Cesium Beam Primary Frequency Standards at NRC

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ABSTRACT

The accuracy and long-term stability of time scales are established and maintained by reference to the primary frequency standards built and operated by national standards laboratories. The internationally accepted definition of the second is the specification for these cesium beam primary frequency standards.

The experience of NRC in continuously operating such standards as clocks (28 clock-years) is summarized, and their capabilities are discussed. Developments that permit better monitoring of clock parameters are described. Possible evolutionary changes to Cs beam clock design are presented and the absence of dramatic improvements to accuracy is discussed.

The use of laser-cooled atomic beams is examined. It appears applicable as the source of slow atoms required to implement Zacharias's dream of a fountain atomic beam with a resonance linewidth of less than 500mHz, and (for Cs) an accuracy approaching parts in 10^{16}.

INTRODUCTION

The accuracy and long-term stability of time scales are established and maintained by reference to the primary frequency standards built and operated by national standards laboratories. Primary frequency standards are cesium beam clocks which have been designed specifically to be certifiable for accuracy. They are laboratory instruments and are usually rather large-several meters or more in length. They operate on the same principles as the commercial cesium clocks, but have specified accuracies that are about two orders of magnitude better. Thus the commercial cesium clocks are best used as secondary frequency standards or clocks calibrated against the primary laboratory clocks at time intervals commensurate with the drift rates of the commercial clocks. This is done annually for example, by the Bureau International de l'Heure (BIH) as it adjusts the average reported rates of commercial clocks from around the world to agree with the rates of the primary frequency standards. The resulting atomic time scale (TAI) has both robust redundancy from the commercial clocks and the accuracy of the primary frequency standards.

PRIMARY FREQUENCY STANDARDS

Primary frequency standards are built to a one-sentence specifiction: "The second is the duration 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". Primary frequency standards now have stated accuracies as small as a few parts in 10^{14}, and in this sense they are the most accurate devices ever built by mankind to any specification. To certify this level of accuracy, a large body of theoretical and experimental knowledge is necessary to relate the set of measured physical parameters of the clock to the frequency offset generated by each parameter. The process of certifying the accuracy of the frequency from a primary frequency standard is called "evaluation". A complete evaluation entails a re-measurement of all clock parameters which can affect the frequency, and is now usually done at time intervals of months to years for each primary frequency standard. The results of these evaluations are reported to BIH for the adjustment of the rate of TAI. Four laboratories operating eight primary frequency standards (or "PFS") report to BIH: NBS (USA, 1PFS), NRLM (Japan, 1PFS), PTB (W. Germany, 2PFS) and NRC (Canada, 4PFS).

Prior to 1975, all primary frequency standards were operated intermittently, with time scales being generated by continuously operating secondary clocks. However, at that time NRC's primary frequency standard, CsV, had demonstrated better short-term stability ($\sigma(\tau) < 10^{-14}$ at 1 day) than even a large ensemble of commercial cesium clocks, and was thought capable of long-term operation (it has operated continuously since then with the exception of ~1 week in 1984 when its ovens needed to be re-loaded with 10 grams of cesium.) In 1978, PTB put their primary frequency standard Cs1 into continuous operation. The PTB design was different than other cesium clocks, having approximate axial symmetry to the atoms' trajectories rather than approximate mirror symmetry. The PTB design brought some excellent features to primary frequency standards, but their flop out design intrinsically has a larger noise background, and poorer short-term stability: to reach a $\sigma(\tau)$ of 10^{-14} would take about 10 days. In the long-term, the frequencies of CsV and Cs1 have generally agreed within 5×10^{-14} and these two clocks exhibit an Allan variance of less than 1.6×10^{-14} out to beyond 1000 days (compared via LORAN-C, Symphonie 2-way satellite time transfer, and GPS common-view time transfer).

NRC has considerable experience in continuously operating primary frequency standards as clocks (more than 28 clock-years at this writing). In this time there have been daily comparisons of the four primary clock frequencies at the level of 10^{-14}, and comparisons with the two NRC masers as well. Interestingly, many of the initial pre-1975 tests of CsV were done vs these masers with a high beam current to give an Allan variance of $< 10^{-14}$ in 1 hour.

Evaluations

At NRC, full evaluations of known systematics are performed annually on all four primary frequency standards. During a full evaluation, the frequency of the clock is determined from the complete set of physical parameters of the clock as measured during that evaluation. Between full evaluations, the clock frequency is maintained by the stability of the physical parameters of the clock, supplemented by (sometimes daily) remeasurement of some physical parameters. The resolution of each of our measurements is sufficiently good so that the result from the most recent evaluation, considered independently of all previous evaluations, is used alone to determine the clock frequency.

Evaluations, and other maintenance, interrupt continuous clock operation. After an interruption the clock is reset to a time determined by its frequency in relation to the other primary (and secondary) clocks. Therefore the time scale of each clock depends somewhat on the frequency stability of the other clocks, but is completely independent of the frequencies of the other clocks. In this way the frequencies of our four primary frequency standards are available to the time community via the four time scales.

The most frequent partial evaluation is now the C field measurement on the three CsVI clocks. The measurement procedure using the $(4, -1) \leftrightarrow (3, -1)$ and $(4, +1) \leftrightarrow (3, +1)$ transitions[1] is now semi-automatic and is done each working day. The C field in CsV is much more stable and does not require measurement each day.

Transient Analysis

The newest addition to our evaluation procedure has been the determination of the velocity distribution from measurements of the dependence of the Ramsey resonance maximum on microwave power level[1]. It is now done during each full evaluation. Velocity distributions typical of the NRC CsVI clocks are shown in Fig. 1. This simple method provides a unique velocity distribution, has ample resolution to determine the second-order Doppler shift to several parts in 10^{15}, and reproduces the Ramsey pattern to better than 1%.

The success of this method led to the examination of the switching transient arising during square-wave frequency modulation both as a further check on the velocity distribution and as a possible means of monitoring several clock parameters while a clock is continuously operating.

The NRC clocks use square-wave frequency modulation to control the frequency of the master 5 MHz VCXO using the 9.192 GHz microwave Ramsey resonance. The linewidth is 60 Hz for CsV and about 90 Hz for the CsVI's. The modulation depth is ±33 Hz for CsV and ±46 Hz for the CsVI's. CsV and CsVI-C operate at a switching rate of 0.08 Hz, while CsVI-A and CsVI-B are normally operated at 0.8 Hz. Each time the frequency in the microwave cavity changes, the Cs atoms in the beam between the two Ramsey interaction regions experience first a pulse of one microwave frequency, then a pulse of the second frequency. It is straightforward to extend Ramsey's analysis[2] to this situation, and show that the transition probability for a particular velocity has a sinusoidal transient from the steady-state baseline.

Calculated transients for three velocities are shown in Fig. 2. The delay of each transient reflects both the distance between the Ramsey interaction regions (1m), and the distance from the cavity to the detector (.4m), while the relative amplitude depends on the number of atoms with that velocity, and the microwave power level. The velocity distribution and microwave power level as previously determined[1] were used to calculate the expected transient. This was convoluted with the measured impulse response of the (fast) electrometer used on the hot-wire detector.

The beam response of CsVI-C during 15000 switching periods was digitized and averaged with a dwell time of 50 μs/channel. The temperature of the hot-wire detector was raised to make its response time short enough to be neglected. No difference could be seen between the two senses of the transient: low-to-high frequency transition and high-to-low. The overall average is shown as the points in Fig. 3. The solid line is the calculated curve, scaled to the peak current. The agreement is better than 1%. Since the transient depends both on the Ramsey equation <u>and</u> the drift time from the second Ramsey region to the detector; thus <u>this</u> is another independent test of the correctness of the deduced velocity distribution. We attribute the small residual discrepancy to the phase transient (~ 5° peak excursion from the ideal microwave phase for ~ 600μs) present due to the PLL in this 12.6 MHz switching synthesizer.

The great merit of this technique is that data can be collected with the clock in normal operation. It can monitor both resonance size (much like the second harmonic monitor of commercial cesium clocks), and microwave power level as seen by the Cs beam (a change of microwave power level shifts the centroid of the transient).

Servo Test

In our 28 clock-years of experience with primary frequency standards, the usual form of component malfunction has been catastrophic and at least visible as a step change in frequency. Our usual method of confirming a diagnosis of the problem, and repairing the fault, has been unit replacement. This technique does not catch intermittent, similar failures in a unit and its backup.

A better plan than unit replacement is to have an on-line monitor that can assure correct operation of the on-line unit. The monitor should ideally operate on a principle as different as possible from the on-line unit. Our new monitor of the servo is shown in Fig. 4. The electrometer output is digitized and added to (or subtracted from) an accumulator which acts as the lock-in amplifier and integrator does in the on-line servo. In our first tests, we used a 12 bit ADC with a 400 μs dwell time, and a computer for the accumulator. With this system, the digital system could only reach a 60% duty cycle, but this was still sufficient to validate the on-line servo's operation in less than a day, as shown in Fig. 5, without disturbing normal clock operation. We are now building a version in hardware with a 16 bit ADC and a 100% duty cycle.

Improvements to Conventional Clocks

In the 30 years since the first laboratory cesium beam frequency standards, there has been almost a factor of 10^4 improvement in accuracy, which has almost entirely been due to work on stabilizing and exactly understanding the lineshape: to the extent that specified accuracies are now less than 10^{-5} of the atomic resonance linewidth. Very little has been done to reduce the linewidth. Much of the work that is in progress (such as optical pumping for state selection and detection) seem directed more at improvements in stability - which can not necessarily be converted into improvements in accuracy. For example, the fact that CsV has been run at 30 times its presently used beam current does not mean that there is a potential $\sqrt{30}$ improvement in accuracy available, although there is a potential $\sqrt{30}$ improvement in stability. Improvements to the accuracy of conventional primary cesium clocks are certainly feasible, but they will not be dramatic improvements.

ZACHARIAS FOUNTAIN

Also 30 years ago, a non-conventional cesium beam clock was designed and constructed (1956). It aimed at observing slow Cs atoms that rose at ~ 10m/s through the microwave cavity (1st Ramsey passage), followed a narrow parabola like a water droplet in a fountain to drop back through the cavity some 2 seconds later (2nd Ramsey passage). This would give a Ramsey linewidth of 250 mHz, some 200 times narrower than typical present-day primary frequency standards, and potentially 10 to 200 times more accurate.

Zacharias's system was cryo-pumped using liquid helium[3], but the collision rates for slow atoms near the cesium oven were too high and no slow beam was ever detected.

In 1984 De Marchi[4] re-examined the Zacharias fountain, adding the ideas of optical pumping (to increase the beam current by pumping all atoms into the clock transition state), optical detection, and wide-open Fabry-Perot microwave resonators. He examined scattering near the cesium oven and concluded that with a $300(\mathrm{mm})^2$ source area, and with the oven operating at 350K, an interesting stability commensurate with the projected accuracy could be obtained. However, our experience leads us to prefer a Cs consumption rate some 100 times lower than this for prolonged operation: thermal sources are not good sources for very slow cesium atoms.

Laser Cooling of Atomic Beams

An atom of mass m travelling at a speed v which absorbs a counterpropagating photon of frequency ν, energy $h\nu$ and momentum $\frac{h\nu}{c}$, has its momentum mv, reduced to $mv' = mv - \frac{h\nu}{c}$ i.e. its velocity has been reduced by $(v - v') = \frac{h\nu}{mc}$. In a characteristic time τ, the lifetime of the excited state, the atom will re-radiate in a direction that is random (neglecting polarization). After N such absorbtions the velocity is expected to be $v_n = v - \frac{Nh\nu}{mc}$, with a standard deviation of $\sqrt{N}\ \frac{h\nu}{mc}$ in both the longitudinal and transverse direction.

This principle was first used with laser light to slow Na atoms. In the first experiment[5], no attempt was made to keep the atoms in resonance as they slowed down and the Doppler shift took them out of resonance. Phillips[6] obtained a continuous beam of slowed atoms by Zeeman-tuning the resonance to compensate for the Doppler shift, and later demonstrated the existence of stopped and magnetically trapped Na atoms. Ertmer et al[7] chose another approach to stop Na atoms: they chirped the laser frequencies to compensate for the Doppler shift. Cesium atoms have been stopped by Watts and Wieman[8] using chirped semiconductor diode lasers. Transverse cooling has been demonstrated as well for beams of Na atoms[9].

Thus enormous progress has been made towards a controlled source of slow Cs atoms, which might be suitable for a Zacharias fountain. What features will be required of this source to be able to attain an accuracy of $< 10^{-5}$ of the atomic resonance linewidth? In our opinion the main feature desired is stability: this may result in a preference for a continuous beam such as might be extracted from the Zeeman tuned method. In addition, microwave interrogation methods will likely have to be developed to handle the servo problem in the case of fluctuating atomic beam intensity (relatively easy) and atomic resonance linewidth fluctuations due to fluctuations in velocity distribution (a much harder problem).

In any case, there now exists the possibility of a source of slow Cs atoms which may be suitable for feeding a Zacharias fountain with an intense beam of slow atoms. Although it is probably premature to discuss a final design, it is instructive to examine whether or not a workable primary frequency standard might be constructed using only demonstrated techniques.

In the first examination, we choose to forego transverse cooling[9] since its limits (and hence its optimal contribution) have not been clearly demonstrated. Although transverse cooling may greatly improve short-term stability, it does not appear necessary to invoke transverse cooling to obtain the intensity of the cooled beam that is required to yield the full accuracy of the Zacharias fountain.

Chirped laser cooling[7] provides a pulsed beam, and this is to be avoided in the quest for servoing the clock frequency to 10^{-5} of the linewidth. Zeeman tuning[6] can provide a continuous beam pumped into a single hyperfine substate. There remains the problem of extracting a continuous, stable beam of atoms in the 5-10 m/s range. What is desired is a velocity sensitive means to remove the Cs atoms from the cyclic resonance $6S_{1/2}$ F = 4, m_F = 4 $\leftrightarrow$ $6P_{3/2}$ F = 5, m_F = 5 cooling states. This might be done by a second laser tuned to another transition. This second laser should be stable to perhaps 10 kHz to avoid contributing noise generated by fluctuations in Ramsey line width due to velocity distribution fluctuations. Another approach to obtain a continuous slow beam is to select a position in the Zeeman shift solenoid. For a given solenoid current, at each position, there is a velocity distribution, and this might be extracted by applying abruptly a Stark shift (electric field of perhaps 50kV/cm) that throws the atoms sufficiently out of resonance to enable them to leave the solenoid.

The length S of the deceleration region in the solenoid depends on the deceleration "a" that can be obtained ($\lesssim 5 \times 10^4 m/s^2$ for Cs) and the initial resonant velocity v_o. Effectively all atoms in the velocity range less than v_o will be slowed down. To reach a final velocity v_f the minimum length S is thus given by $v_o^2 - v_f^2 = 2aS$, or $S \approx \frac{v_o^2}{10^5\ m/s^2}$. In the absence of transverse cooling, the highest flux is obtained for a relatively short S (eg. 10 cm with v_o = 100 m/s, cooling about 1/50 of the initial Cs beam to ~ 10 m/s). The slow atoms leaving the solenoid should then be separated from the fast atoms, perhaps with hexapole lenses.

The atoms leaving the solenoid will be in one hyperfine substate, but not in the (4,0) or (3,0) substates suitable for clock operation. In addition, it is very important to be able to evaluate the C field using the (4,+1) $\leftrightarrow$ (3,+1) and (4,-1) $\leftrightarrow$ (3,-1) microwave transitions. The required (almost pure) substate preparation can be obtained by repeated adiabatic fast passage[10]: eg. the sequence (4,4) $\rightarrow$ (4,3) $\rightarrow$ (4,1) $\rightarrow$ (4,0) (and sometimes $\rightarrow$ (4,-1) for C field evaluation).

The Fabry-Perot open resonators suggsted by De Marchi[4] may be suitable for the Ramsey microwave resonator. However, more intricate resonators with perhaps 3 microwave frequencies, present simultaneously, may be useful if there is noise due to variations in the Ramsey resonance linewidth due to fluctuations in velocity distribution.

The C field required to resolve the Rabi pedestals will be in the range of 0.5 to 4 milligauss, depending on the resonator design. Depending on the purity of the adiabatic fast passage substate preparation that could be obtained, significantly lower C fields might be suitable. Thus there appears to be no insurmountable obstacle in evaluating the C field frequency offset to a few parts in 10^{16}.

The ideal detector for the Zacharias fountain would be state sensitive, to measure the intensity ratio of the (4,0) to (3,0) states after the atoms' second passage (down this time) through the Ramsey resonator. This would eliminate noise due to intensity fluctuations in the process of cooling and preparing the (4,0) state beam. The detector should also be large in area (10 - 100cm^2), contribute no noise, and be position-sensitive. All these wonderful attributes appear to be available from a two-photon (one resonant, one non-resonant) photoionization detector.

Conclusion

Dramatic improvement of the accuracy of cesium beam primary frequency standards (now a few parts in 10^{14}) appears to require a correspondingly great increase in the observation time of the atoms in the cesium beam. One approach has been presented: the Zacharias fountain fed by a laser-cooled beam of slow Cs atoms. There appears to be no problem which would admit of no solution. A realistic ultimate goal for such a primary frequency standard might be an accuracy of a few parts in 10^{16} in a standard capable of continuous operation.

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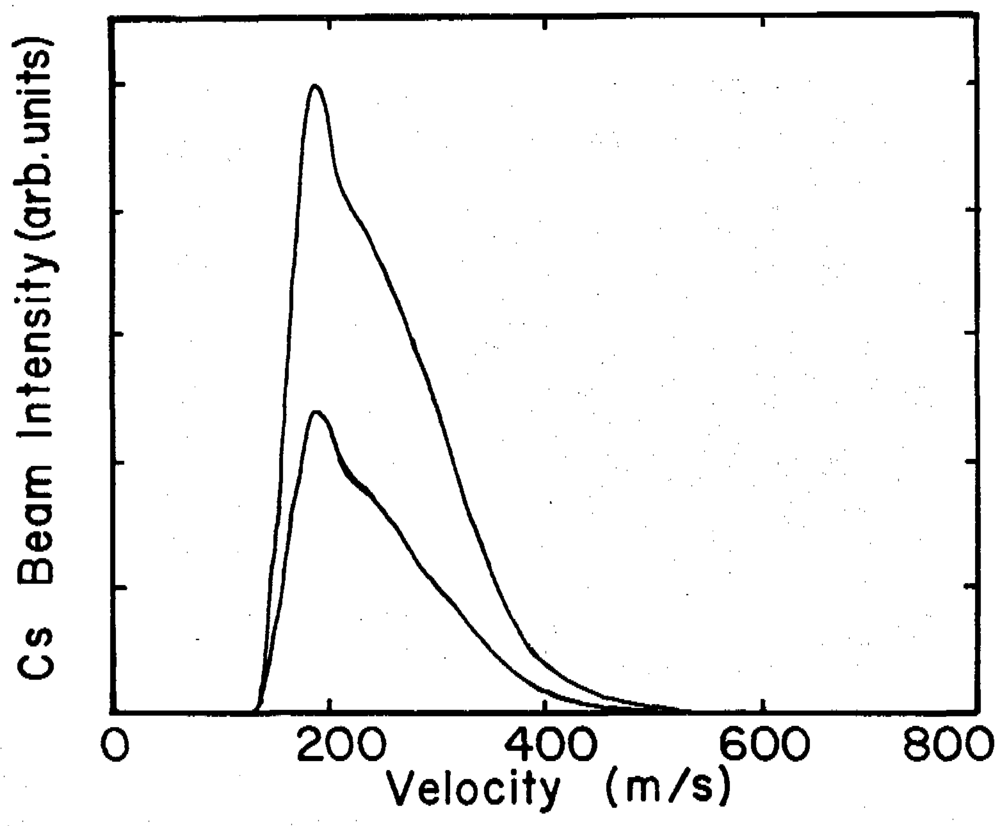

Fig. 1 - Velocity distributions for a CsVI clock, determined using the method of reference 1. The lower curve is for an oven temperature of 85°C, and has an average velocity of 248.5 m/s. The upper curve shows the effect of raising the oven temperature to 95°C: the average velocity is 250.9 m/s.

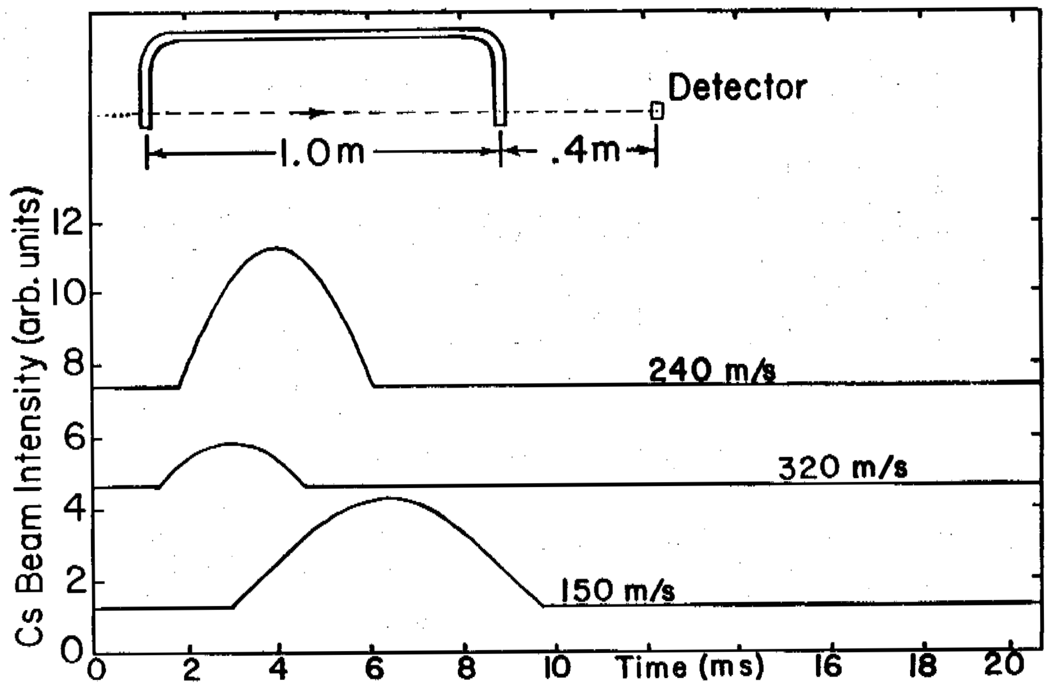

Fig. 2 - Square-wave FM switching transients for three sample velocities of Cs atoms, calculated for a CsVI clock. The inset shows the geometry of the two microwave regions and the detector for a CsVI clock.

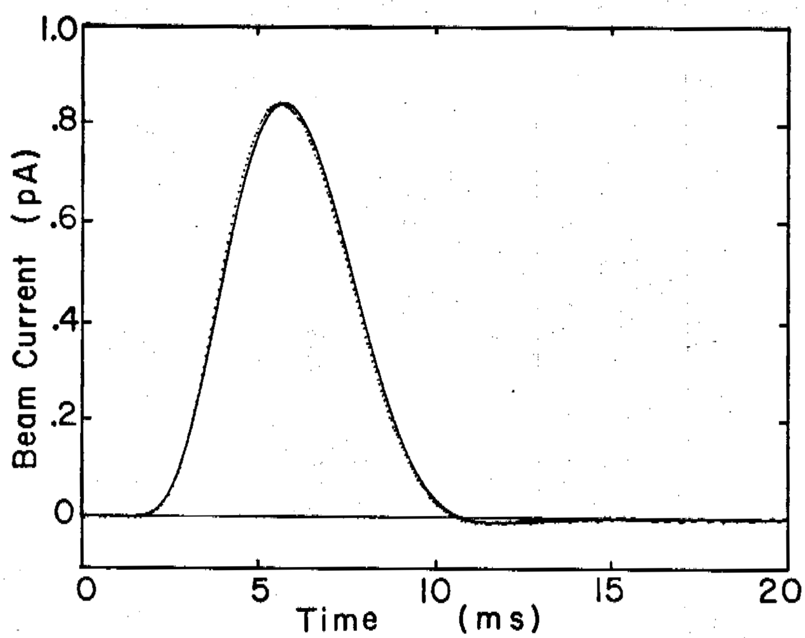

Fig. 3 - Experimental and theoretical transients for CsVI-C. The dots are measured values and the solid curve is calculated, using no free parameters except a scaling to the experimental beam current in the transient.

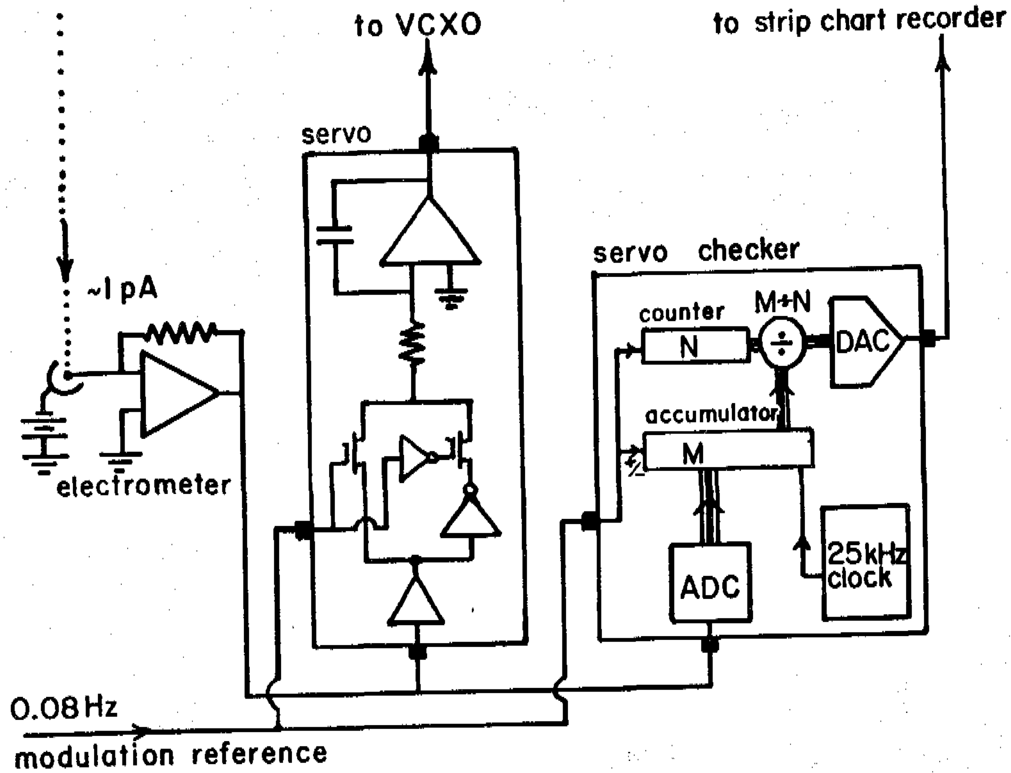

Fig. 4 - Schematic diagram of the essentials of the servo lock-in amplifier and the digital servo checker.

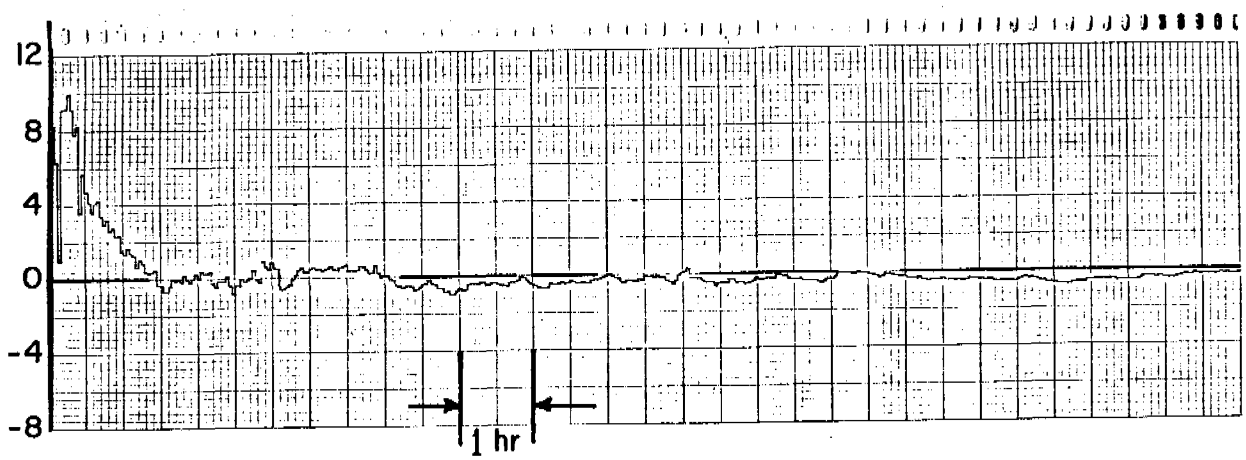

Fig. 5 - Strip chart recording showing the difference between the servo lock-in amplifier (servo loop closed) and the digital servo checker (running with a 60% duty cycle). The units of the vertical scale correspond to a fractional frequency offset of 10^{-14}.