Time Comparison using Cs-Clocks, Uncertainty Evaluation

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***Abstract*— In Nordic and Baltic countries there are several national and other time & frequency laboratories having atomic clocks. The accuracy ot the time is mostly based on factory calibrated GPS receivers without knowledge on the effect of local cabling and other delays. Thus the time error could easily be 10 ns or more. To improve the situation, an Euromet project 860 was started. At the same time an analysis of uncertainties dealing with time comparison using Cs-clocks was carrier out.**

I. Introduction

In N-MERA meeting in March 2004 in Norway/Kjeller (JV), Nordic delegates K. Kalliomäki (MIKES), K. Jaldehag (SP) and K. Lind (JV) discussed the need of a Nordic time comparison project. Later on, METROSERT (Tallinn), LV (Riga) and LT (Vilna) joined the project.

The first phase started at Oct 31, 2005. MIKES's Cs clock was transported to Stockholm (STUPI). One hour later the journey was continued to Borås (SP) for overnight comparison.

In connection with EFTF07 meeting in Geneva we had "a shadow cabinet" with Baltic (R. Miskinis, Vilna, and S. Kasjanenko, Riga) and Swedish (K. Jaldehag, Borås) Euromet delegates. We agreed to complete this Euromet project with new clock transports both to the Baltic countries and to Sweden. We abandoned the rubidium clock due to its inaccuracy, and selected the Cs-clock. Our goal was to obtain ± 1 ns accuracy.

The final phase of this prolonged Euromet project took place in autumn 2008. A Cs clock of MIKES was transported both to Baltic countries and to Sweden. Altogether 6 timing laboratories in four countries were visited. Maybe the best result arises from the careful "Round Trip Cs-clock uncertainty analysis", which points out that ± 1 ns accuracy is nearly impossible to attain.

II. ROUD-TRIP CS-CLOCK UNCERTAINTY ANALYSIS

A. *Local time uncertainty*

<u>Cs-clocks in Latvia (LV) and Lithuania (LT):</u> Local time (UTC-UTC(k)) is as a rule calculated by BIPM and published in Circular-T. The calculation data originates from GPS Common View measurements. The results are published on 5 day intervals monthly. Typical comparison noise is 3...4 ns, which limits the initial accuracy of UTC-UTC(k).

Typical phase drift (rms, standard tube) in laboratory conditions seems to be:

$$dT = 3\ \text{ns} \cdot \sqrt{T} \tag{1}$$

where T is elapsed time in days and dT the probable (1 σ) phase deviation.

Under these circumstances, the phase may drift by 7 ns in any direction during the 5-day BIPM re-evaluation. Between those check points the total time uncertainty consists of the Common View (3...4 ns) and flicker (3 ns) noise, altogether 4...5 ns rms.

If one uses a High Performance Cs-beam clock as a Master Clock, flicker noise is approximately one third of the above mentioned value. Then Common View noise dominates.

Assuming that laboratory clocks are ordinary Cs-clocks, the local time uncertainty is the above mentioned 3...4 ns rms.

In principle one can improve the comparison accuracy by averaging those BIPM 5 day interval points. In case of standard Cs-beam tubes, averaging is risky because of the dominating random walk drift. In case of High Performance Cs-beam clock, averaging of several points, up to one month, is acceptable. As far as the measured points sit on the straight line, one can consider adding more than 2...3 points to linear regression fit. See Fig. 1. One has to figure out, that in these

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cases the adopted UTC(lab) is the regression estimate (average time over applied points). See Tables I and II.

Hydrogen masers of SP and MIKES: Hydrogen Maser clocks utilize phase lock to hydrogen line (1.420 GHz) instead of the above mentioned frequency lock. Then the random walk (flicker) disappears.

Phase slips are possible in hydrogen masers if the frequency of the local crystal oscillator jumps suddenly. In this case the magnitude of phase slips is N · 704 ps (1 / 1.420 GHz) where N is an integer.

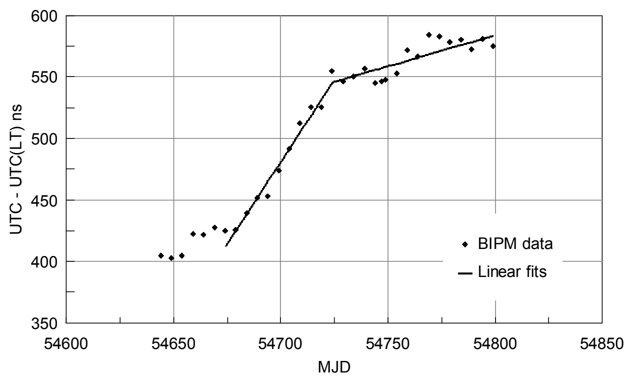

Figure 1. Circular-T values for LT

TABLE I. CIRCULAR-T VALUES FOR (UTC-LT), (UTC-LV) AND LINEAR FITS. "MIKE CS1" SHOWS VISIT TIME

MJD	LT and LV times			
	UTC-LT Vilna	Linear estimate	UTC-LV Riga	Estimate
54734	550.3	551.5	2161.8	2164.9
54739	556.8	554.0	2184.6	2187.5
54744	545.1	556.5	2210.6	2210.1
54745		557.0	MIKE Cs1	2214.6
54746	MIKE Cs1	557.5		2219.1
54747	MIKE Cs1	558.0		2223.6
54748		558.5	MIKE Cs1	2228.1
54749	547.5	559.0	2232.4	2232.6
54754	553.0	561.6	2256.5	2255.2
54759	571.8	564.1	2282.4	2277.8

Standard Cs-beam clock in Vilna, high performance Cs-clock in Riga

The maser frequency drifts slowly, leading to a parabolic phase drift. The parabolic phase drift is quite stable in laboratory conditions. By using hydrogen maser as a master clock, one can apply averaging techniques for Circular-T data for a period of a couple of months.

TABLE II. CIRCULAR-T VALUES FOR (UTC-SP) AND LINEAR FITS

Date	SP time in Nov 2008			
	MJD	UTC-SP +0.15 ns/d -0.61 ns/d	Linear fit over month Regr. down	Regr up
20-Oct	54759	26.6	26.4	
25-Oct	54764	26.8	27.2	
30-Oct	54769	28.1	27.9	25.8
02-Nov	54772		28.4	24.0
03-Nov	54773	MIKE Cs2		23.4
04-Nov	54774	22.8		22.8
09-Nov	54779	19.7		19.7
14-Nov	54784	16.7		16.7

SP rate adjustment in Oct 30: -0.77 ns/d

B. *Estimation of Cs-clock behaviour during transport*

HP/Agilent 5071A Cs-clocks: We have two HP 5071A clocks, one standard version (Cs1) and the other originally High Performance version (Cs2). Random walks of Cs2 and Cs1 follow quite nicely forms $3\ \text{ns}\cdot\sqrt{T}$ and $4\ \text{ns}\cdot\sqrt{T}$, respectively, where T is in days.

Round trip comparison improves the accuracy simply by a factor $\sqrt{2}$. Round trip simulations using real data confirm this anticipated improvement. The above mentioned random walk equation for round trip comparison using Cs1 is as follows:

$$dT = 3\ \text{ns}\cdot\sqrt{T} \tag{2}$$

where T is one way time in days.

Table III presents the schedule and estimated error (SD) of the carried clock during time comparison in Baltic countries. Here METRO means Metrosert in Tallinn, and LV and LT are national laboratories in Riga and Vilna.

TABLE III. THE SCHEDULE OF TIME COMPARISON IN BALTIC COUNTRIES

MJD	Elapsed days	Laboratory	Cs1 Error ns	UTC time	Travel time h:min
54745.13		MIKE	0.0	03:00	
54745.31	0.18	METRO 1	1.3	07:20	4:20
54745.39	0.26	METRO 2	1.5	09:15	
54745.60	0.48	LV 1	2.1	14:30	5:15
54746.23	1.11	LV 2	3.2	05:35	
54746.48	1.35	LT 1	3.5	11:25	5:50
54747.25	2.13	LT 2	3.6	06:05	
54747.44	2.31	LV 3	3.4	10:30	4:25
54748.26	3.13	LV 4	2.0	06:10	
54748.45	3.33	METRO 3	1.5	10:50	4:40
54748.53	3.41	METRO 4	1.3	12:50	
54748.72	3.59	MIKE	0.0	17:10	4:20

The numbers after laboratory abbreviations mean "in" and "out" occasions. Especially LV (Riga) comparisons against High Stability Cs supported our estimations from the untroubled behaviour of our Cs1 during transport.

In LT (Vilna), however, the clock rate seemed to be reversed. This change is only partly (1ns/day) due to elevation. The rest of this change is within ± 2 SD of the estimated rate variation.

In Sweden we visited three laboratories during less than 3 days. STUPI is a private laboratory, SP is the national laboratory, and Onsala is a Space and VLBI observatory having hydrogen masers. See Table IV.

TABLE IV. THE SCHEDULE OF TIME COMPARISON IN SWEDEN

MJD	Elapsed days	Laboratory	UTC time	Travel time h:min	Cs2 estimate 2·√T
54772.59		MIKES	14.17		
54773.26	0.67	STUPI 1	6.35	16:11	1.6
54773.3	0.71	STUPI 2	7.10		1.7
54773.5	0.91	SP 1	11.92	04:49	1.9
54774.31	1.72	SP 2	7.53		2.6
54774.39	1.8	Onsala 1	9.36	01:49	2.0
54774.43	1.84	Onsala 2	10.31		1.9
54774.48	1.89	SP 3	11.64	01:20	1.9
54774.52	1.93	SP 4	12.55		1.8
54774.71	2.12	STUPI 3	17.09	04:32	1.6
54774.74	2.15	STUPI 4	17.85		1.6
54775.35	2.76	MIKES	8.33	14:29	

Modelling of the behaviour of the transportable clock: The time (phase) model of the transportable clock is usually a straight line between departure and return time tags. The noise around this line is considered above.

The only question is the adequate comparison time in the reference laboratory. In other words, how many measurements UTC (reference lab)-UTC (Cs) should be carried out to set the time tags.

The answer is included in Eq. (1). This points out that only short comparison time is allowed, e.g. one hour. This hour must be the last hour before the departure or the first hour when returning, see Fig 2. Here the five last points (50 min) were selected to find the beginning (Tag 1) to the phase model. After selecting the end points (time tags), the "drawing" of straight line is a straightforward work.

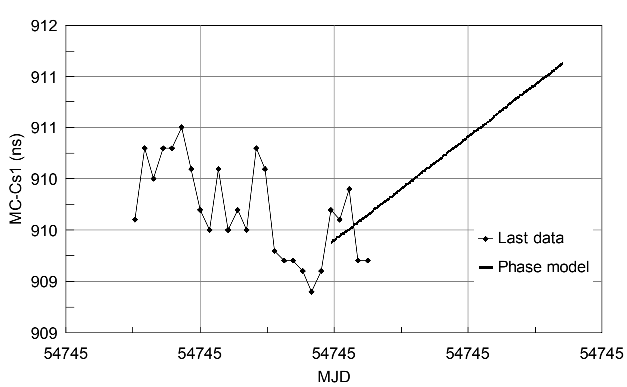

Figure 2. Selecting the beginning of the phase model

Checking the validity of straight line approximation: The control of the stability of the clock during transport is practically not possible.

On the other hand, it is quite easy and important to calculate the rate (ns/day) of the clock during driving sections. First one calculates the average rate of the clock during the whole trip. Then one divides the route into sub routes, which start or stop at time and frequency laboratories.

Assuming that the local clock in the laboratory is similar or better than the transported clock, one simply calculates the phase shift during the visit and corresponding clock rate. Finally one can calculate the phase shift and rate during the total driving periods.

Naturally the calculated clock rates differ from each other. The question is how much they can differ. The answer is hidden in the random walk equation (1). By dividing it by T, one obtains random walk rate equation (3) for Cs1:

$$\frac{dT}{T} = \frac{4\text{ ns}}{\text{day}} \cdot \frac{1}{\sqrt{T}} \tag{3}$$

where T is elapsed time in days.

For example, if one spends one day in any laboratory, the probable clock rate may deviate ± 4 ns/day from the adopted average. If one spends only one hour in some laboratory, rate may differ ± 20 ns/day. The examples do not include rate variation caused by a local clock.

In LV, Riga clock rate was within expected limits of ± 5 ns/day.

In LT, Vilna the measured clock rate was peculiar. Expected SD of rate was 6.5 ns/day. Now we have about 15 ns/day difference, which is equivalent to 2.3 standard deviations. The elevation of Vilna explains only 1 ns/day of the difference.

It seems that the clock rate has been significantly higher on the road than in the labs.

The last STUPI comparison suffers from high phase rate during that short time. Statistically it is three times higher than expected for Cs2. All other phase changes are within expectation values for Cs2.

C. *Evolution of MIKES reference time*

Preface: Since 1972 we have traced Finland's official time mostly to Swedish time. In the eighties we also had several time comparisons with VNIIFTRI (RU). Nowadays MIKES has been responsible for Finland's official time since the beginning of 2000, and now our goal is 1 ns uncertainty.

Since 1996 we have calibrated GPS-receivers (XR5 and Motorola) at SP, Borås. In 2005 we used a Cs-beam clock for the first time for comparison. The desired uncertainty was better than ± 10 ns. Since 2004 BIPM has reported UTC-UTC(MIKE) values in Circular-T. Now we know that one must have a maser as a master clock and be very careful with measurements when trying to attain 1 ns accuracy.

Fortunately we have three hydrogen masers in addition to Cs-beam clocks. The masers are compared to each other and possible phase slips or exceptional aging can be located.

On stabilities of masers in MIKES: If we forget phase slips, which happen in one of MIKES's masers, the remaining problem is the aging of the frequency. The average aging rates of our masers are as follows:

- PHM (passive hydrogen maser) $-0.6 \cdot 10^{-15}$ /day
- AHM1 (active hydrogen maser 1) $-1.6 \cdot 10^{-15}$ /day
- AHM2 (active hydrogen maser 2 $+0.3 \cdot 10^{-15}$ /day

The natural variation of the aging seems to be $\pm 0.2 \cdot 10^{15}$/day, pp. This figure is obtained by comparing the masers against each other.

Assuming that the master clock is a maser and aging is constant, one can filter noisy clock data up to one year. In practice, varying aging rates limit the useful filtering time to a couple of months.

If one uses a third degree polynome, linear drift of the aging can be included and longer data fits are possible.

Naturally one has to keep an eye on residuals between the real data and the estimation polynome. A basic parabolic fit is inaccurate at both ends but a third degree polynome may produce a significant residual error near the centre of the data range.

BIPM publishes UTC-UTC(Lab) values in 5 day intervals. The scatter of values is around 3 ns. If one wants to reduce noise down to 1 ns, at least 9 points (45 days) are needed.

Such a long filtering time is the central problem when studying the local clock stability.

An experimental data fit over 200 days using masers as interpolators: In autumn 2008 we had two clock transports. The first one was a trip to Baltic countries and the second one was a trip to Sweden four weeks later. Naturally Murphy's law came true after the first trip. First we adjusted the frequency of the master clock and two days later the most reliable GPS receiver broke down. We had to replace it with a new, uncalibrated receiver. So we were lacking valid results for one week and then we had to find out a calibration for the new receiver. In addition, maser frequency adjustment is not absolute. The real frequency change may differ by several percent from the setting.

Our Cs-clocks did not help at all. Due to random walk noise, the estimated time changes over the gap varied by 10 ns. Masers helped a lot, but extrapolations using data from both sides of the gap produced 1…2 ns differences in the centre of the gap. Remaining GPS receivers (Motorola) suffer from temperature variations and unknown drifts. The estimated error was 3…4 ns. GPS CV (BIPM) data did not help immediately due to the data noise and the low number of data points, see previous chapter. Thus we were in real trouble with our 1 ns goal. It affects primarily Baltic comparison, because SP is best supervised.

Finally we carried through an ambitious plan to build ±100 days phase "bridge". It means a very long phase estimate over this gap to produce an uniform UTC(MIKE) time to cover both clock transports. The basic idea of this bridge was to match aging, frequency and phase of the master clock to the existing GPS-data on both 100 days long sides of the gap. GPS data was corrected using Circular-T (UTC-GPS) values.

200 days long accurate phase model necessitates the knowledge of maser aging variations; we know only the average aging reliably. Because our goal was better than 1 ns matching, we selected aging as a variable in our model.

To check the validity of the model, one has to look residuals between real data and the phase estimate under development.

After a few hours one has an optimal phase model for the master clock. In our case every average phase residual is below 1 ns (SD 0.19 ns) and the frequency jumps are less than $1 \cdot 10^{-15}$ (SD $0.22 \cdot 10^{-15}$).

The differences on critical dates (Baltic or Swedish trip) deviated by less than 0.5 ns.

III. Comparison Results

A. Corrections applied

The first correction is UTC-UTC(Lab) correction. This is thoroughly explained earlier. Note, that UTC-UTC(lab) here is not Circular-T point but regression fit.

The time reference point was defined to be at the open end of a 5 meter long coaxial cable. The other end of this cable was fixed to the tick output of the Cs-clock. The only correction connecting to this cable is trigger level correction. The rise time of the tick pulse was about 3 ns and amplitude 2.5 V into 50 Ω. If possible, we used 1 V trigger level. In SP, however, the trigger level setting was 1.5 V. It causes 0.4 ns correction.

The reference time, UTC-UTC(Lab), is usually defined to be in the start input of the time interval counter. Because laboratory clocks are connected to this counter via multiplexer, one has to take into account the multiplexed delay. In SP this delay is 19 ns and in MIKES 24.5 ns.

In Baltic countries (Estonia, Latvia, Lithuania) the definition of UTC-UTC(lab) differed. The time was simply defined to be at the tick output of the master clock. Then the cable delay between tick output and start input of the time interval counter is significant. In METROSERT this delay was 5 ns, In LV 10.2 ns and in LT 40.6 ns. These delays come from the laboratory files.

B. Results

Table V presents the most essential results from the time comparison trip in Sweden. The round trip differences are surprisingly small. Closing error estimates are less than 0.5 ns.

TABLE V. RESULTS FROM TIME COMPARISON IN SWEDEN

	First-last point differences			All difference data	
Trip Course	Comment	data, ns	Adopted	Average	(SD)
MIKE - SP	gps1 delay	164.4	164.1 ±0.28	164.65	0.88
SP - MIKE	mike-gps1	163.8			
MIKE - STUPI	raw(1)	9.5	9.9 ±0.44	9.55	0.47
STUPI - MIKE	stupi-mike	10.4			
STUPI - SP	raw(2)	32.3	32.0 ±0.30		
SP - STUPI	stupi-sp	31.7			
SP - ONSALA	raw	18629.74	18629.8 ±0.03		
ONSALA - SP	sp-oso	18629.79			

(1) Uncorrected STUPI data, MIKE trusts on above mentioned GPS1 delay

(2) UTC-UTC(SP) 22.78 ns, UTC-UTC(STUPI) 9.5 ns

SP-MIKE difference (Table V) corresponds to the new delay setting of GPS1 (Fastrax 1). An old estimated delay was 177.9 ns. This value was based on SP 2005 calibration trip.

Our assumption to explain the quite high difference is that last time a multiplexer delay was not taken into account. At that time we did not realize, that a simple relay box may have a significant delay.

In case of STUPI, only raw readings are used, because accurate multiplexed delay values were not available. The first assumption was 6.9 ns, but it is not used to avoid confusion in later checkings.

Although the comparison results are very good, random walk is hidden somewhere. Hence we estimate that the obtained delay error of Fastrax 1 GPS may be ±1 ns.

Because our older XR5 GPS is calibrated against Fastrax over one week gap, its delay error is estimated to be ± 2 ns. This error affects results in the Baltic countries.

In the Baltic countries results were not as excellent as in Sweden, see Table VI.

Metrosert does not have Cs-beam clocks, only two GPS controlled rubidium clocks (Fluke). 20 ns time deviation is within specifications for the short term comparisons. It corresponds to $1 \cdot 10^{-13}$ relative frequency error between two visits.

In LV results were quite good and clearly within estimations (SD 2.1 ns) when using Cs1 as a transportable clock.

In LT we were not so lucky. The results are within two standard deviations ($2 \cdot 3.5$ns) of estimations. Random walk of clock(s) seems to escalate just in Vilna.

In any case UTC-UTC(Lab) seems to be well controlled both in LV and LT.

TABLE VI. RESULTS FROM TIME COMPARISON IN THE BALTIC COUNTRIES

	First-last point differences			All difference data	
Trip Course	Comment	data, ns	MIKE - Lab, ns	Average ns	(SD) ns
MIKE - MS (1)	gps Rb	-34.0	-44.7 ±10	-33.8	
MS - MIKE	gps Rb	-55.4		-53.6	
MIKE - LV	High perf Cs	5.8	+3.6 ±2.2	7.6	
LV - MIKE		1.4		3.9	
MIKE - LT	Standard Cs (Cs1)	-11.9	-6.5 ±5.4	-7.5	
LT - MIKE		-1.2			
LV - LT (2)	LT - LV time diff.	18.8	10.8 ±7.3	Direct comparison with Cs1	
LT - LV		3.5			

(1) MS: METROSERT, Estonia

(2) Direct comparison with Cs1

Uncertainty of UTC-UTC(MIKE) is estimated to be ±2 ns compared to SP time

IV. CONCLUSIONS

Our 1 ns accuracy goal was too optimistic when using a standard Cs-beam clock. Local time uncertainties and random walk of the transportable clock limits the accuracy.

Local times should be based on masers or at least on high stability Cs-beam clocks. Travelling time with a clock should be the minimum and the clock itself of high stability type.

In any case local timescales in Nordic and Baltic countries seem to be well controlled. During all those transports and data processing, we have learned a lot on precision timing on the way to the picosecond world.