operated only for short periods at a time between experiments.

[2]This would be a real Zacharias fountain.

Frequency transfer

The International Bureau of Weights and Measures (BIPM) is always in need of better accuracy. Hence it is imperative to transfer the improved accuracy of the cesium fountains as soon as possible. It will also be most interesting to compare implementations of these new frequency standards by various groups[6] [13] [14] as early as possible. Hydrogen masers appear to be most attractive as frequency transfer standards until the fountains can be operated in the clock mode, i.e. periods of continuous operation of months or more. The uncertainty in any proposed frequency transfer process is likely to be the dominant term in the uncertainty budget, and so we developed a reliable method[2][15] for evaluating this uncertainty, which has its origins in the random-walk frequency noise and the frequency drift of the maser.

We used the following hydrogen maser characteristics which includes white phase noise ($\alpha = 2$) contributed by the maser and phase measurement system and typically $h_2 = 6.7 \times 10^{-23}$, flicker phase noise ($\alpha = 1$) with $h_1 = 2.9 \times 10^{-30}$, white frequency noise ($\alpha = 0$ - shot noise on the atomic beam of the fountain also contributes noise of this form) with $h_0 = 2.9 \times 10^{-27}$, flicker frequency noise ($\alpha = -1$) with $h_{-1} = 7.2 \times 10^{-31}$, and random walk frequency noise ($\alpha = -2$) with $h_{-2} = 4.9 \times 10^{-37}$. The frequency stability described by this random noise model is shown in Figure 3 (thick line) as the two-sample deviation (Allan deviation) of the average frequency vs averaging time τ.

The light straight line on Figure 3 is the cesium fountain noise with a frequency uncertainty of $3 \times 10^{-14}\tau^{-1/2}$. This is what could be expected from a pulsed cesium fountain with a 1 s cycle time (0.5 Hz Ramsey line-width) with 1% dead time per cycle [1], with an ideal atomic shot noise of about 4×10^5 detected atoms per second (assuming ideal atomic polarization detection, without background or detector noise). The curved lines, labeled $t_a = 3000s$ and $t_a = 10000s$, tangent to the maser curve at large τ, are the expected uncertainty limits of the frequency transfer for a single calibration of the hydrogen maser for a time t_a (the active time of the cesium fountain) centered in the interval time τ between time transfers. It can be seen that we gain a factor of two on the maser stability alone at large τ.

The dotted lines are the expected frequency transfers for multiple calibrations, each one done once a week. Using a multiple calibration to remove the drift rate of the hydrogen maser, we can improve in the long run the frequency transfer. For a cesium frequency standard running less than an hour per week, four weeks are needed to transfer the frequency to an accuracy of 10^{-15}. If the fountain is running nine hours once a week, two weeks only are needed to reach the same accuracy.

Interlaboratory Frequency Transfer

The above discussion applies only to frequency transfer in the confines of the laboratory, where phase resolutions of less than 1 ps and longer term stabilities of the order of 10 ps are possible. The accuracy of interlaboratory frequency transfer can probably best be achieved by two-way time transfer (TWTT) via common-view geosynchronous communications satellites, preferably at Ku band, or with GPS (Global Positioning System) satellites if time calibrators are used for the receivers to measure the carrier phase. The current state of the art of TWTT shows time transfer precisions of 2 ns (long-term) with short-term precision of 0.2 ns. With dynamic calibration, it is expected to get a long-term precision as good as the short-term calibration.

Figure 4 shows the trend line for the frequency uncertainty within a laboratory for a calibration time t_a = 3000 seconds, the maser characteristics (thick curve) and the frequency uncertainty that might be delivered to a remote laboratory by two-way time transfer, with a full time transfer precision for each transfer of δt = 2 ns and 0.2 ns. In remote calibrations, we need only to add in quadrature the standard uncertainty of the second cesium fountain's frequency to get the full frequency transfer uncertainty delivered to a second time laboratory. For comparisons with the frequency of a second laboratory's cesium fountain, the effects of their hydrogen maser (or local oscillator used for the frequency transfer) must also be added. With the present two-way time transfer precision of 2 ns, the intercomparison uncertainties for weekly calibrations would require more than nine weeks to reach the level of 10^{-15}. At the 10 day reporting interval used by TAI, the intercomparison uncertainty is better than 5×10^{-15} for the weekly trend line.

Conclusion

We presented the latest results from our hydrogen masers H-3 and H-4. The Fluoroplast F-10 coating appears to be an improvement over the FEP-120 Teflon. We also presented our activity on the cesium fountain project. Although we are not planning to use our hydrogen masers as local oscillators, they show they have the stability required to provide the proper timekeeping capacity for interlaboratory comparison in the early age of cesium fountains.

Two-way time transfer or perhaps GPS carrier-phase based (geodetic) time transfer are able to achieve interlaboratory frequency transfer accuracies of better than 10^{-15} over periods of many weeks. To keep in pace with the expected development of the cesium fountain's frequency standard, an improvement in the transfer techniques, or in the transfer oscillators, is needed to achieve comparable frequency transfers in a shorter time.

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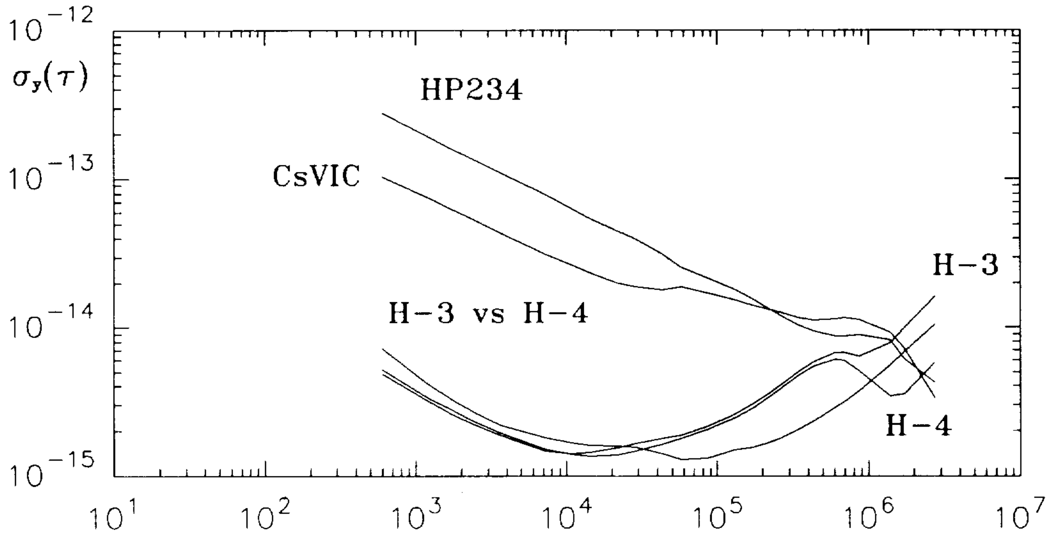


Figure 1
Stability of H-3, H-4
and cesium clocks at NRC
versus the ensemble.

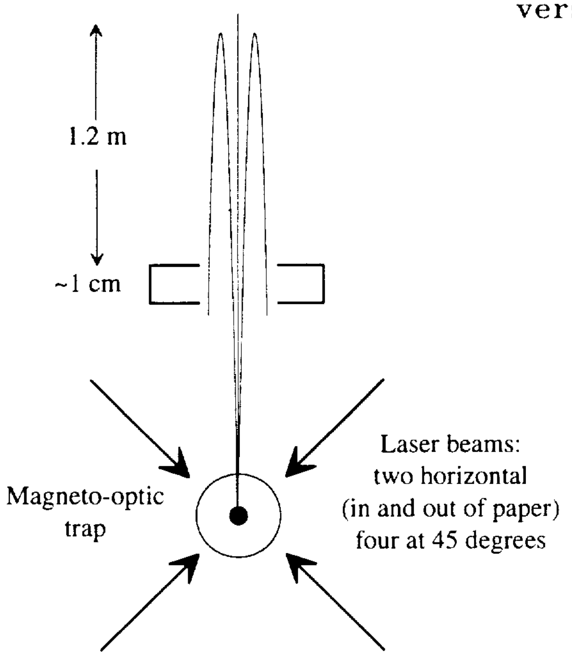
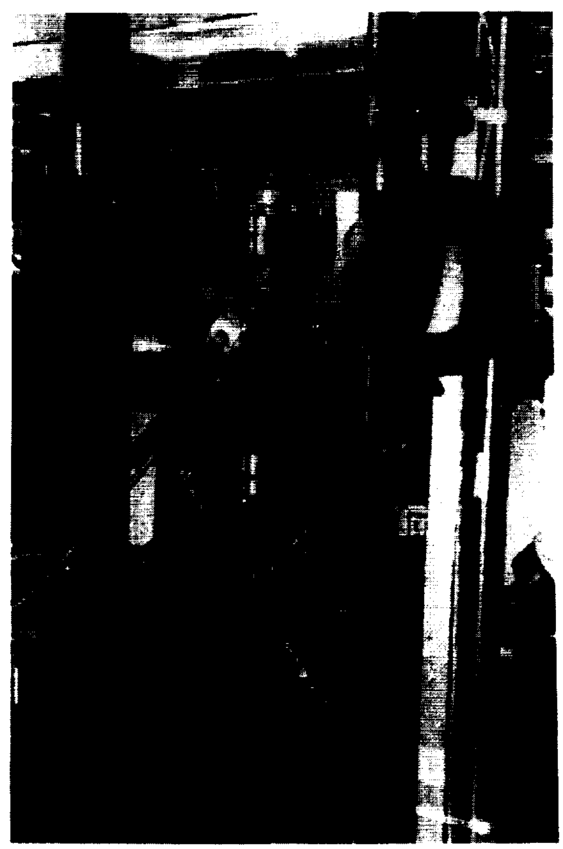


Figure 2
The tall cesium fountain. The picture at right
is the magneto-optical trap already built.



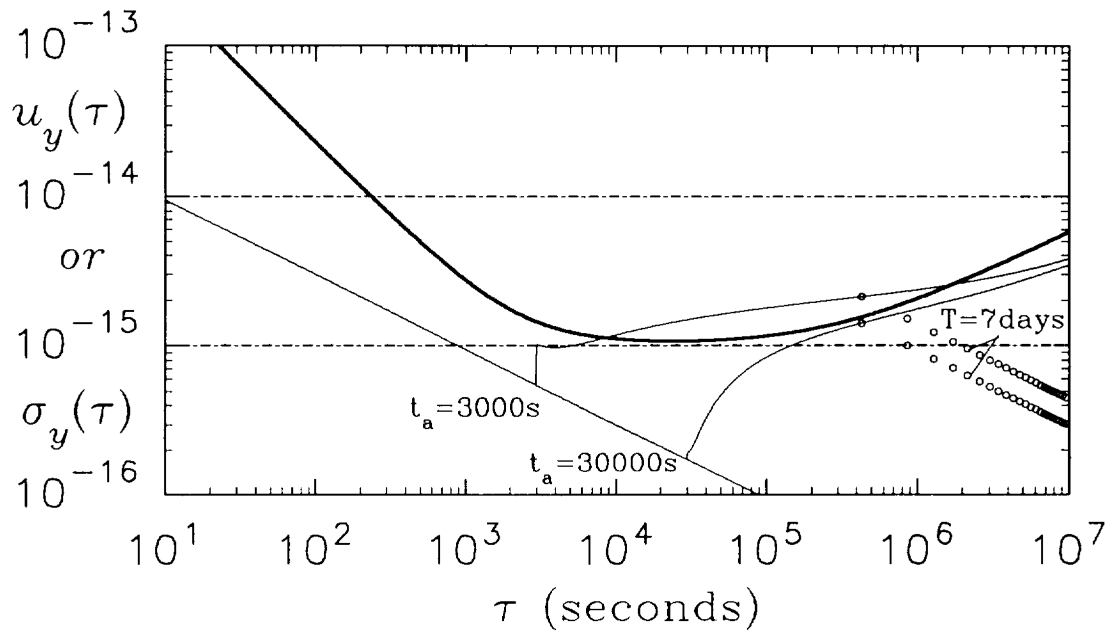


Figure 3
Frequency transfer uncertainty with a hydrogen maser.

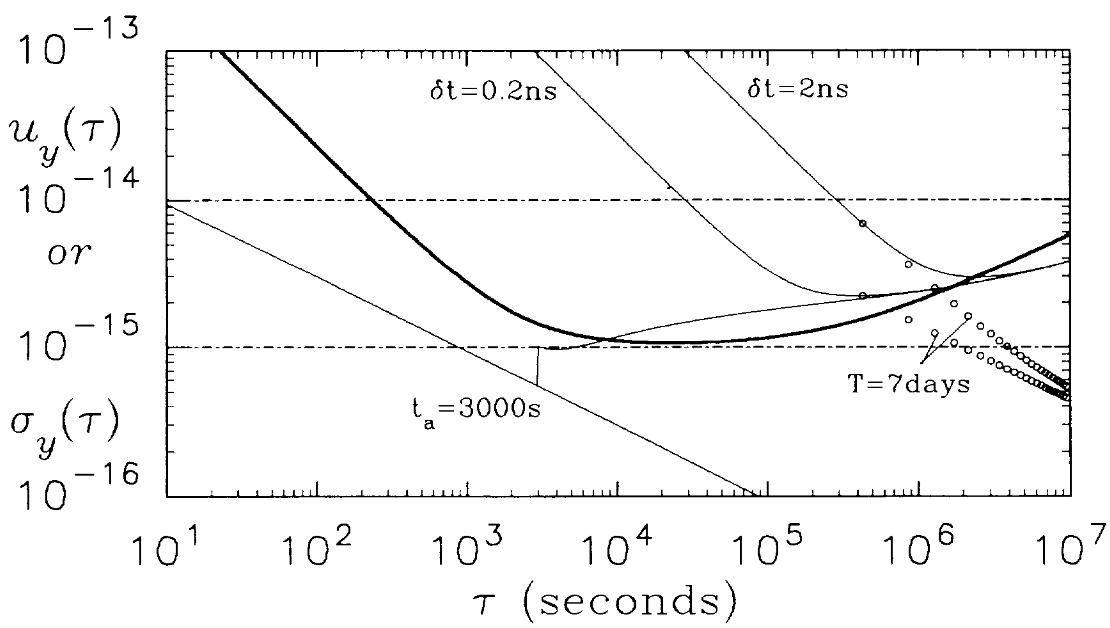


Figure 4
Frequency transfer uncertainties with a hydrogen maser and two-way time transfer