PERFORMANCE AND OPERATION OF THE NRC PRIMARY CESIUM CLOCK, CsV

A.G. Mungall, H. Daams, D. Morris, and C.C. Costain
National Research Council, Ottawa, Canada

ABSTRACT

Since May 1, 1975, the NRC primary cesium beam frequency standard, CsV, has operated as a primary clock, generating directly a new time scale, PT(NRC CsV). Steps in the development of CsV from a frequency standard to a clock, and new error evaluations using the two NRC autotuned atomic hydrogen masers as stable frequency references are outlined. Details of both mechanical and electronic construction leading to successful clock operation are also discussed. The design of a new 12.632 MHz frequency synthesizer and modulator with very low spurious sidebands is outlined. Methods of partial reevaluation of systematic errors and frequency offsets during clock operation, a procedure necessary in order to maintain primary standard accuracy, are described. The accuracy of PT(NRC CsV) is estimated to be about ± 9 ns per day if all systematic errors are additive, and about ± 5 ns per day if they act independently in a random manner. The frequency stability of PT(NRC CsV) is about 1 to 2 x 10^{-14} for periods greater than 4 hours, the short term stability being determined by the low cesium beam resonance amplitude of 1.6 to 2.0 pA normally employed for clock operation. Replenishment of the two cesium ovens is expected to be necessary at intervals of several years.

INTRODUCTION

In 1967 the internationally accepted unit of time, the SI second, was redefined as 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. This definition was chosen as that most likely to provide the best basis for a unit which could be realized independently and without recourse to other standards. However, its implementation has produced two basically different types of devices, the primary long beam laboratory cesium frequency standard and the primary short beam commercially produced cesium clock. The former is devised so as to reproduce physically the unit of time to a very high degree of accuracy, but only for short periods of a few hours or days. The latter also reproduces the unit of time, but to a lesser degree of accuracy, and in addition, accumulates these units over an indefinite period up to several years to produce a time scale.

Historically, laboratory frequency standards were the first to be developed and were used to calibrate the frequency or rate of one or more clocks used to generate an atomic time scale. Initially such clocks consisted of free-running quartz crystal oscillators whose output was frequency-divided so as to yield the required hours, minutes, and seconds of the time scale. Later developments resulted in the replacement of these free-running oscillators with ones controlled by an atomic resonance, but the principle of operation remained the same. In general, frequency standards operate only for short periods either because they are not designed to function continuously or because their systematic errors are time-dependent and prolonged operation reduces rather than enhances the accuracy of a calibration.

Primary clocks have undergone intensive commercial development[1-3] during the past 10 years. Attention has centered on small, light-weight, portable instruments with accuracies of several parts in 10^{12} and stabilities over periods of weeks or months sometimes attaining and occasionally exceeding a part in 10^{13}. In national laboratories such instruments have usually been used in groups of at least four, and the primary aim has been to average their individual time scales, often with complicated weighting procedures, so as to obtain a mean scale exhibiting greater uniformity or rate stability than that provided by any member of the group. Such a mean scale can, if desired, be steered by means of periodic calibrations, widely separated in time, by a primary laboratory frequency standard so as to produce not only a more uniform but also a more accurate time scale than that realizable with any of the individual clocks. The period required for each calibration depends primarily on the stability of the clocks in the group, but may also be affected by the long term stability of the primary standard if its systematic errors are time dependent. In general however, the accuracy of the time scale so produced can only approach but never equal that of the primary standard, unless the mean rate of the ensemble is so uniform and the primary standard so stable that successive calibrations result in a statistical improvement in the accuracy. In practice, such improvement is unlikely. It is thus apparent that the application of such techniques constitutes a compromise resulting from the combination of unstable secondary clocks capable of extended periods of operation and very accurate primary laboratory frequency standards capable of continuous and accurate operation only over short periods.

The method of time-keeping used at NRC[4,5] until very recently followed this compromise procedure, with CsIII, a long beam laboratory frequency standard developed in 1963, providing twice-weekly calibrations of several Hewlett-Packard clocks, each of which produced alternate physical realizations of UTC(NRC) and AT(NRC). Because only two or three such clocks were usually in operation at any one time, the best was chosen as the basis of the scales actually used.

As mentioned in an earlier publication[5], it was decided about six years ago to try to combine the high accuracy of a long beam primary cesium frequency standard with the continuous operating characteristics of clocks so as to produce a single high-accuracy clock. The design had to be such that not only was continuous operation possible over extended periods, but also that the systematic frequency shifts be small, constant, and re-evaluable during clock operation, with only brief inoperative periods resulting from equipment failure or certain of the re-evaluation procedures. Such a clock has now been in operation at NRC since May 1, 1975, and its performance to date indicates that these design considerations have been met.

The results to be described in this paper show that it now appears possible to produce a highly uniform, accurate, and reliable time scale based on a single long-beam primary cesium clock and only a few stable auxiliary secondary clocks necessary to maintain continuity during evaluation periods. These results indicate that the time scale, PT(NRC CsV)*, generated by the new NRC primary clock, CsV, exhibits a uniformity of the order of ± 100 ns over an initial six-month period of operation. Comparisons with the International Atomic Time Scale, TAI, also show that the rate of PT(NRC CsV) has remained within 1.4×10^{-13} of previous short term measurements made during 1973 and 1974, which were in close agreement with those made with respect to the primary cesium standards at the National Bureau of Standards of the USA and the Physikalisch-Technische Bundesanstalt of West Germany.

In addition to these improvements and simplifications in time-keeping at NRC, continuous operation of CsV has also greatly simplified routine calibrations of commercial frequency and time standards.

EXPERIMENTAL

1. Physical and Electronic Design

Since the general physical characteristics of CsV and its performance as a frequency standard have already been described in a

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*The terminology PT is used instead of AT since it represents a scale of proper time with no corrections being applied for altitude above sea level.

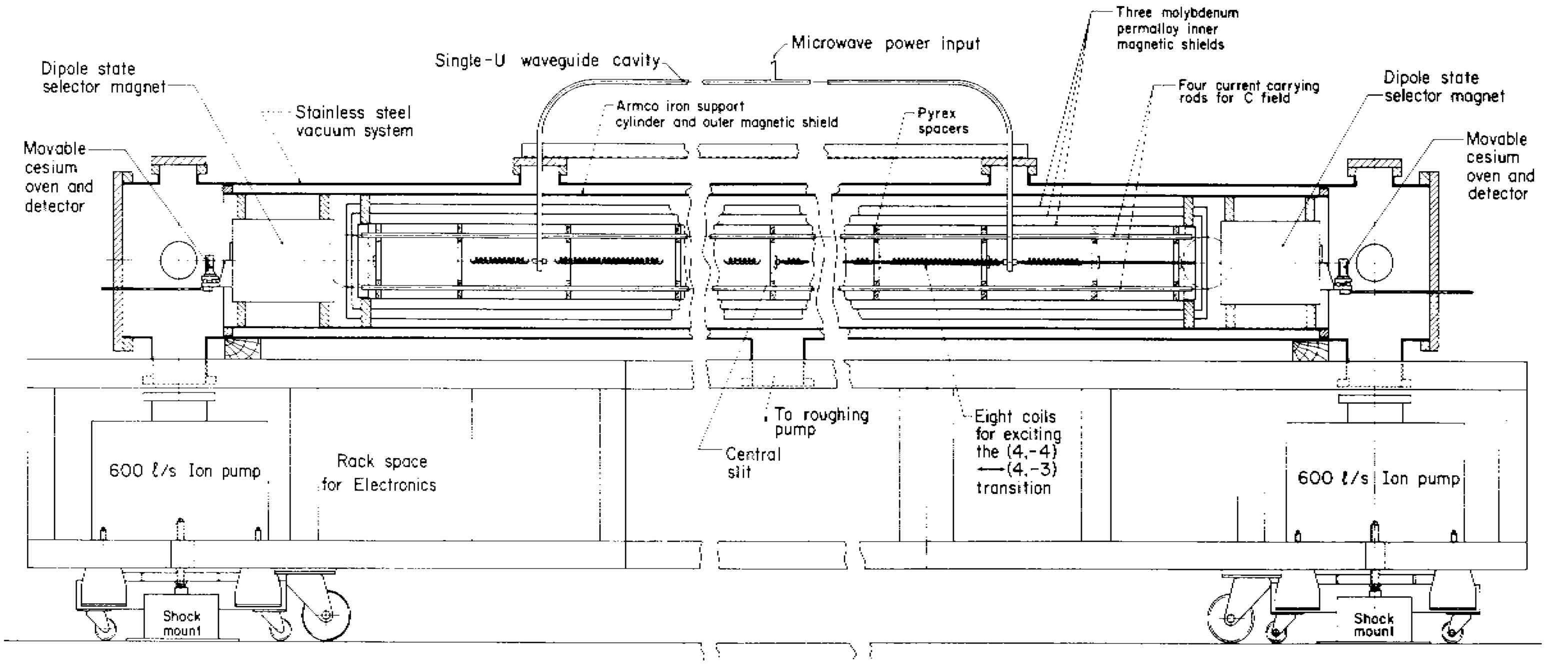

Figure 1. The NRC cesium beam primary clock, CsV.

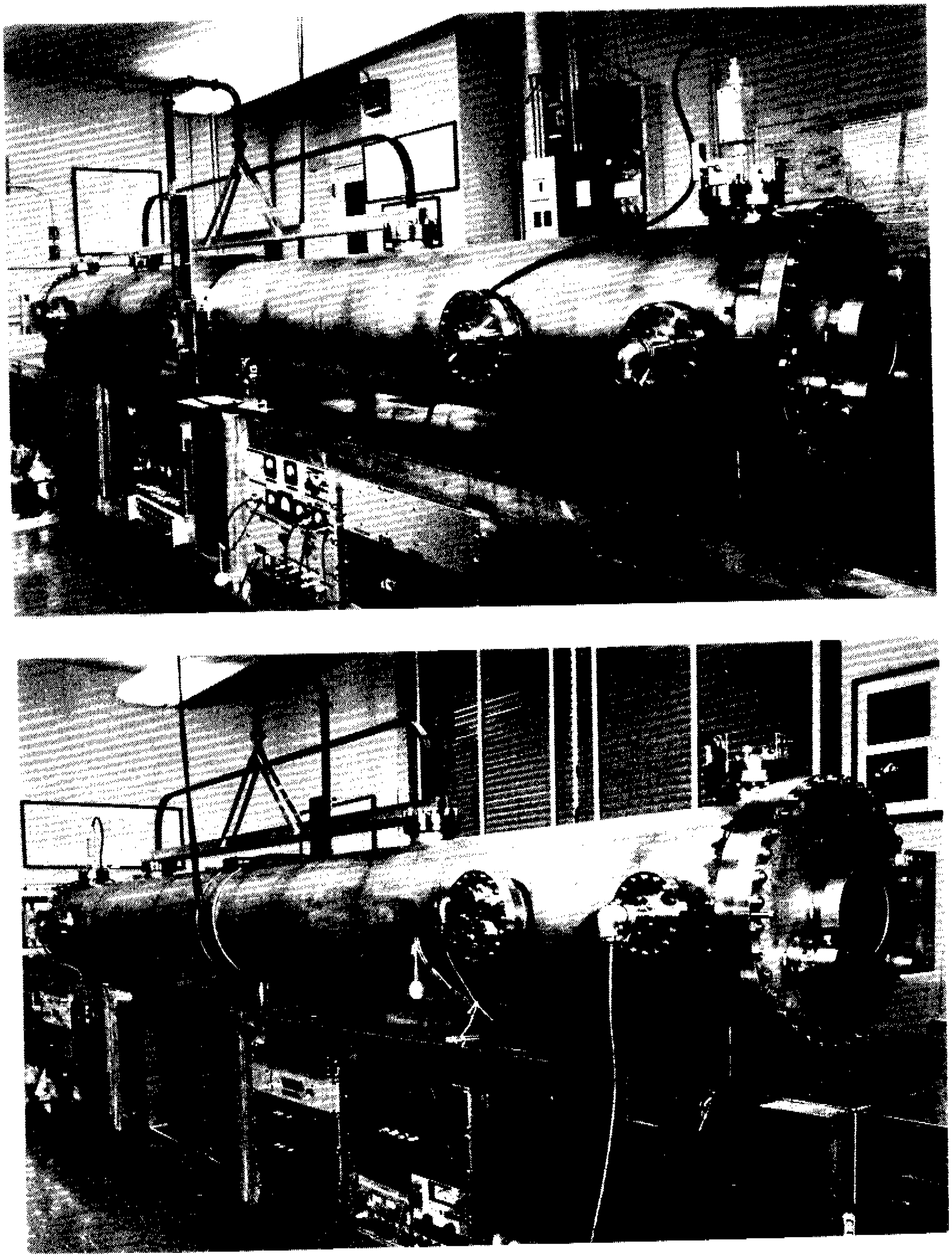

Figure 2. - Photographs of CsV showing the beam tube and all electronics required for clock operation. Battery supplies are shown in the background of the lower photograph.

previous paper[7], and no major modifications to the device have been made, other than modifications to the electronics systems, only a brief outline will be given here.

A section drawing of CsV is shown in figure 1, and two photographs of it with all the modified electronics required for clock operation are shown in figure 2. In essence, CsV consists of a conventional transverse C field device with a bi-directional ribbon-type cesium beam. The dipole state selector magnets are placed outside the atomic transition region which consists of a central space magnetically shielded by three concentric molybdenum permalloy cylinders. This space contains a four-rod current-carrying structure providing a C field uniform within ± 0.06%. A series of optically ground pyrex glass spacers provides accurate alignment of the rods and also support for a series of coils used to excite the $(4,-4) \leftrightarrow (4,-3)$ transitions required for C field measurement. The shields and state selector magnets are mounted inside an Armco iron cylinder which also provides additional magnetic shielding. The 2.1 m long microwave cavity is external to the shields and vacuum system and enters through slots in the four cylinders. The cesium beam is produced by either of a pair of transversely movable ovens, one at each end of the vacuum tube, and is detected by one of a pair of simple hot wire 80% platinum, 20% iridium detectors mounted adjacent to each oven. Each oven and detector pair is mounted on a movable carriage attached to the outer end of each state selector magnet. A low hot wire temperature of less than 800°C is used to minimize incidental heating of the adjacent oven and to provide a detector noise level of about 3×10^{-16}A in a 1 Hz bandwidth. For clock operation and a frequency stability of a few parts in 10^{14} over a 1 h averaging time, a beam current of 1.5 to 2.0 pA is required, and for frequency standard operation and systematic error evaluation, beam currents up to 20 pA provide correspondingly better stabilities. For the lower beam current required for clock operation, the 4 g cesium charge in each oven should provide an operating life of several years. The vacuum system is pumped continuously by two 600 ℓ/s ion pumps which provide a typical operating pressure of 2 to 4 x 10^{-9} Torr. All electronic systems, including one ion pump supply but excepting the second which is operated from 220 vac, are supplied by a pair of 28 v batteries and are mounted in the table below the vacuum tank. Total power consumption is about 200 w or 7.3 A at 28 v. The two batteries are float-charged by 0.01% voltage regulated power supplies operated from a 115 vac line emergency protected by two diesel generators.

The previous publication on CsV gives details of the general performance as regards the microwave and low frequency spectra, and these will not be repeated here. However, extensive modifications have been made to the microwave excitation system, particularly as regards the 5 MHz crystal oscillator, and multiplier and synthesizer

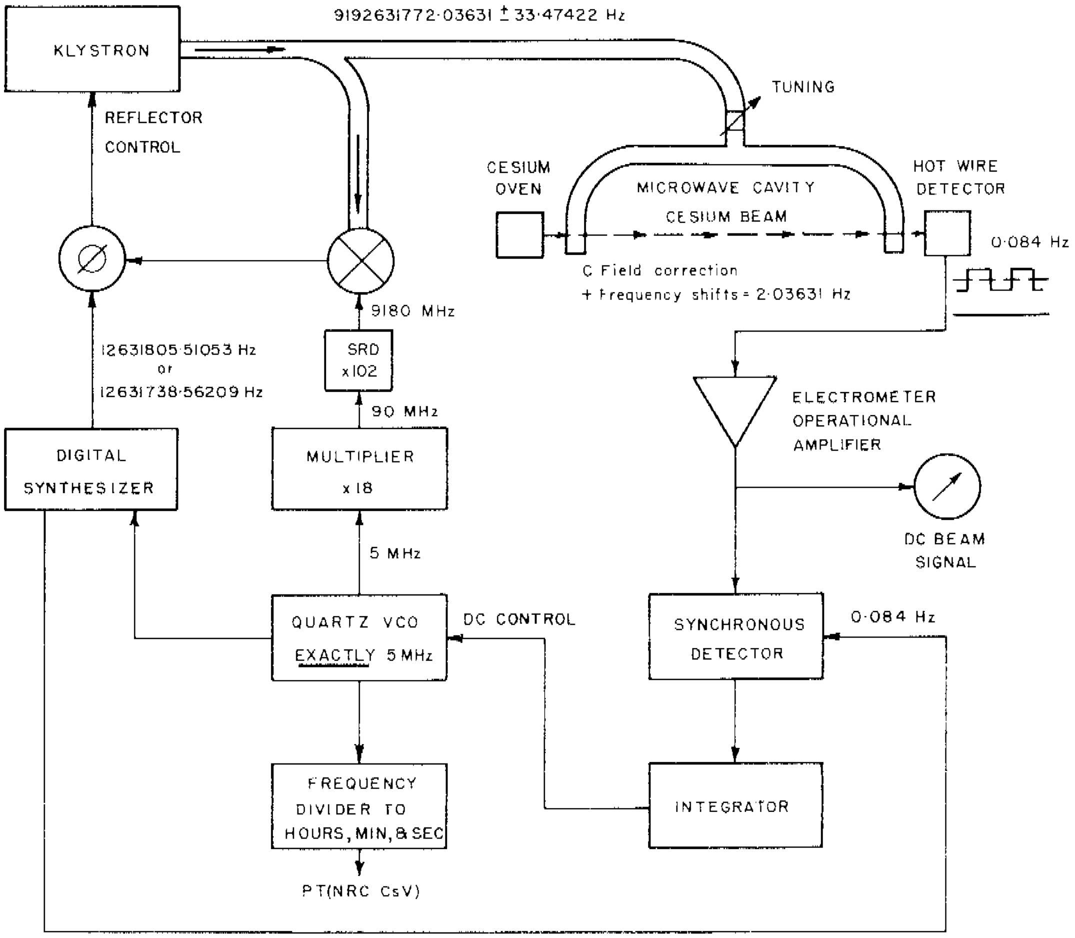

Figure 3. Complete electronics system for microwave excitation of the cesium resonance and servo control of the 5 MHz oscillator.

systems. The modified electronics systems are shown in figures 3 and 4. As a result of the improved design of the oscillator, distribution amplifier, solid state 5-90 MHz multiplier, and 12.6 MHz synthesizer and klystron phase lock system, the power dependent frequency shifts which had precluded clock operation earlier were essentially eliminated. These shifts apparently arose from time-dependent spectral impurities in the microwave excitation signal which were produced or enhanced by each of the units mentioned above. A klystron was used in preference to a Gunn diode as the microwave oscillator since the latter appeared to contribute to the spectral impurities mentioned. With the new microwave excitation system, the power dependence of the resonance

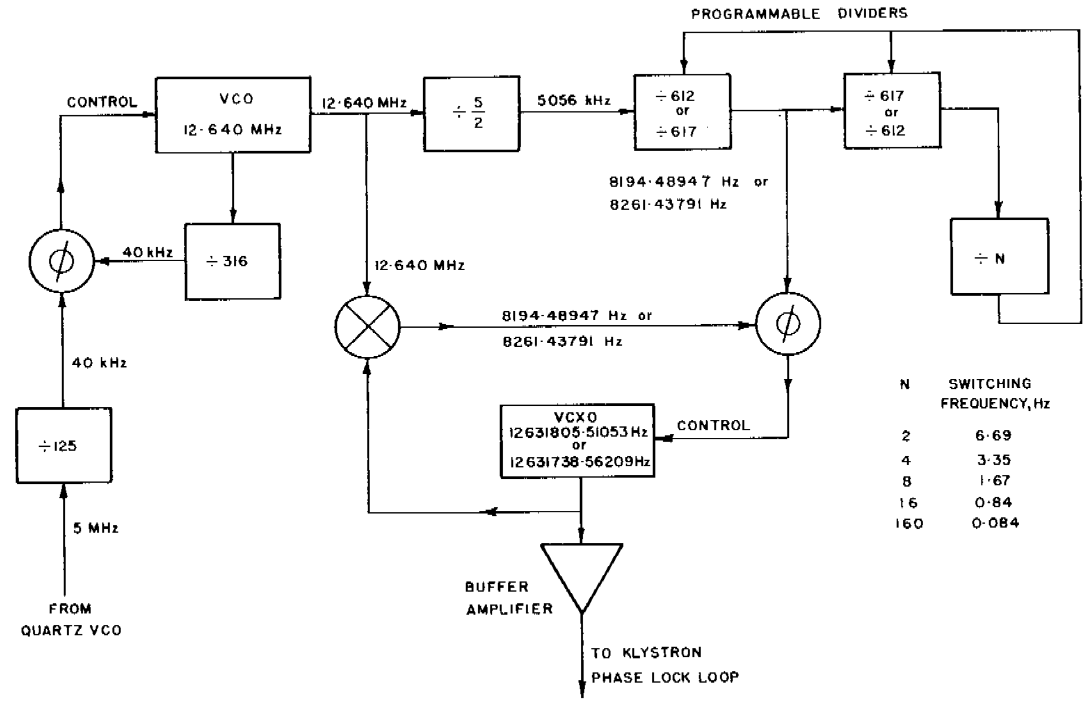

Figure 4. The 12.6 MHz digital synthesizer.

frequency is approximately that to be expected from the combined effects of the second order Doppler shift and the cavity phase difference.

One of the most important circuit modifications concerned the 12.6 MHz synthesizer, the earlier model of which had been found to give rise to troublesome sidebands at the cesium resonance frequency. A new synthesizer of fundamentally different design was constructed. With this design no sidebands occur within 8 kHz of the central frequency, and the levels of those which do occur are below 85 dB with respect to carrier. Figure 4 indicates the principle of operation. From an input frequency of exactly 5 MHz two phase-locked output frequencies of 12 631 805.510 53 and 12 631 738.562 09 Hz are selected alternately at switching frequencies of about 6.69, 3.35, 1.67, 0.84, or 0.084 Hz. The lowest frequency is normally employed for clock operation, since, as will be mentioned later, it gives rise to a negligible systematic frequency shift. Mixing of these two 12.6 MHz frequencies with the 9180 MHz signal produced by frequency multiplication from the same 5 MHz signal then provides alternately two beam excitation microwave frequencies of 9 192 631 738.562 09 and 9 192 631 805.510 53 Hz. These two frequencies, which have a mean of 9 192 631 772.036 31 Hz are separated by about 66.9 Hz, which is slightly greater than the CsV resonance line width of about 60 Hz. Since the cesium resonant frequency is defined as exactly 9 192 631 770 Hz, the synthesized frequency is thus exactly 2.036 31 Hz or 2 215.15 parts in 10^{13} above this defined value. The sum of all the systematic frequency shifts in the CsV resonant frequency is then adjusted by altering the C field so as to be approximately equal to this offset of 2 215.15 x 10^{-13}. This is accomplished through discrete current steps in the C field supply, each step corresponding to a frequency shift of about 3.5 x 10^{-14}. Consequently, the frequency of CsV can be set with a precision of about ± 2 x 10^{-14}.

A choice of frequencies was provided for the switching rate between the two synthesized frequencies so as to enable tests to be made for possible dependence of the CsV frequency on this parameter. For frequencies of 1.67 and 3.35 Hz systematic frequency shifts of -5 and -25 x 10^{-14} from the value for 0.084 Hz were observed. No significant change occurred between switching frequencies of 0.084 and 0.84 Hz. For normal clock operation a switching rate of 0.084 Hz was chosen so as to avoid any significant systematic error and also to permit low temperature operation of the hot wire detector and consequent low detector noise level.

It will also be noted from consideration of the method used to obtain the switching frequencies that the times of frequency switching coincide with the zero crossing of the two switched frequencies, thereby obviating possible problems arising from phase discontinuities in the microwave exciting signal.

In addition to the method of synthesizing the 12.6 MHz signals outlined above, which is that normally used for clock operation, an alternate system was also devised. The latter employed a commercial synthesizer of completely different design and hence different sideband structure. Consequently, it was possible, by comparing the clock frequencies produced by the two different systems, to determine whether these sidebands caused significant resonant frequency shifts. The alternate synthesizer was one which could be binary-code remotely programmed by a specially constructed auxiliary unit so as to switch between frequencies of 631 772.036 ± 30 Hz at switching rates of 0.1 and 1.0 Hz. Summation of these frequencies with exactly 12 MHz derived from the master 5 MHz oscillator then provided the 12.6 MHz signal required for the klystron phase lock loop. Measurement of the CsV output frequency for operation with either synthesizer system indicated that no significant frequency difference existed. Since it was known that the sideband levels for the synthesizer normally used were very much lower than those for the alternate system, frequency shifts arising from any such sidebands were considered to be negligible.

2. Measurement of Systematic Frequency Shifts

A. General

As mentioned in the previous section, the C field correction is adjusted so that the sum of it, the frequency offset arising from the method of frequency synthesis, and all the known calculable or measurable systematic shifts are approximately zero, within the limits of precision of setting of the C field current source. In this way, the clock frequency is adjusted to within 2×10^{-14} of the nominal value.

In CsV the known systematic frequency offsets are those arising from the C field, δf_H, the cavity phase difference, δf_c, the Millman effect, δf_m, and the second order Doppler effect, δf_d. In general each of these is dependent on both the beam direction and the C field direction, and these two parameters can be denoted by the subscripts AB, BA, N, and R, the first pair referring to beam direction, and the second pair to normal or reversed C field direction. A normal C field direction is one for which the magnetic field is in the same direction throughout both state selectors and the C field region.

Measurements of the changes in the CsV frequency are made with respect to the stable reference frequency provided at 1420 MHz by one of the two auto-tuned NRC hydrogen masers. If the cesium and hydrogen normalized frequencies are defined by f_{CsV} and f_M, and a constant K is used to account for the setting of the synthesizer in the 5 to 1420 MHz maser frequency synthesizer chain required to provide a suitably slow beat between the cesium and hydrogen frequencies, the following relationships may be shown to exist between them and the systematic frequency shifts. In these expressions, δf_m and δf_c are arbitrarily chosen as those for the AB and N subscripts, and the sign of each changes with either beam or C field reversal. The beat frequency, normalized with respect to 1420 MHz, is a measure of the difference $f_{CsV} - f_M$.

$$\Sigma\delta f_{iAB,N} = + \delta f_m + \delta f_c + \delta f_{HAB,N} + \delta f_{dAB} = f_{CsVAB,N} - f_M + K \qquad (1)$$

$$\Sigma\delta f_{iBA,N} = - \delta f_m - \delta f_c + \delta f_{HBA,N} + \delta f_{dBA} = f_{CsVBA,N} - f_M + K \qquad (2)$$

$$\Sigma\delta f_{iAB,R} = - \delta f_m + \delta f_c + \delta f_{HAB,R} + \delta f_{dAB} = f_{CsVAB,R} - f_M + K \qquad (3)$$

$$\Sigma\delta f_{iBA,R} = + \delta f_m - \delta f_c + \delta f_{HBA,R} + \delta f_{dBA} = f_{CsVBA,R} - f_M + K \qquad (4)$$

Methods of determining each of these quantities will now be outlined.

B. C field Correction

As mentioned in the earlier paper describing CsV, the C field correction δf_H is determined from the mean square value of the $(4,-4) \leftrightarrow (4,-3)$ transition frequencies measured by means of the 6 axially oriented low frequency exciting coils which are located between the two microwave interaction regions. As in the previous analysis the value of δf_H was given by the expressions

$$\delta f_H = \Delta f_H / 9\ 192\ 631\ 770$$

and

$$\Delta f_H = 427.18 \left[\Sigma (f_o/349746)^2\right] /6$$

where f_o is the resonant frequency measured for each of the coils, and the two constants are those which were experimentally verified in the previous evaluation. In practice, however, because of the ± 0.06% C field uniformity the simpler expression

$$\Delta f_H = 427.18 \left[\frac{\Sigma f_o/6}{349746}\right]^2$$

provides the same result within 2×10^{-16} with reference to the cesium resonance frequency. Because of uncertainties in the experimental determination of the two constants, which have not been improved since the previous evaluation, the uncertainty in the values of δf_H is of the order of $\pm 4 \times 10^{-14}$ with reference to the cesium resonance frequency.

C. Second Order Doppler Effect

The second order Doppler effect, which gives rise to the frequency offset δf_d, is determined from the shape of the Ramsey resonance by means of a curve-fitting technique described in a previous publication[8]. This technique is based on the assumption that a truncated Maxwellian velocity distribution can be used to approximate the actual distribution of atomic velocities which exists in the detected beam. Small alterations in the beam optics subsequent to the first evaluation of CsV and prior to inception of clock operation resulted in velocity distributions which were essentially the same for both beam directions. Figure 5 shows the Ramsey resonances for the two beam directions, measured for an exciting power level 3 dB below that for maximum transition probability. The closest fit between experimental and calculated resonances occurs for $p_{min} = 1.0$ and $p_{max} = 1.8$, the parameters p_{min} and p_{max} representing the ratios of the low and high beam velocity cutoffs with respect to the most probable atomic velocity in the cesium oven. For these values δf_d is -4.1×10^{-13}, and the estimated uncertainty resulting from errors in curve-fitting is about 2×10^{-14}.

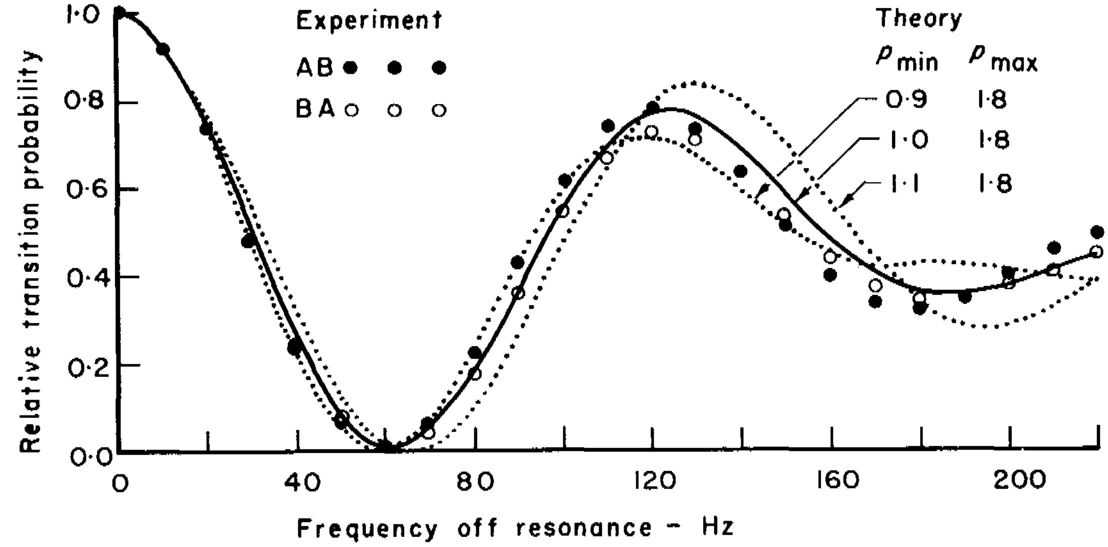

Figure 5. Measured and calculated Ramsey resonances for both beam directions.

D. Cavity Phase Difference and Millman Effect

The systematic errors resulting from a cavity phase difference and from a change in angle between the C field and the microwave exciting field along the beam direction, represented by δf_c and δf_m respectively, can be determined by C field and beam reversal. The quantity δf_m, which represents the Millman effect[10] as applied to σ transitions, cannot be isolated from δf_c by means of beam reversal alone, since both δf_m and δf_c change sign with reversal of the beam direction. However, C field reversal does not affect the sign of δf_c, and consequently the two frequency shifts can be separated, as is apparent from inspection of equations 1 to 4. In practice, also, since both δf_c and δf_m as well as δf_d are dependent on the beam velocity distribution [9, 10], and hence the microwave excitation level, these frequency shifts must be determined as a function of the exciting power level. The dependence of δf_m on power level is, however, of much lesser importance[10]. With regard to δf_c and δf_d, since the sign of the former reverses with beam direction, for a given C field direction the power shifts tend to cancel for one beam direction and add for the other.

The values of δf_m, δf_c, and the combined power dependence of

δf_m, δf_c, and δf_d were measured both immediately prior to inception of clock operation on May 1, 1975, and again after about 4.5 months of continuous operation, in mid-September. In the April series of measurements the beam direction was reversed a total of 4 times, and the C field 12 times. In the September series, the C field was again reversed 12 times, but the beam direction only once, so as to minimize time scale errors during the period that the clock was inoperative. No significant differences were found between the two sets of measurements, the value of δf_m being 2.0×10^{-13} for both cases, and value of δf_c being $- 3.1 \times 10^{-13}$ for the first and $- 3.4 \times 10^{-13}$ for the second.

It is difficult to estimate the total uncertainty for δf_c and δf_m, and also δf_d and their combined power dependence, since they all act simultaneously. In addition, it is not known how accurately the power dependence predicted by the theory[8,9,10] based on the assumption of a truncated Maxwellian velocity distribution portrays the actual physical conditions. As indicated in the previous paper describing CsV as a frequency standard[7], a total frequency decrease of about 3 or 4 parts in 10^{14} is predicted as the power level drops to zero from the usual operating level 3 dB below that for maximum transition probability. For the A to B beam direction, the measured shift was about 5×10^{-14} and for the B to A direction about 3×10^{-14}, as determined from both the most recent measurements made in September and those made earlier in April, 1975. The uncertainty of these measurements was affected to some degree by barometric-pressure induced frequency shifts of several parts in 10^{14} in the frequency of the reference hydrogen maser[13]. However, a combined uncertainty in the determination of δf_c and δf_m of about $\pm 2 \times 10^{-14}$ appears not unreasonable on the basis of these measurements.

An important factor influencing the accuracy of determination of δf_c is the time elapsed between clock operation for one beam direction and in the reverse direction. At the time of the most recent beam reversal in September, it was found that the long, 4.5 month period of clock operation in the A to B direction had resulted in poisoning of the hot wire detector which was adjacent to the A oven. A period of about 26 h was required to restore normal operation of the A detector hot wire, the temperature of which was maintained near to 1200°C for about 7 h in order to evaporate from the wire the deposited cesium. It is hoped that in future it will be possible to avoid such long inoperative periods by at least partial prior cleaning of the detector wire to be used after beam reversal. However, despite the 26 hour period during which CsV was inoperative because of poisoning of the hot wire, comparisons with the best NRC secondary clock, HP 911, show that a time scale error exceeding 5 ns is unlikely.

One of the problems inherent in the experimental determination of δf_m by C field reversal concerns changes in the magnetic characteristics of the magnetic shields arising from reversal of their direction of magnetization. As might be expected, following each C field reversal the value of δf_H did not repeat exactly, even though the current through the C field rods remained constant. A gradual decrease of several parts in 10^{15} in δf_H occurred, as shown in table I, for the most recent series of measurements.

Table I - Change in C field correction, parts in 10^{13}, with successive C field reversals, for both beam directions.

Beam Direction A-B			Beam Direction B-A		
Run No.	$\delta f_{HAB,N}$	$\delta f_{HAB,R}$	Run No.	$\delta f_{HBA,N}$	$\delta f_{HBA,R}$
1	2220.43		1	2218.31	
2		2216.51	2		2208.11
3	2220.42		3	2218.27	
4		2216.64	4		2208.07
5	2220.39		5	2218.21	
6		2216.58	6		2207.99
7	2220.39		7	2218.24	

E. Time Dependent Variation of the C Field

One of the most important factors limiting the accuracy of a primary cesium clock is the long term stability of the C field, since the C field frequency offset, δf_H, can be remeasured only at relatively widely spaced intervals. Earlier experiments with CsIII had shown that occasional frequency variations up to several parts in 10^{13} could occur as a result of C field changes which were not due to changes in the current flowing in the C field rods. Presumably, alterations in the magnetization of the magnetic shields were responsible for such changes. In CsIII only one mu-metal shield was used, although, as in CsV, an Armco iron support cylinder did provide some additional shielding. In the design of CsV much more complete magnetic shielding is provided, with three concentric molybdenum permalloy cylindrical magnetic shields enclosing the C field region, as shown in figure 1.

The long term C field stability of CsV, shown in figure 6, is much superior to that of CsIII, but some variation, which is probably not due solely to a gradual drift of the current in the C field rods, does occur. Only partial correlation between this current, measured by means of a standard resistance in the C field current circuit and a differential voltmeter, and the C field correction was observed. The

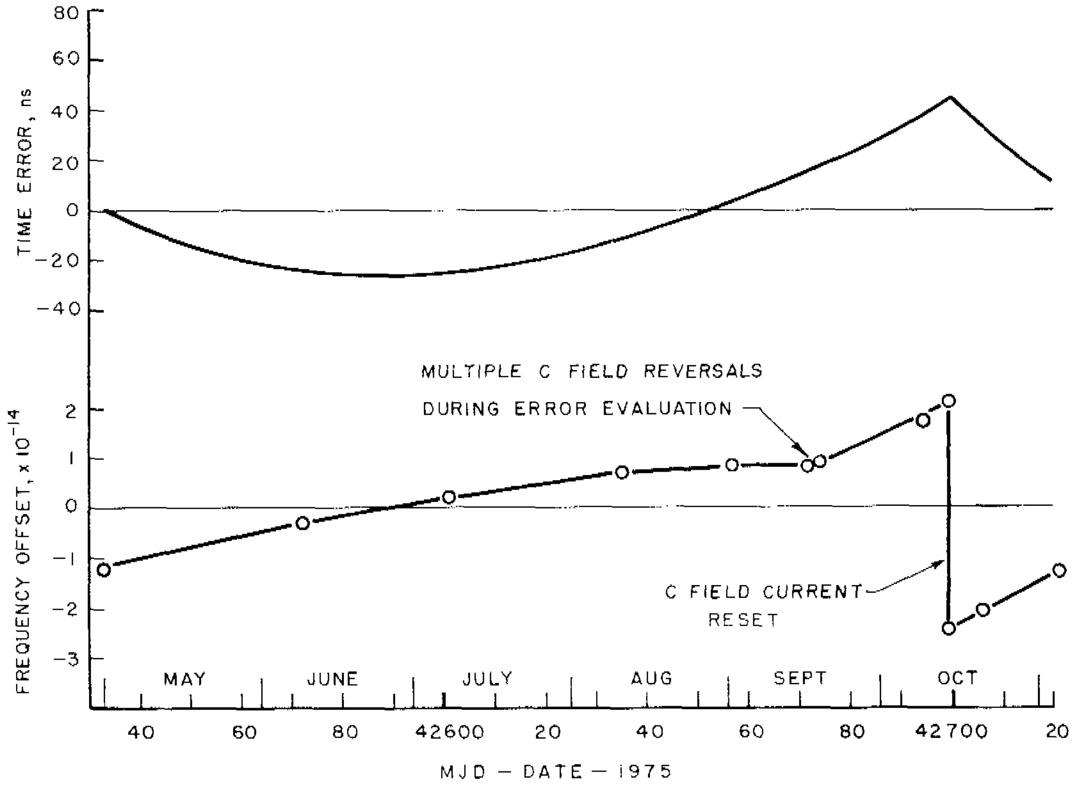

Figure 6. Time dependence of the C field correction, δf_H, during the period May-October, 1975, and resultant time scale error.

change in slope of the graph of figure 6 at the time of the most recent re-evaluation, which included multiple C field reversals, indicates that changes in magnetization of the shields are probably responsible for a considerable portion of the C field variation, which averaged about 5 x 10^{-15} per month. Also shown in figure 6 is the time dependence of the time scale error, which attained a maximum value of about 45 ns on October 14, 1975. Resetting of the C field current on that date resulted in a steady diminution of this error.

F. Frequency Dependence on Beam Intensity

It is essential that the frequency of a primary clock not be dependent on the beam current intensity since systematic errors are normally determined at high beam currents with concomitant improved short term frequency stability and clock operation depends on prolonged operation at low beam currents. Although such a dependence would not actually be anticipated, it is important to ensure that it does not in fact exist.

Subsequent to reversal of the beam direction in September, 1975, three consecutive relatively long CsV - H maser comparisons were made for cesium beam currents providing peak-valley resonance amplitudes of about 1.7, 4.2, and 1.7 pA. As shown in figure 7, the frequency of CsV appeared to be independent of the changes in beam current, although the short term stability was noticeably worse at the lower beam current, with values of $\sigma(2,2h)$ of about 2 to 4 x 10^{-14} occurring over the first and last measurement periods, each about 20h in duration. The value of 1.3 x 10^{-14} for the higher beam current is typical of the relative stability obtainable during systematic error evaluation.

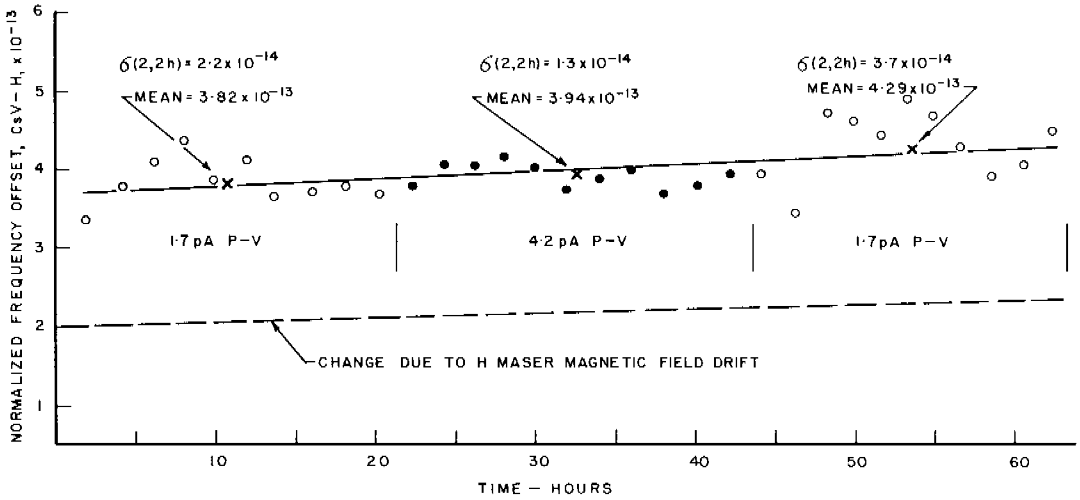

Figure 7. Dependence of the frequency of CsV on beam current.

Also shown in this figure is a dashed line indicating a 3 x 10^{-14} frequency drift arising from changes in the magnetic field of the maser. This drift is based on two measurements of the magnetic field immediately prior to and following the 70 hour total measurement period. The mean frequency offsets for each of the three runs indicate a somewhat larger drift of about 5 x 10^{-14}. The difference between these two drifts of 2 x 10^{-14} could have been in part the result of barometric pressure effects on the maser or simply a statistical fluctuation of the measurements.

G. Summary of Systematic Frequency Shifts

In the following table summarizing the uncertainties in the systematic frequency shifts characteristic of CsV, it is assumed that any variation of the frequency with beam current intensity is negligible, implying that the frequency is the same for either clock operation or operation as a frequency standard.

In addition, any frequency uncertainty arising from pulling of the resonance by cavity mistuning is considered to be the same as in the previous evaluation, or 2×10^{-15}.

Table II - Summary of the uncertainties of the known frequency shifts characteristic of CsV

Frequency Shift	Uncertainty, e_i Parts in 10^{14}
Second order Doppler effect, uncertainty in curve fitting	2
Combined uncertainty in values of δf_m and δf_c and power dependence of δf_m, δf_c, and δf_d	2
Combined uncertainty in value of δf_H arising from (a) constants used in its calculation (b) measurement of the mean square value of the (4,-4) ↔ (4,-3) transition frequencies	4
Servo system frequency offset based on measured shift with modulation frequency	2
Frequency pulling for estimated maximum cavity detuning of 5 MHz	0.2

Total uncertainty for:

(a) random individual uncertainties, $(\Sigma e_i^2)^{\frac{1}{2}} = 5.3 \times 10^{-14}$ or 4.6 ns/day

(b) additive individual uncertainties, $\Sigma e_i = 10.2 \times 10^{-14}$ or 8.8 ns/day.

It also must be stressed that this table summarizes only the uncertainties of the known systematic errors, and no attempt has been made to predict or compensate for errors which may appear as further experience with CsV is gained during future operation. In this regard, it could be mentioned that the Millman effect, discussed in this paper, did not appear to be significant at the time of the first evaluation of CsV in 1973, but did in the two evaluations carried out during 1975. Improved measurement techniques were probably responsible for the appearance of this effect, although possible changes in the standard itself cannot be ruled out entirely. It is, however, important to note that although in the 1973 evaluation the Millman effect was not isolated from the cavity phase difference frequency shift, the combined effects were compensated for by beam reversal. It would, indeed, be surprising if future work at NRC and other laboratories were not to uncover other new and unsuspected sources of systematic frequency shifts, especially as measurement techniques improve. If such shifts appear they will be reported and the rate of PT(NRC CsV) will be adjusted accordingly.

3. Time Comparisons with Secondary Clocks and Other Time Scales

A. General

Although internal estimates of accuracy and stability such as those outlined above are essential in the evaluation of the performance of a primary standard such as CsV, they are of little value unless they are corroborated by comparisons with other clocks or frequency standards either within or outside the laboratory. Such comparisons leading in general to support for the accuracy and stability estimates given for CsV have been made with the NRC hydrogen masers, the three best NRC secondary cesium clocks, the present NRC primary cesium frequency standard, CsIII, the International Atomic Time Scale, TAI, and the UTC time scales of the National Bureau of Standards and the US Naval Observatory. Details of these comparisons are given below.

B. Frequency Comparisons with CsIII

During the period May-October, 1975, a total of 36 6h comparisons were made between the frequencies of CsIII and CsV, as shown in figure 8. The estimated uncertainties of each of the comparisons is about 2×10^{-13}, and the value of $\sigma(2,T,\tau)$ for T, the time between measurements, of about 4 days, and τ, the time for an individual measurement, of about 6 h, is 1.6×10^{-13}. The comparisons indicate that the mean frequency of CsIII is 10.7×10^{-13} above that of CsV. The value found in 1973 for a much shorter period of several days[7] was 10.5×10^{-13}. An unpublished value measured in mid-1974 and given at the July 1974 meeting of the Consultative Committee for the Definition of the Second was 11.0×10^{-13}. The latter was based on 15 6-hour measurements. The close agreement shown in these three comparisons is, however, probably fortuitous, since it is apparent from figure 8 that

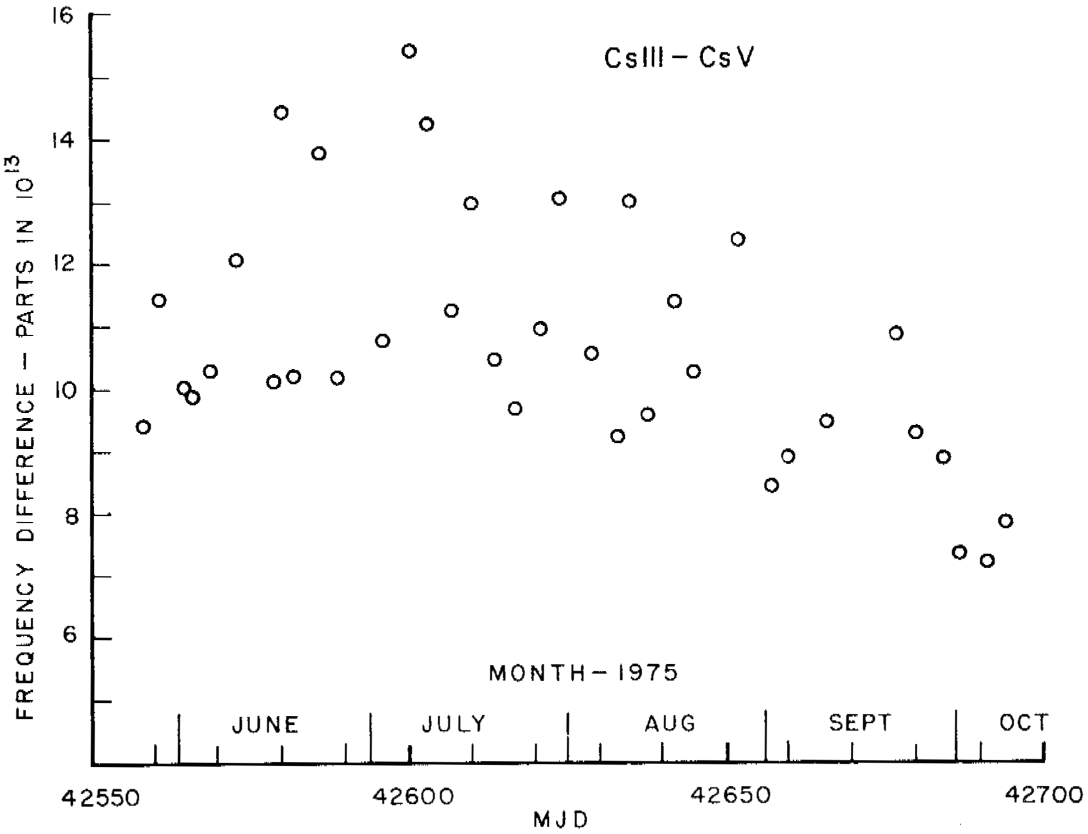

Figure 8. Frequency difference between CsIII and CsV measured over 6-hour calibration periods during the interval May-October 1975.

a gradual change of several parts in 10^{13} probably occurred in the frequency of CsIII during the period May to October, 1975, and, in addition, comparisons between the NRC time scales based on CsIII and TAI indicate that frequency variations over several months of about 2×10^{-13} are not uncommon. Such variations in CsIII may arise from changes in the spectral purity of the microwave exciting signal. However, within the lower accuracy and precision attainable with CsIII, of about 10^{-12} and 2×10^{-13} respectively, there appears to be no conflict between the internal estimates of accuracy and stability given for CsV and those determined with respect to CsIII.

C. Frequency Comparisons With the NRC Hydrogen Masers

Data already presented indicate that the relative frequency stability of CsV and the NRC hydrogen masers, for sufficiently high beam currents in CsV, appears to be of the order of 10^{-14} for periods of several hours. For longer periods of up to several days, maser magnetic field drifts and effects on the maser cavity of barometric pressure changes tend to increase this value to several parts in 10^{14}.

D. Time Comparisons with NRC Secondary Clocks

Although time scale comparisons with secondary clocks do not in general provide useful accuracy estimates they do provide some indication of long term stability. Figure 9 shows a $\sigma(2,\tau)$ - τ plot for 48, 80, and 112 day time comparisons between CsV and the best of the NRC secondary clocks, HP 911, a Hewlett-Packard cesium clock

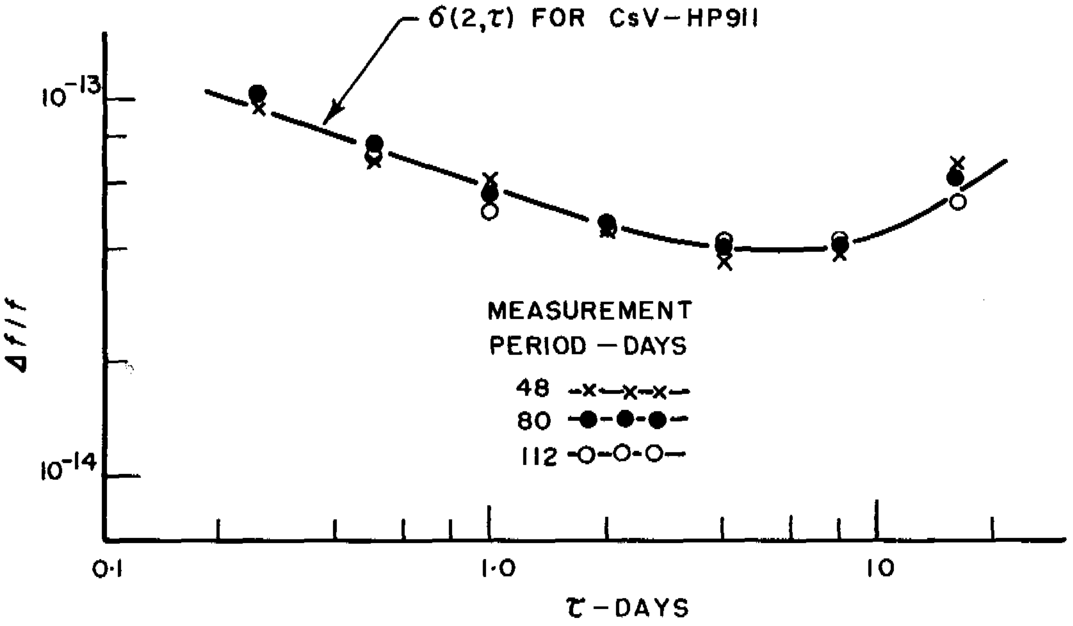

Figure 9. Relative fractional frequency stability, $\sigma(2,\tau)$ for CsV and HP 911 for three concurrent measurement periods of 48, 80, and 112 days.

equipped with the high performance cesium beam tube. It is apparent from comparison of the values of $\sigma(2,\tau)$ for these three concurrent periods of 48, 80, and 112 days, for $\tau<16$ days, that the statistics describe an effectively stationary noise process, since no significant changes occur for the different total measurement periods. The minimum value of $\sigma(2,\tau)$ is about 4×10^{-14} for $\tau = 6$ days.

Essentially the same data is shown in a different form in one of the graphs of figure 10, which indicates the time difference between PT(NRC CsV), the time scale based on CsV, and that provided by HP 911. Despite the apparent stationarity of the data for $\tau< 16$ days, it is evident that a change in slope of this graph occurs about the beginning of August, and that the new slope is maintained thereafter with no observable change. The absence of any significant change in slope in the vicinity of September 18 - 19, when a re-evaluation of CsV including beam reversal was carried out, indicates that any change in the frequency of CsV at that time is unlikely to have exceeded 2×10^{-14}.

Two other graphs in figure 10 show comparisons of PT(NRC CsV) and the time scales derived from the HP clocks 122 and 267, both of which are equipped with the standard cesium beam tubes. Some correlation between the 267 and 911 plots is apparent in this figure, and if it were not for the other plots, to be described later, which indicate no such correlation, it might be inferred that the frequency of CsV had altered some time during July or August by almost 1×10^{-13}. Such an alteration is, however, extremely unlikely, as outlined below. The third plot, showing CsV versus 122 indicates no correlation with the CsV-911 or the CsV-267 graphs.

It is evident that the results of these comparisons between CsV and the NRC secondary clocks are not in conflict with the internal stability estimate for CsV.

E. Time Scale Comparisons With Other National Laboratories

In comparing the time scale PT(NRC CsV) with those of other national laboratories an additional problem arises in any estimate of either the accuracy or stability, since the means of comparison may introduce significant errors[5], especially in the case of methods involving the transmission and reception of radio signals. However, if comparisons made with respect to the time scales maintained by two different laboratories are carried out using two quite different propagation paths, uncertainties arising from changes in propagation delay may be at least partially compensated for.

Comparisons of PT(NRC CsV) with UTC(NBS) and UTC(USNO) are shown in figure 10. These indicate, in the absence of propagation anomalies

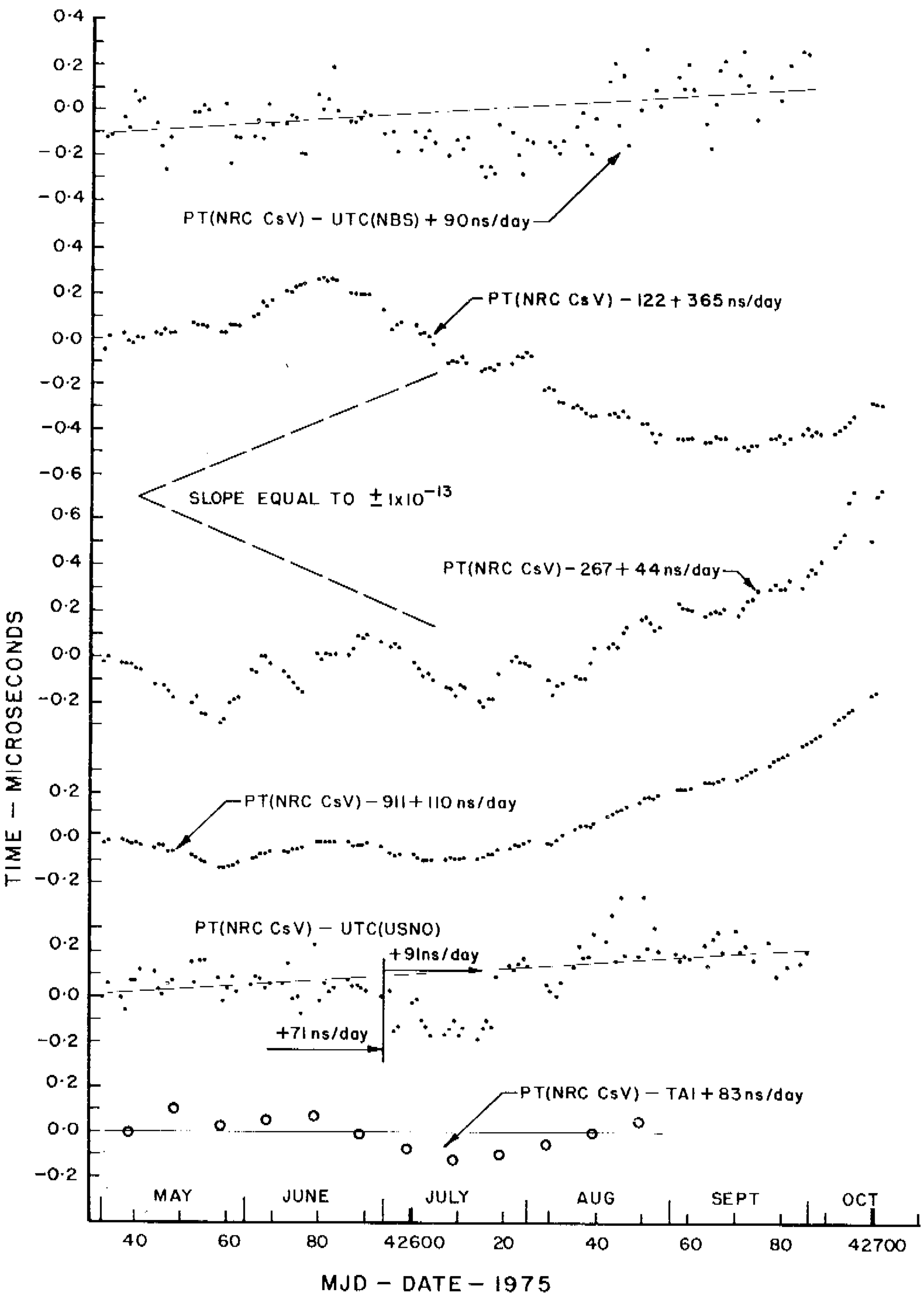

Figure 10. Time scale comparisons between PT(NRC CsV) and UTC(NBS), UTC(USNO), TAI, and the NRC secondary clocks 122, 267 and 911.

in the Loran C signal used as the basis of the comparisons, that the uniformity of PT(NRC CsV) is probably appreciably better than 1 x 10^{-13} over any one month period, and is likely to be a few parts in 10^{14} over the entire 6-month period. In connection with the USNO plot, it will be noted that the rate change of 20 ns/day made to UTC(USNO) on July 1, 1975, has been taken into account.

The PT(NRC CsV) - UTC(NBS) plot also provides a comparison of the absolute values of the frequencies of CsV and the NBS primary frequency standards NBS-4 and NBS-6. According to the NBS time and frequency bulletins for 1975,

$$f_{UTC(NBS)} = f_{Cs} \left(1 + (6.9 \pm 1.2) \times 10^{-13}\right)$$

The frequency offset of UTC(NBS) from PT(NRC CsV) derived from the mean slope of the PT(NRC CsV) - UTC(NBS) plot is about 89 ns/day or 10.3 x 10^{-13}. There is, therefore, a difference of about 3.4 x 10^{-13} between the NRC and NBS estimates of the cesium resonant frequency and hence the SI second. This difference is greater than the sum of the error limits for the primary standards of the two laboratories, which is less than 2 x 10^{-13}. Possible implications of this rather large discrepancy will be discussed in the next section.

F. Time Comparisons With TAI

The relationship between PT(NRC CsV) and TAI is also shown in figure 10. Point scatter for this plot is less than for any of the others and this appears to imply better uniformity. This plot also provides the only long term estimate of the rate of TAI based directly on a primary laboratory cesium clock. According to this comparison the frequency of TAI is above the nominal value by about 83 ns/day, or 9.6 x 10^{-13}, implying that the TAI second is of too short a duration by this factor. In the 1973 evaluation of CsV the comparable value was 10 x 10^{-13}. Measurements made by the PTB indicated a value of 12 x 10^{-13} in mid-1973 and a decrease prior to this of about 1 x 10^{-13} per year[11]. If such a decrease continued during the period 1973 - 1975, the PTB value would be in the vicinity of 10 x 10^{-13} by mid-1975, and hence in close agreement with the NRC CsV value. It may also be mentioned that since the frequency of CsIII has been very close to that of TAI during the period 1973 - 1975, the mid-1974 value mentioned earlier for the ratio of the CsIII and CsV frequencies of 11.0 x 10^{-13} also applies to the rate of TAI at that time. The frequency offset for TAI quoted in the 1974 BIH report, and based on NBS, PTB, and NRC measurements, was 1 x 10^{-12}, which is also in good agreement with the present NRC CsV value. Indeed, the NBS mid-1974 value for the rate of TAI was[12] 10 x 10^{-13}. However, the mid-1975 NBS value for TAI, which can be derived from the plots of figure 10 and the rate of UTC(NBS) with respect to NBS-4 and NBS-6, is only 6.2×10^{-13}, implying that the rate of TAI must have decreased by 3.8×10^{-13} over the one year period from mid-1974 to mid-1975. This discrepancy of 3.4×10^{-13} between NBS and NRC estimates of the rate of TAI can only indicate the presence of unrecognized systematic errors in either the NRC or NBS primary standards.

In connection with the contribution to TAI of PT(NRC CsV) it is interesting to note that the weight attributed to the NRC secondary clock 267, which, from figure 10, is noticeably less stable than CsV, is 100. This constitutes the maximum weight attributable to any of the clocks contributing to TAI. Since the uniformity of PT(NRC CsV) is quite comparable with that of UTC(NBS) or UTC(USNO), or even TAI, the question then arises as to what weight should be attributed to a primary clock such as CsV which is clearly similar in both accuracy and stability to quite large groups of other less accurate or stable clocks. As additional such primary clocks, similar to CsV, become available, a modified weighting procedure for TAI may become necessary if the best uniformity and accuracy for this scale are to be attained.

CONCLUSIONS

Operation of CsV as a primary clock during an initial 6-month test period has shown that the intended goal of a highly accurate and stable atomic time scale based primarily on a single, continuously operating laboratory-type cesium beam standard has been achieved.

It is expected that as of January 1, 1976, the NRC time scales UTC(NRC) and AT(NRC) will both be derived directly from CsV.

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QUESTION AND ANSWER PERIOD

DR. HELLWIG:

I would like to comment on accuracy. We have been very cautious in quoting accuracy numbers over the past year and in a certain way I am surprised that you are reducing your accuracy number into the 10^{-14} region where, at the same time, we have a drifting apart of the primary standard values as you have correctly stated, and I should add to that that PTB, the third primary standard activity in the world, is drifting also away, in many parts in 10^{13}.

Our approach at NBS is to be very, very careful in not overstating accuracy at the present moment because we have encountered effects we have not previously considered. In other words, if one states an accuracy budget it contains elements which you know and some elements where you might have only an idea that they might cause trouble or not cause trouble and to restrict an accuracy budget only on the effects you know can have consequences of 10 sigma deviations from internally stated accuracy values.

So, I don't believe our own one part in 10^{13}, which we quoted a year ago, totally anymore.

DR. WINKLER:

The answer is that you both may be wrong. Or, I should say, at least one of you is wrong, whichever you prefer. But, I do have two questions that are related to that and number one is, when you make your magnetic field measurements, do you make them while the standard is still operating in its microwave resonance, or what do you do to insure continuity of your clock operation?

DR. COSTAIN:

Well, it is monitored normally with the hydrogen masers operating or when we make the C-field measurements or against 911 and we feel that we lose no more than 1 to 2 nanoseconds.

DR. WINKLER:

I see. So, you don't do it simultaneously?

DR. COSTAIN:

That's Right.

DR. WINKLER:

The second question, on one of your slides you said it was the difference NRC-3 minus NRC-5 and it gave something like 13 parts, an average, there was some scatter, 13 parts in 10^{13}. Is that correct?

DR. COSTAIN:

Yes.

DR. WINKLER:

The difference between your two primary standards was 13 parts in 10^{13}?

DR. COSTAIN:

Individual measurements, yes. The advertised, published, claimed value for cesium-3 was 15 parts in 10^{13}. It has proved to be correct.

DR. WINKLER:

But, I don't understand how the difference between these two standards can be that large.

DR. COSTAIN:

There is a large difference in the noise level, the efficiency in the detector, the efficiency of the magnetic shielding and in claiming, making the claim of accuracy that we have at the present time it is, and I have to admit this, it is our known errors and based on experimental measurements against the error of hydrogen, among other things.

If there are unknown errors, we don't know them. I am sorry that is all I can say.

DR. WINKLER:

I have not explained myself. My question was, the slide stated the difference between two primary standards, not their frequency and stability. The difference between two primary standards and that was the order of between 10 and 16 parts in 10^{13}. In other words, how do you explain that in the face of claims that accuracy has a standard deviation of 1 part in 10^{13} or 4 parts in 10^{14}? How can the difference be that large?

DR. COSTAIN:

Well, in their evaluation of cesium-3, I believe its claimed accuracy initially was 1 part in 10^{11}. Eventually, with some improvement in the magnetic shielding, 15 parts in 10^{13} and this is 10 parts. It is well within our claim. It had been much more stable, in fact, than the frequency offset. We think it has changed only about 2 parts in 10^{13} over the past five years. But, its accuracy is certainly less than 10 parts in 10^{13}.

All of these, I think, and the lessons that we learned in cesium-3, I think we have taken into account, and we can be wrong in our evaluation of the cesium-5, but they have been essentially the figures we give, the results of the past three years of measurements. So, we will have to see.

DR. REINHARDT:

Victor Reinhardt, Goddard Space Flight Center.

You mentioned that an accuracy of a couple of parts in 10^{14} was due to an uncertainty in the G factor?

DR. COSTAIN:

Yes.

DR. REINHARDT:

Did you convert from Zeeman frequency to magnetic field units and then convert again?

DR. COSTAIN:

We have done both in measuring the low frequency resonance, the delta f displacement of the high frequency transitions and with the present current that we can put on the C-field, the present values, the experimental determination is about the same accuracy as the previously published values of the G factor.

We think we can improve that measurement by an order of magnitude.

DR. REINHARDT:

My question is, did you take into account the cancellation that occurs in the equations if you use direct Zeeman frequency.

MR. COSTAIN:

Yes. That comes out essentially to the same limitation, 4 parts in 10^{14}.

DR. HELLWIG:

I would like to comment on unknown errors, two subparts. Part A is what you said, we don't know them. Though I claim that you have a hunch at getting a numerical value on those and the hunch is if you compare devices of different design, accuracy claims without the unknown errors, or sort of discounting the unknown errors, and that is exactly what I tried to state. That is the disagreement between the primary standards of the world. They are of different design. They disagree by many parts in 10^{13} now, so that is a good estimate of the unknown errors.

Part B of the unknown errors are the errors where we don't know how to measure them, but we know they exist. Just to quote one and that is what I call the distributive cavity phase shift which is a trajectory-dependent frequency shift, especially, in beam tubes featuring large beams of high intensity. Our best theoretical estimate at that for beam tubes of your and our design is about 1 to 1 . 5 in 10^{13}. This best estimate is based on optimistic assumptions about conductivity of the cavity walls, symetry of cavity design and so on.

We put this unknown error into our error budget. I would like to add we don't know yet, really, how to measure that but we have to account for it.