THE PERFORMANCE OF PRIMARY Cs BEAM CLOCKS USING QUADRUPOLE AND HEXAPOLE DEFLECTION SYSTEMS. CONSEQUENCES FOR TIME KEEPING

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ABSTRACT

Since 1978 the time-and-frequency standard CS1 of the Physikalisch-Technische Bundesanstalt (PTB) has operated continuously as a "primary clock". Its uncertainty (7.10^{-15}) is considerably smaller than that of the other existing primary standards. CS1 is equipped with a combination of quadrupole and hexapole magnets and uses a longitudinal C-field. Consequences of utilizing primary clocks of this quality for the generation of the International Atomic Time Scale TAI are discussed.

INTRODUCTION

In contrast to the other existing primary time and frequency standards the Cs standard CS1 of the Physikalisch-Technische Bundesanstalt (PTB) is equipped with a two-dimensional beam deflection system and a longitudinal C-field. Details of the construction and the performance can be found in /1, 2, 3, 4/. Uncertainty evaluations were published in 1969 /5/, 1974 /6/ and 1979 /7/. Measurements of the frequency of the International Atomic Time Scale TAI carried out since 1969 with CS1 have revealed for the first time a rather strong frequency deviation from nominal and a frequency drift of TAI of about -1.10^{-13} per year /8/.

In 1974 the uncertainty of CS1 was evaluated at 26.10^{-15} using the beam reversal method and selecting slow atoms in the beam. Since it was thought at that time that unknown frequency shifting effects might exist, the uncertainty of CS1 was settled at $1.5 \cdot 10^{-13}(1\sigma)$. In the course of further experimental and theoretical investigations /3, 4, 9/ it was possible to gradually reduce the uncertainty. The 1979 evaluation /7/ resulted in an uncertainty of $7 \cdot 10^{-15}(1\sigma)$ and an instability of $4 \cdot 10^{-15}$, both values based on a measurement time of 80 d (Table 1).

CS1 is one of the three standards used for the "steering" of the TAI frequency. The other standards have been developed at the National Research Council (NRC), Canada, /10/ (the 1σ uncertainty of the standard CsV being 53.10^{-15}) and at the National Bureau of Standards (NBS), USA, /11/ (the 1σ uncertainty of the standard NBS-6 being 85.10^{-15}).

Since July 1978 CS1 has operated continuously as a "primary clock". The NRC standard has operated continuously since 1975 /12/. The NBS performs about one TAI frequency calibration with reference to NBS-6 per year.

The quality of CS1 is based on the following:

a. principal advantages of the quadrupole/hexapole beam deflection and a longitudinal C-field

b. specific technical design of CS1

c. operating practice of CS1

Principal qualities of Cs beam standards with a quadrupole/hexapole deflection system

Holloway and Lacey proposed a flop-in Cs beam standard with hexapole magnets, a coaxial resonator and a ring detector /13/. The realization of a coaxial resonator with an interaction length of about 0.8 m failed at the PTB. Little chance was given for the usefulness of a flop-in ring detector in combination with an analyser hexapole magnet. In /14/ it is shown that a conical quadrupole analyser magnet in combination with a ring detector is preferable. Nevertheless, in view of the relatively large ring detector surface necessary the flop-out system with a point detector on the axis is preferred at the PTB. We have had no experience with a double dipole flop-in analyser magnet as proposed by Kartaschoff /15/.

Figure 1 shows the basic arrangement of the standard CS1. In the following, it is assumed that the functioning principle is known. The characteristic qualities of this arrangement will be discussed.

1. Beam deflection system

The dimensions of the quadrupole/hexapole deflection system used as the polarizer and analyser are given in /4/. It selects atoms with an average velocity of 92,7 m/s (in a relatively narrow velocity range of about 7%) from the atoms leaving the oven with a modified Maxwell-Boltzmann velocity distribution (Fig.2 and Fig.3). The temperature of the selected atoms is about 65 K. Due to the small velocity and velocity range, the first and second order Doppler shifts are small. In dipole system standards, velocity ranges of, e.g., 30 to 50% are used. Phase differences between the end resonators cannot be completely avoided. Changes of the HF radiation then produce changes of the frequency ("power shift") which, of course, are smaller for small velocity ranges in the beam.

The conclusion that a device using only a small velocity range is disadvantageous because of "wasting" atoms is unjustified /4/. The aperture of the beam optics for quadrupole and hexapole magnets is much larger than that of a dipole system.

As shown in /3/ and /4/ the velocity range in the beam is larger for a hexapole polarizer than for a quadrupole polarizer assuming comparable dimensioning of the magnets. If, e.g., for simplicity of construction, only one magnet is used, either hexapole or quadrupole, in many cases, the quadrupole magnet will be advantageous. Its velocity range decreases with decreasing magnetic field.

A long interaction length necessitates a very precise deflection of the atoms in the polarizer. This means that the shape of the pole tips should be as close as possible to ideal.

In the interest of a high beam intensity in relation to the Cs consumption, the beam source diameter d has to be rather small. A single channel with d = 0.1 mm and a length of some tenths of mm is used in CS1. It is necessary to operate the oven at a rather high temperature (160 to 180°C) in order to achieve an adequate Cs beam. This means that the relative content of atoms with the desired velocity referred to the total flux is less favourable than in the case of dipole devices whose oven temperature is only of the order of 100°C. The directivity factor χ of the CS1 beam source is rather low under the conditions described. On the other hand, the large aperture angle of the polarizer system limits the admissible χ-factor to a value which in practical cases will be below 10.

2. Phase distribution in the end resonators

The CS1 uncertainty evaluation of 1974 /6/ already took into account the existence of a phase gradient (of about $1.6 \cdot 10^{-5}$ rad/mm) in the end resonators perpendicular to the beam direction. For the uncertainty estimation it was assumed that the beam paths for both beam directions might differ by a few tenths of mm. In the evaluation of 1979 /7/, the frequency uncertainty due to the phase distribution in the end resonators is the largest contribution to the total uncertainty.

Obviously, this most important uncertainty can be reduced by reducing the beam diameter and by proper alignment. CS1 uses a beam diameter of 3 mm. In dipole devices beam widths of about 10 mm and more are used. Hence, it can be expected that the problem of the phase distribution is less severe by a factor of about 3 for CS1.

In the dipole system, the actual phase difference between the end resonators is dependent rather strongly on the HF radiation power: increasing, e.g., the radiation favours faster atoms at different trajectories to contribute to the signal. This results in a specific power-dependent frequency shift due to the phase distribution. Not only is the velocity range in the quadrupole/hexapole system much smaller, but the velocity distribution across the beam has also a rotational symmetry cancelling the power-dependent phase difference between the end resonators to the first approximation. Taking this into account it is supposed that, altogether, the phase distribution problem is more severe by a factor of 3 in the dipole device than in the CS1 device.

3. Magnetic C-field

The magnetic shielding of CS1 consists of three concentric Mu metal cylinders with a wall thickness of 5 mm each. The longitudinal magnetic field H produced on the axis by a solenoid has been measured with a magnetometer. Neglecting the measured difference between $\overline{H}^2$ and $\overline{H^2}$ produces an error of $1 \cdot 10^{-17}$ only.

As a primary clock, CS1 operates with H ≈ 4A/m. Due to the following reasons, operation with such a low field is feasible without overlapping of the adjacent transitions: These resonances are relatively small due to the low beam velocity and, additionally, due to the long interaction length in the Rabi field; the atoms pass the waveguide in its longer diameter. Furthermore, the HF exitation amplitude for the atoms passing the waveguide is a sinusoidal and not a rectangular function as in the case of a design with a transverse C-field. If necessary, H could be reduced even further. It is not necessary to apply HF excitation below optimum radiation.

The shielding factor in the direction of the axis of a shielding cylinder is smaller than that perpendicular to the axis. This may be a basic disadvantage of devices with longitudinal C-field.

In order to avoid Majorana transitions between the different Zeeman levels, longitudinal "guiding fields" are used between the deflection magnets and the magnetic screening.

4. Detector

The surface necessary of a hot wire detector located at the focal point of the analyser may be as small as 0.1 mm^2 /4/. This allows a considerable reduction of the Cs background flux.

5. Signal-to-noise ratio

It may be of interest to compare the Cs beam flux on the detector, N_D, for a quadrupole/hexapole system (4P/6P) with that of a dipole system (2P). Using a formula for N_D(4P/6P) derived in /4/ in the case of a standard such as CS1 and describing the dipole system by a rectilinear beam of velocity v and a velocity range Δv(2P) results in:

$$\frac{N_D(4P/6P)}{N_D(2P)} \approx 8 \cdot \frac{r_0 - r_{CD}}{d} \cdot \frac{1}{k} \cdot \frac{v}{\Delta v(2P)} \; \frac{\chi(4P/6P)}{\chi(2P)}$$

for beams with the same cross section and with the same average velocity v. r_0 (1.5 mm) is the radius of the beam, r_{CD}(0.4 mm) is the radius of the central disc according to Fig.1. k (1,8) is a constant characterizing the deflection /4/, χ(4P/6P) (about 2) is the directivity factor of the beam source and χ(2P) is that of the dipole device. Values for CS1 are given in parentheses. With a multi-channel source $\chi(2P) = 50$ may perhaps be achievable. Assuming $\Delta v(2P)/v \approx 1/3$ results in

$$\frac{N_D(4P/6P)}{N_D(2P)} \approx 6 \; .$$

The superiority of the 4P/6P system is lowered by a factor of 2 if in the 2P system both hyperfine levels are used. An additional reduction of the signal-to-noise ratio occurs due to the flop-out operation and the less favourable oven temperature of the 4P/6P System under discussion. There seems to be no fundamental difference between the two systems with respect to the S/N ratio.

Specific technical design and operating practice of CS1

In the following, information concerning the specific design and operation of CS1 which is not related to the two-dimensional beam deflection, is reviewed from the papers referred to.

Beam reversal is performed every 6 weeks (= 42 d). Each calibration interval of 80 d contains both beam directions of almost the same durations. The oven chamber (containing the oven and the polarizer) and the detector chamber (containing the analyser and the detector) are directly exchanged. This method ensures the application of the same beam in both beam directions. Operation of CS1 can be continued 1 h later after beam reversal.

The multiple line-width modulation method /3, 4, 9/ is applied on a routine basis. The application of this method is favoured by the specific form of the Ramsey resonance shown in Fig.3.

So-called "full evaluations" of the primary standards are performed at the NBS and the NRC from time to time, e.g., every year. The operating practice used at the PTB consists of an almost continuous supervision of all important operational parameters. Further information on the operating practice can be found in /7/.

Measurements with the standard CS1

Fig.4 shows a frequency comparison between the Canadian standard NRC:CsV and the standard PTB:CS1. The standard deviation of independent measurements is about 6.10^{-14}. Since it contains contributions from propagation changes of the LORAN-C links, this result of a 4-year-comparison is considered to be very satisfactory.

Frequency measurements of some time scales including the free time scale EAL of the BIH from which TAI is derived by frequency corrections (steering) are shown in Fig.5. Seasonal frequency changes of free time scales produced with industrial Cs clocks can be seen from the measurements with CS1 since 1969. An analysis of the free time scale of the PTB revealed seasonal frequency changes with an amplitude of 4.10^{-14} /7/. It is estimated at the PTB that a change of the environmental temperature of +1 K may cause a frequency change of about -1.10^{-13}. However, the clocks differ in their behaviour. Measurements of the temperature coefficient of an industrial Cs clock performed in Japan /16/ resulted in a value as small as $-0.2 \cdot 10^{-13}$/K.

Fig.6 shows a time comparison between the Canadian and the German primary clock. The slope of the regression line indicates that the frequency of the standard NRC:CsV is higher by about 4.10^{-14} which is within the uncertainty limits claimed.

The deviations Δt of the measured time differences from the regression line are primarily due to time transfer changes of the LORAN-C link between North America and Europe. Δt has a standard deviation of about 160 ns. This is an unexpectedly small value since it is based on four LORAN-C time comparisons: one each at the NRC and the PTB and two performed by the USNO. Time comparison results using the NTS-1 and NTS-2 satellites had a considerably larger standard deviation /17/.

To the first approximation Δt represents the fluctuations of the USNO time comparisons with the Norwegian Sea LORAN-C Chain (LC/7970) published in /18/. The interpretation of TAI as consisting of two components is justified, a North American one and a European one, fluctuating against each other by Δt.

Since the clocks of North America and of Europe contribute almost to the same amount to TAI, about 50% of a change of Δt should appear on the European component of TAI and, with the opposite sign, on the North American component of TAI*. This can be seen from Fig.7 showing a comparison of TAI with the time scales of the Canadian primary clock CsV and the German clock CS1, using the data published by the BIH in its Circ.D (curves A). In most cases the fluctuations of the curves A have in fact opposite signs; the amount of the TAI changes with respect to the primary clocks is, however, not quite the same for both curves: the fluctuations of the North American TAI component are by about 50% stronger. Applying 40% of Δt as a correction to the European TAI and 60% of Δt as a correction to the North American TAI results in the curves B which are much smoother: the Δt corrected TAI has a better frequency stability; the splitting of TAI into two components is reduced.

Fig.6 shows that Δt may have a systematic deviation from the average over a few months. The deviation between October 1978 and February 1979 is probably a seasonal effect. A consequence of a systematic change of Δt with time is that determinations of the TAI frequency in North America and in Europe result in two different values, even when the standards used, do not differ. As shown in Fig.8 the frequencies (80 d averages) of the two TAI components may differ by as much as 7.10^{-14}. The standard deviation between the two TAI components for 80 d frequency averages in the interval investigated is $3.5 \cdot 10^{-14}$ and $4.3 \cdot 10^{-14}$ for 60 d averages.

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* The existence of this "mirror effect" of the fluctuations has, as far as the author remembers, already been mentioned by Granveaud (BIH) at the CIC 1974.

With regard to the steering of TAI, the effect of the TAI frequency splitting is not negligible. It is also important to understand the reasons for possibly divergent TAI calibration results in order to be able to develop confidence in the capabilities of primary clocks that is necessary if allowing them to assume greater influence within the international time-keeping system.

Due to the (assumed) seasonal fluctuation of Δt erroneous seasonal frequency fluctuations on time scales of the other continent are observed. The rules for applying the Δt corrections are as follows:

For a comparison of a North American (NA) time scale with a European (EU) time scale:

$$(TA(NA)-TA(EU))_{corr.} = (TAI-TA(EU))_{Circ.D} - (TAI-TA(NA))_{Circ.D} - \Delta t.$$

For time scale comparisons with TAI:

In Europe:

$$(TAI-TA(EU))_{corr.} = (TAI-TA(EU))_{Circ.D.} - p_A \cdot \Delta t$$

In North America:

$$(TAI-TA(NA))_{corr.} = (TAI-TA(NA))_{Circ.D} + p_E \cdot \Delta t$$

p_E is the relative European weight, and p_A is the relative North American weight. By definition $p_E + p_A = 1$.
$p_E = 0.6$ (and correspondingly $p_A = 0.4$) seems to fit best up to now. In principle, the TAI data published by the BIH in the Circ.D could already include the propagation corrections.

Fig.9 and 10 show some Δt-corrected measurements. It should be noted that TA(NBS) is not a free time scale but a steered one. The comparison with TA(NBS) suffers from additional link fluctuations.

Due to the noise on the Δt corrections optimum smoothness of the curves is sometimes observed if only 50 to 80% of the corrections are applied.

Future role of primary clocks

A few years ago it was thought that the calibration of the TAI frequency with a primary standard (with an assumed calibration uncertainty of about 1.10^{-13}) necessitates not much more than one measurement a year considering that the EAL frequency drift turns out to be less than 1.10^{-13} per year. The situation has since changed: the calibration uncertainty is now about 1.10^{-14} (utilizing the propagation corrections made available by primary clocks) and the newly detected seasonal effects of the EAL frequency are larger than the calibration uncertainty by about a factor of 10. As a result, it can be said that the information available from a continuously running standard is of considerably more value than that of a standard which is switched on only once a year.

The present international time system necessitates a great deal of effort (e.g., daily LORAN-C time comparison measurements) to keep its synchronism to a few tenths of a microsecond. Two primary clocks with a maximum instability of e.g., 5.10^{-15} over unlimited time intervals require comparisons only very rarely for the synchronization uncertainty quoted, e.g., once a year. This may be of importance for countries which have no access to TAI and UTC when LORAN-C is not available.

At present there are only two primary clocks, though a number of laboratories throughout the world are dealing with the construction of Cs clocks. Since it appears that in the future too, the number of primary clocks will increase only very slowly the question arises as to how to make the best use of existing primary clocks for the establishment of TAI.

It should be realized that the accuracy and stability of the time scale of a primary clock (assuming the performance discussed in this paper) is much superior to that of EAL or TAI.

At its meeting in 1979 the CCDS "Working Group on the Steering of TAI" discussed the question of whether TAI could be based totally on the primary clocks of the NRC and PTB. A decision of this kind cannot be taken by the Working Group but only by the CCDS. Nevertheless, this proposal is an indication of the interesting development which lies ahead of us.

The PTB is in favour of this proposal. We believe that a solution can be found to combine the superiority of the primary clocks with the operational reliability of the present TAI system.

With respect to steering methods /19/, primarily three types of steering can be distinguished:

1. Correction of a TAI frequency departure from nominal; "accuracy steering"

2. Correction of the TAI frequency in order to compensate a frequency change which has occurred; "stability steering"

3. Correction of the TAI frequency in order to keep approximate time synchronism of TAI with the time of a superior clock or clock ensemble; "time steering"

The first method has been in operation since 1977. Due to the delays caused by the time necessary for the computation of EAL and the evaluation of the TAI frequency calibrations, the necessary frequency corrections are applied rather late. The TAI frequency may have changed meanwhile. A frequency correction is only justified if the departure from nominal is outside the 1σ uncertainty limit of the calibration. In the case of a systematic frequency drift of TAI this causes a systematic frequency deviation of about 1σ from the primary standards as well as an increasing time difference with them.

For the second method only the stability and not the accuracy of a contributing standard is important. Stability steering in the form of a correction applied later is not in use. It is more reasonable to incorporate the standard in the clock ensemble as the basis for the computation of EAL. The present ALGOS computation method of the BIH limits the weight of a contributing clock to 100. The total weight of the clocks is at present about 5500. Since the stability of EAL is significantly smaller than that of a primary clock, the clock should receive an ALGOS weight which is significantly higher than 5500.

The opinion has been expressed that the weight given to a primary clock could be determined with ALGOS. This, however, is not possible, because the weight given to a clock is, in principle, derived from the instability of the clock as measured by the rest of the clock ensemble. It is, of course, impossible to measure the instability of a very stable clock using unstable clocks.

When ALGOS was established, the specialists thought that a new type of clock could be given a specific upper limit weight to be determined from statistics based on a sufficiently large number of these clocks. There are not enough primary clocks, of course, to apply this principle to them.

Objections have been expressed to giving the primary clocks a high ALGOS weight because this could result in discouraging those contributing to TAI with industrial standards. The advantage of having the primary clocks included in the ALGOS computation with a high weight would be that they would immediately contribute to the stability, whereas all steering methods with later corrections cannot prevent the fluctuations due to the control system. A possible compromise would be to start with a primary clock weight of, e.g., 500 and to increase the weight later when sufficient experience has been gained. A reasonable weight would presumably stimulate the work on primary clocks. The present ALGOS weight for primary clocks is only 100.

If those operating primary clocks derived their UTC(i) from their primary clock at the same rate, UTC(i) would drift away from UTC(BIH) when the first two steering methods are applied. To maintain approximate agreement between UTC(i) and UTC(BIH) the quality of UTC(i) could either be decreased and steered to conform with UTC(BIH) or the TAI frequency could be steered to avoid an increasing departure of UTC(BIH) from the UTC(i) produced by primary clocks. This latter method is what has been called "time steering". In the case of several slowly diverging primary clock time scales, TAI could be adjusted to follow their time average.

At its 1979 meeting, the CCDS Working Group requested the BIH to steer TAI in a way that would avoid a systematic time departure from the primary clocks. This corresponds to a time steering method.

It seems that in the future, we shall see primary clocks greatly influencing international time keeping, resulting in a reduction of the principal role of the industrial Cs clocks in some cases. The practical role of these clocks will certainly not be reduced, as they ensure the accessibility to TAI. Concerning the role of the metrological institutes operating primary clocks, it should be noted that it is quite normal that a comparatively small number of them ensures the availability of the reference standards of international metrology.

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Table 1*

Relative uncertainty and instability of the standard CS1 of the PTB in continuous operation, based on 80 d average

Parameter	Relative uncertainty 10^{-15}		Relative instability 10^{-15}
Resonator phase difference	<5		<5
Beam path	<9	+	<3
Beam velocity	<0.1		<0.1
Second order Doppler shift	<0.4	+	<0.1
Resonator detuning	<1	+	<0.1
Magnetic field strength	<1		<1
Magnetic field inhomogeneity	<0.1	+	<0.1
HF sidebands 50 Hz	<1.3	+	<1
Adjacent transitions	<1	+	<0.1
Demodulator	<1	+	<1
Shot noise	2		2
Square root of the sum of squares	<10.8		<6.4
Sum of the amounts	<21.9		<13.5
1σ value **	6.5		4.0

+Contributions to the systematic uncertainty

*Translation from /7/

**The 1σ value is achieved according to an evaluation method published by Wagner /20/ and recommended by PTB: upper limit values of uncertainty contributions are divided by $\sqrt{3}$ resulting in an estimation of a 1σ value of these contributions.

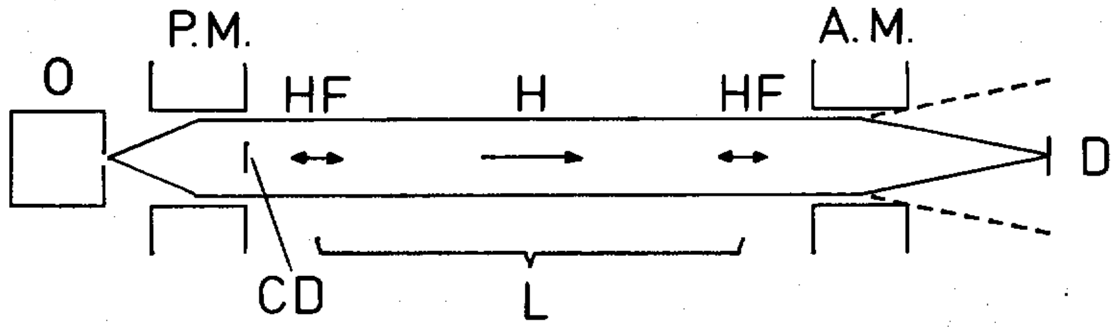

Fig. 1-Basic arrangement of the primary Cs standard of the PTB. P.M polarizer, A.M. analyser, both consisting of a combination of quadrupole and hexapole magnet, O, oven; F, detector; L, interaction length (0.8 m); CD, central disc as beam stop; HF, high frequency field; H, static magnetic field, both in beam direction. The dotted lines refer to the beam trajectory in case of resonance

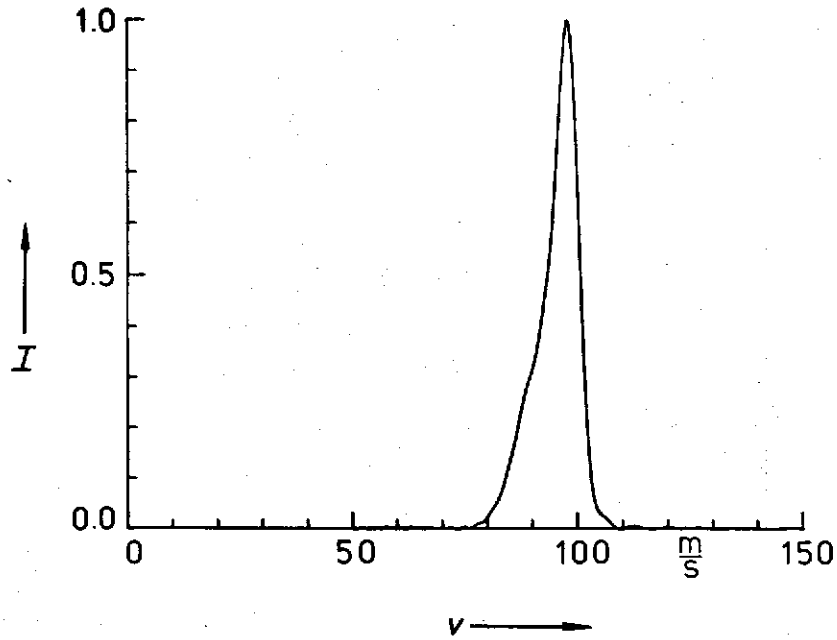

Fig. 2-Velocity distribution in the atomic beam of CS1 evaluated from the resonance curve Fig.3; intensity I in arbitrary units. The average velocity is now 93 m/s, lower than shown in the graph

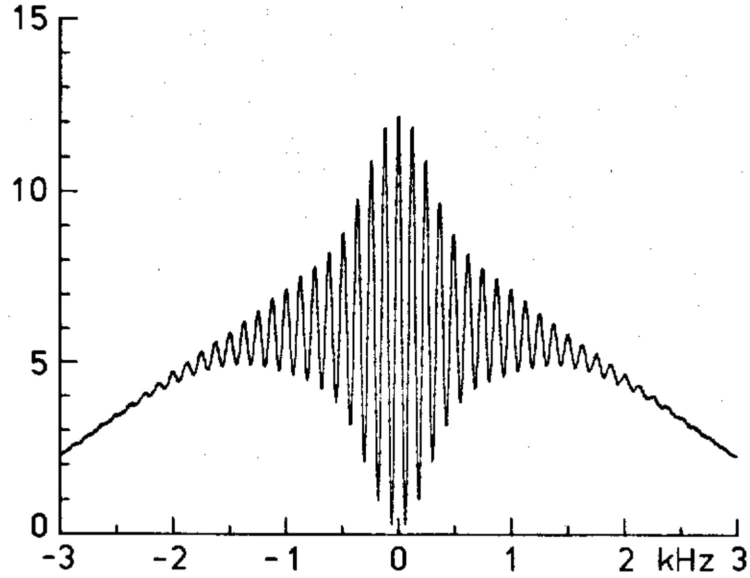

Fig. 3-CS1 resonance curve; line width 59 Hz

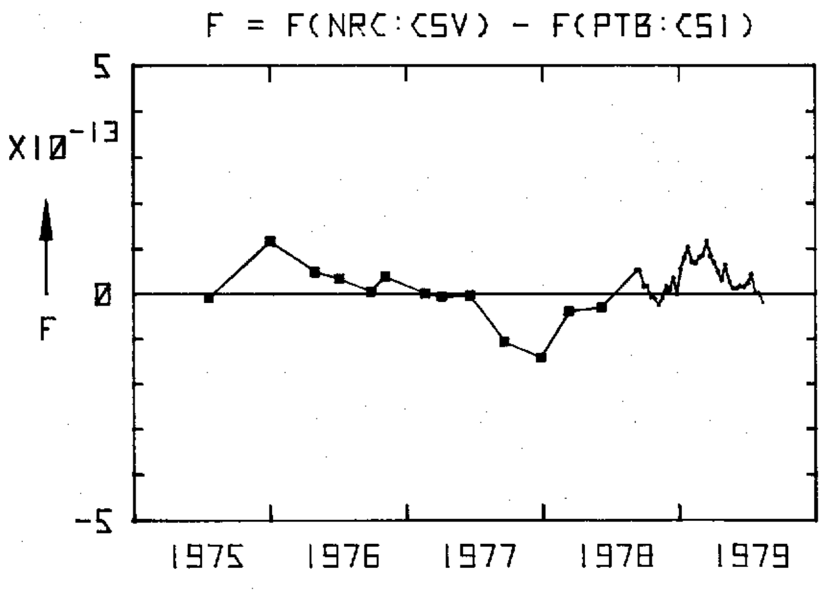

Fig. 4-Relative frequency difference F (80d averages) between the standards NRC:CsV and PTB:CS1 with reference to sea level. Since the beginning of the continuous operation of CS1 in 1978, sliding averages are shown, in steps of 10d

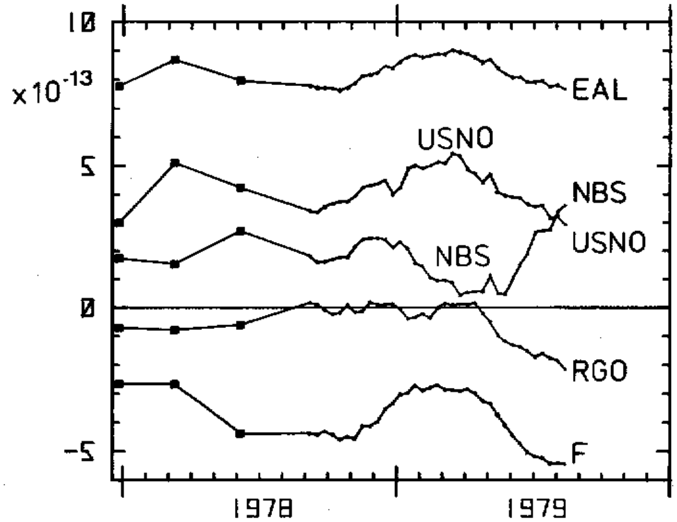

Fig. 5-Frequency measurements of some time scales TA(i) and of EAL with the standard PTB:CS1. F refers to the French time scale and RGO to that of the Royal Greenwich Observatory. Seasonal effects of different sizes can be seen

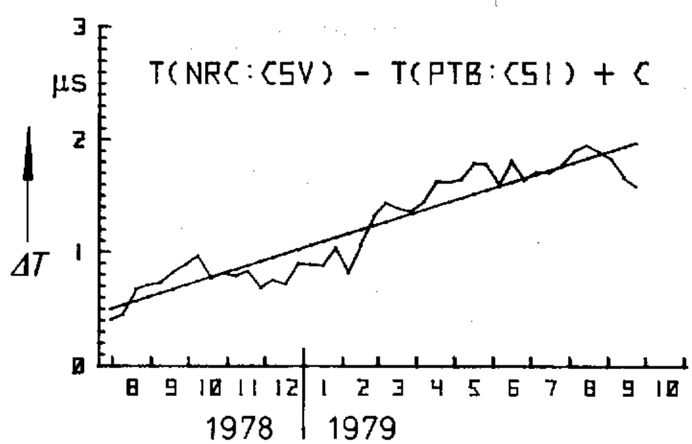

Fig. 6-Time difference ΔT (plus an arbitrary constant C) between the standards NRC:CsV and PTB:CS1 (with reference to sea level) evaluated using the Circ.D data of the BIH. The departure Δt from the regression line has a standard deviation of 160 ns

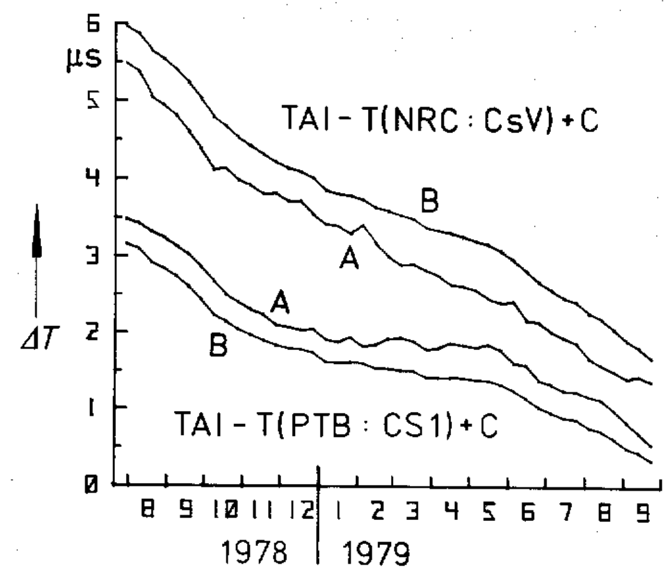

Fig. 7-The curves A show the time difference ΔT between TAI and the time T(NRC:CsV) and T(PTB:CS1) respectively, using the Circ.D data. Applying the propagation correction results in the curves B. A European weight of 60% and a North American weight of 40% of Δt was chosen for the corrections. An arbitrary additive constant C is chosen to seperate the curves

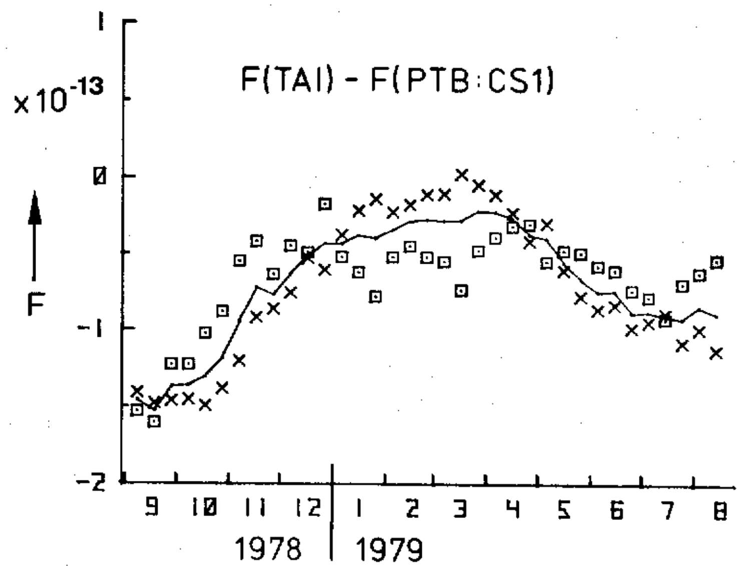

Fig. 8-Measurement of the TAI frequency (80d sliding averages in steps of 10d) with the standard PTB:CS1. Crosses: no Δt correction; squares: correction is 100% of Δt; solid line: correction is 40% of Δt

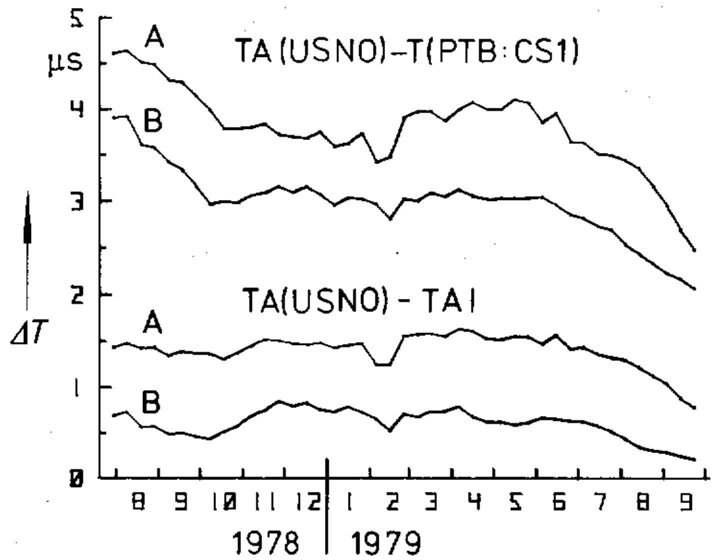

Fig. 9-Time difference ΔT of the time scale TA(USNO) (with rate corrections and arbitrary additive constants) from the time scales T(PTB:CS1) and TAI respectively. Curves A without Δt correction; curves B with Δt correction

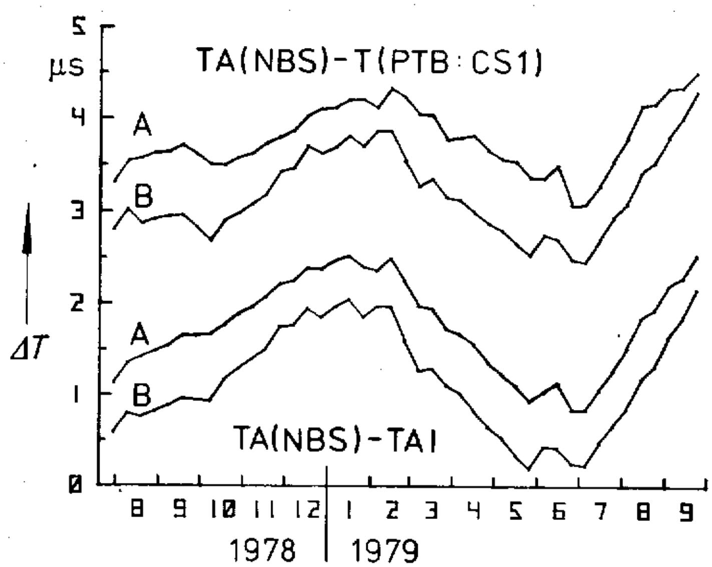

Fig. 10-Time difference ΔT of the time scale TA(NBS) (with rate corrections and arbitrary additive constants) from the time scales T(PTB:CS1) and TAI respectively. Curves A without Δt correction; curves B with Δt correction

QUESTIONS AND ANSWERS

MR. CHI:

Dr. Becker, I noticed in your final vu-graph you showed the time difference of about 2 microseconds for about 400 days, that is between PTB and NRC, which represents about 5 nanoseconds per day of 5 parts, 10 to the 14th. Is that systematic?

DR. BECKER:

This is in fact at present the difference between the two standards and it is within the uncertainty limits which are claimed by both institutes.

MR. CHI:

I have one more question. That is, in the other comparison of time when they use the Loran-C, there seemed to be a high peak, perhaps it is due to seasonal variation. In the case of comparison between NRC and PTB there is just a systematic straight line. How was that comparison made?

DR. BECKER:

You mean this one here?

MR. CHI:

In the systematic there is no peak. In the others, like NBS and NRC, there is always a peak on the comparison.

DR. BECKER:

Yes. This is Loran-C.

MR. CHI:

How about the first one. How is that measured? The one before that?

DR. BECKER:

The one before? Loran-C. The other one, from bulletins. That means I took the weekly bulletins which I get from Canada and from Dr. Winkler from the USNO and our own. And only one day is taken out. The specific day is every 10 days at one point and I took down these data.

MR. CHI:

There is no solution?

DR. BECKER:

If you take just the results which are published for that specific date then it looks like that. It is interesting to see that they are similar in type. That means maybe there is some kind of typical weather which changes slowly. It should be a temperature problem I think.

DR. FRED WALLS, National Bureau of Standards

Could I see the vu-graph showing the relative uncertainties and instabilities? I had a question about that.

DR. BECKER:

Can we have the slide once more?

DR. WALLS:

Two questions. One, under the relative uncertainty, under beam path you have 9 times 10 to the minus 15th. This is an estimate or a calculation of what the maximum uncertainty might be?

DR. BECKER:

This value is achieved in the following way. The theoretical consideration estimated the phase gradient to be expected and calculated the frequency change per millimeter, shifting beam per millimeter. Then, we did a beam shifting, an actual beam shifting and tired to verify this estimation and as it turned out it was the same order and so we relied on our knowledge and in this case I simply chose .3 millimeter, 10 percent of the beam. I think it is better but just because we didn't know it, then we chose .3 millimeter.

DR. WALLS:

I see. For statistical things, maybe dividing by the square root of 3 might be appropriate but for a systematic thing such as the beam path to quote a one sigma value less than the uncertainty there perhaps is a problem.

But let us talk about the relative instability, the column there on the right. These are, again, estimated rather than measured, is that true?

DR. BECKER:

Estimated. Yes.

DR. WALL:

When you compare against your commercial cesiums in your time scale, what kind of stabilities do you measure between season one and your--

DR. BECKER:

This is the value which is of interest. This is shot noise. We are using .3 grams here and there is an instability in a second of about 5.5 parts in 10 to the minus 12th.

DR. WALL:

So that it takes about 25 to 40 days in order to average down to that 6 or 7 times 10 to the minus 15 on both your standard and against maybe commercial standards. So that is a very long time to make a claim of stabilities of 4 or 5 or 6 times 10 to the minus 15 and to then base an estimate of weighting for TAI on a calculated stability rather than a measured one, I think, is quite risky.

DR. BECKER:

The method of evaluating an instability is up to the scientist. If he can measure it, the better. But if he cannot measure it because he has no comparable device, he is allowed to estimate it in the same way as he is allowed, and this is done also at NBS, to estimate the uncertainity. This is the same type of procedure.

By the way, this is a conservative estimation, more or less. Consider please that for commercial clocks the instability is much smaller than the so-called uncertainty. The same could also be for other clocks. But you can be quite sure that the instability is certainly not larger than the uncertainty is. As you see it is only a factor of two here taken. There is no other method of evaluating the instability by theoretical considerations.

Of course you have these things here, magnetic field strength. Well, this is based on regular measurements of the magnetic field and for 80 days we have 11 such measurements and you know how they fluctuate and this is not an estimated but a measured quantity.

DR. COSTAIN:

Dr. Becker, do you have any contribution from the power dependents? In other words your excitation power?

DR. BECKER:

This specific feature, the reason it is not in, the power shift is not an isolated effect and cannot be listed here. You have to go down to the roots of the physical behavior.

QUESTION:

Should it not be possible to use a long time running hydrogen maser which does exist, they run for hundreds of hours. You could use that maser as a direct method of measuring the changes that you have for instance due to beam path reversal and that would not require any estimates. You could really measure it.

DR. BECKER:

We are going to compare our hydrogen maser directly with this cesium. It is just going to be made. Yes. And as far as possibly we will try to measure what is possible.

DR. MICHEL GRANVEAUD, Bureau International de l'Heure

I would have two comments. The first one is about the annual term and I think we have to make the difference between the local time scale and the international one. It seems that in the case of PTB, for example, the local time scale of PTB it has some annual terms and this annual term can come only from the atomic clocks themselves or from the algorithm that is used. In the case of the international time scale, we have furthermore the transmissions using Loran-C.

My second comment is about the use of the difference in our cesium-5, minus cesium-1. Can I see the vu-graph?

DR. BECKER:

Let me first refer to the first question. In fact, if you refer to our time scale TA, is it?

DR. GRANVEAUD:

No. I refer to TA(PTB).

DR. BECKER:

Oh, TA(PTB). Those have a seasonal term yes.

DR. GRANVEAUD:

Please?

DR. BECKER:

Have a seasonal term, yes.

DR. GRANVEAUD:

And about the second comment? I was thinking of the differences in our cesium-5 minus cesium-1.

DR. BECKER:

Frequency or time?

DR. GRANVEAUD:

The curve. The plateau we saw.

DR. BECKER:

Yes. Frequency or time? Time difference?

DR. GRANVEAUD:

Time differences.

DR. BECKER:

Time differences. Das war das systematischen, wissen Sie, mit dem drien kurven. This one?

DR. GRANVEAUD:

Yes. And we think that it could be a bit dangerous to use the smoothing of the data in our cesium-5 minus PTB cesium-1, and it is better to use, when available, satellite data. As you can see there is a smaller frequency difference between the smoothing line and the satellite results.

DR. BECKER:

Yes. You are absolutely right. I said to the first approximation. If you have these data available then it is the best as you are doing, and have written me in your letter, that a combination of both informations is profitable, to use satellite data and these measurements of the standards. You are right.

DR. DAVID ALLEN, National Bureau of Standards

One note of clarification. I suspect there are many here who don't know what a weight of 5,500 means. The miximum amount a clock can receive in the international time scale is the weight of 100, currently, in the ALGOS algorithm, and 5,500 means the total accumulated weight of all the clocks. And when Dr. Becker says that the weight of primary standards would be equivalent to all of those, he means to the total accumulated weight of 5,500 of all the clocks. In other words, if you look at the uncertainty associated with his error budget there that would be the resulting calculation.

The other point I would make is that a lot of the graphs that we see, especially those for NBS, as Dr. Becker pointed out, the Loran path across the NBS/Boulder is a significant problem in our communicating time and frequency to international atomic time. We are aware of that and are working strongly toward curing that problem. And as long as we use Loran-C we will be limited and so a lot of the data that we saw in his presentation is an analysis of Loran-C, not of primary standard.