Final report - EURAMET Project 860

Time comparison using Cs-clocks, uncertainty evaluation

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Introduction

A Nordic time comparison was first discussed in a N-MERA meeting organized by JV in March 2004 at Kjeller, Norway. At that time, the persons and institutes involved were MIKES (K. Kalliomäki), SP (K. Jaldehag), and JV (K. Lind). An agreement was reached that one of MIKES's Cs-clocks would be transported to Stupi AB (Stockholm, Sweden), SP (Borås, Sweden) and JV (Kjeller, Norway). Later on, Metrosert A/S (Tallinn, Estonia), LATMB (Riga, Latvia) and VMT (Vilna, Lithuania) joined the project.

The first phase was initiated on Monday 31.10.2005 when MIKES Cs clock (Cs2) was transported by car and ferry to Sweden, first to Stupi AB. One hour later the journey continued to SP for an overnight comparison. On hindsight, the first clock transport experiment was akin to practical training with an uncertainty on the order of 10 ns.

In the Euramet meeting in spring 2006, Dr. R. Miskinis (VMT, Lithuania) expressed his interest to join the project and, consequently, the next clock transport experiment to the Baltic countries begun on 25 May 2006. As Metrosert A/S was on the same route, we shortly visited them also. A commercial rubidium clock (PRS-10) was used as a transportable clock, as it had shown very stable performance under laboratory conditions. Initially we expected that 10 ns uncertainty could be reached, but after the results were processed we realized that only 100 ns uncertainty was realistic. After fairly involved data processing, including temperature, aging and air pressure effects, we were able to reduce the uncertainty to the level of a few tens of nanoseconds.

In connection with EFTF07 meeting in Geneva we had "a shadow cabinet" with Baltic (R. Miskinis and S. Kasjanenko) and Swedish (K. Jaldehag) delegates. We agreed to complete this Euramet project with two new clock transport campaigns, one to the Baltic countries and one to Sweden. At that time we projected that an uncertainty of 1 ns could be reached with a commercial Cs-clock.

The final phase of this prolonged Euramet project took place in autumn 2008. A MIKES Cs clock was transported to Baltic countries and Sweden. Altogether 6 timing laboratories (SP, VMT, LATMB, Metrosert A/S, Onsala Space Observatory, and Stupi AB) in four countries were visited. The most important result of this project arises from the careful "Round Trip Cs-clock uncertainty analysis", which allows us to estimate realistic uncertainty of time transfer through clock transport and concludes that it is practically impossible to reach the originally projected 1 ns uncertainty.

1. Round trip Cs-clock uncertainty analysis

1.1 Local time uncertainty

The reference point of the comparison is SP, the national metrology institute of Sweden that has both BIPM calibration and a two-way time link and, consequently, lowest time uncertainty. For other participants the Circular-T values were calculated from GPS Common View (CV) measurement, in which case the type A uncertainty of a single Circular-T data point is a few nanoseconds. Thus, the uncertainty of the time comparison with a transportable clock is dominated by the uncertainty of the local time in laboratories reliant on standard caesium or GPS-referenced rubidium clocks. On the other hand, transportable clock is the dominant source of uncertainty in comparisons with laboratories employing high-performance caesium clocks or hydrogen masers that allow averaging of the Circular-T data.

1.2 Cs-beam clocks, LATMB (Latvia) and VMT (Lithuania)

Cs-beam standards are prone to random walk of the phase. This behaviour originates from the frequency lock principle used in Cs-clocks. Only long interval average frequency is controlled, allowing random-walk phase fluctuations. For our clocks (HP/Agilent 5071A) we have found the typical 1σ phase fluctuation to be:

(1) $$dT = 4\ \text{ns} \cdot \sqrt{T} \quad \text{for Cs1 and} \quad dT = 3\ \text{ns} \cdot \sqrt{T} \quad \text{for Cs2,}$$

where T is time in days and dT is phase deviation. This value applies in controlled environment and the corresponding manufacturer specification for harsh environment is $17\ \text{ns} \cdot \sqrt{T}$. Thus, assuming reasonable laboratory environment, the phase uncertainty is 7 ns (1σ) for the 5-day interval. For HP/Agilent 5071A with a standard tube, as in VMT, the time uncertainty between two Circular-T data points is composed of the time transfer uncertainty and random-walk of the phase ($4\ \text{ns} \cdot \sqrt{T}$), yielding total uncertainty on the order of 5 ns. For clocks with high performance tube the random-walk uncertainty is approximately one third of the value above. In this case the Common View uncertainty dominates and the total uncertainty is somewhat lower. This is the case in LATMB. However, if we assume - for simplicity - that statistical properties of the clocks correspond roughly to HP/Agilent 5071A with a standard tube, a reasonable estimate for the type A local time uncertainty is somewhat below 5 ns (1σ) for laboratories reliant on Cs-clocks only.

In principle one can reduce uncertainty by averaging the Circular-T data. The physics of a Cs-beam clock leads us to assume that linear model for the phase drift is sufficient and higher order models would not give meaningful results, making linear regression an acceptable tool. For clocks with standard Cs-beam tubes, averaging of Circular-T data points does not significantly improve uncertainty due to dominance of the random-walk phase noise over the relevant timescale and only two adjacent data points are used in the calculation. High performance clocks are more stable and smoother phase fluctuations may allow averaging over several data points. For periods when the clock is 'well behaving' and phase develops approximately in linear fashion, one can consider adding more points to the regression fit, see Fig. 1. When interpreting the results below, the reader has to keep in mind that the adopted UTC(k) is calculated from such regression estimate and not from a direct measurement, see Tables 1 and 2.

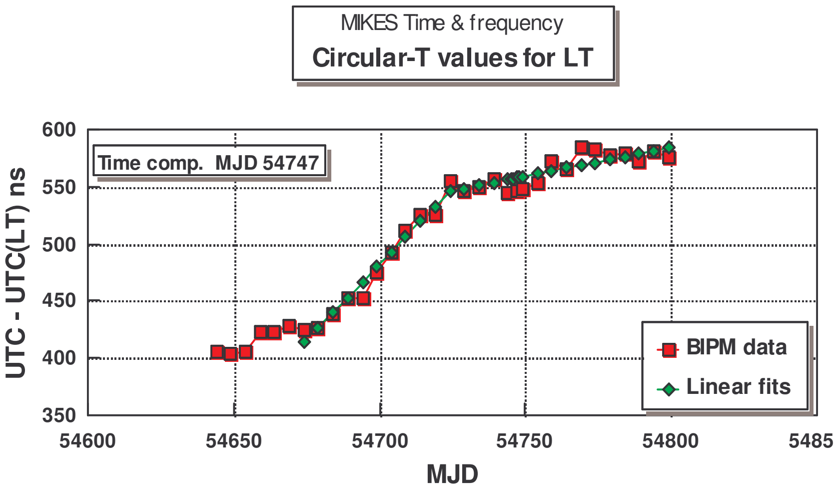

Figure 1. An example of two regression fits to obtain an estimate of UTC(k) between the Circular-T data points.

Table 1. Circular-T values for VMT, UTC(LV), and LATMB, UTC(LT), and linear fits. Entries "MIKE Cs2" in the UTC columns indicate times of visits.

		LT and LV times			Circular-T
Date	MJD	(UTC-LT) Vilna	Linear Estimate	(UTC-LV) Riga	Linear Estimate
25/09	54734	550.3	551.5	2161.8	2164.9
30/09	54739	556.8	554.0	2184.6	2187.5
05/10	54744	545.1	556.5	2210.6	2210.1
06/10	54745		557.0	MIKE Cs1	2214.6
07/10	54746	MIKE Cs1	557.5		2219.1
08/10	54747	MIKE Cs1	558.0		2223.6
09/10	54748		558.5	MIKE Cs1	2228.1
10/10	54749	547.5	559.0	2232.4	2232.6
15/10	54754	553.0	561.6	2256.5	2255.2
20/10	54759	571.8	564.1	2282.4	2277.8

Standard Cs-beam clock in Vilna
High performance Cs-clock in Riga

1.3 Hydrogen masers, SP (Sweden) and MIKES (Finland)

In hydrogen masers a crystal oscillator is phase-locked to an RF-field present in the high-Q resonator, making phase noise processes different from what are commonly seen on Cs-beam clocks. For a hydrogen maser the short-term random walk of the phase is negligible and short-term noise is approximately white. However, in hydrogen masers there are several processes, including cavity pulling, that are difficult to compensate for and affect the observed frequency of the hydrogen line. As a consequence, the maser frequency drifts slowly, leading to a parabolic phase drift. The parabolic phase drift is highly predictable in laboratory environment. Thus, if a hydrogen maser is available, averaging techniques for Circular-T data can be applied over a time period of a couple of months and uncertainty contribution of the time transfer method can be made sufficiently small to achieve ns-level type A uncertainty. This is the case in SP, Stupi AB, and Onsala Space Observatory (Sweden) and MIKES (Finland).

Table 2. Circular-T values for UTC(SP) and linear fits. Entry "MIKE Cs2" in the UTC column indicates time of the visit.

		SP time 11/2008		Circular-T
Date	MJD	UTC-SP +0.15 ns/d -0.61 ns/d	Linear fits over month Regr down	Regr up
20/10	54759	26.6	26.4	
25/10	54764	26.8	27.2	
30/10	54769	28.1	27.9	25.8
02/11	54772		28.4	24.0
03/11	54773	MIKE Cs2		23.4
04/11	54774	22.8		**22.8**
09/11	54779	19.7		19.7
14/11	54784	16.7		16.7

' rate adjustment 30/10: -0.77 ns/d

2. Comparison by clock transport

2.1 Transportable Cs-clock (HP/Agilent 5071A)

Our results from three HP/Agilent 5071A Cs-clock transports indicate that the performance of these clocks is not significantly affected by a carefully arranged transport. This allows us to use our full ten-year data to predict statistical clock performance during transport, which is essential, as it is nearly impossible to gather phase data while travelling. All clock transports were designed in a round-trip fashion, as this approach provides further insight to clock performance during transport and significantly reduces the uncertainty caused by random walk of the phase.

We have two HP 5071A clocks, one standard version (Cs1) and one high-performance version (Cs2). However, due to the short lifetime of the high-performance tube, we have replaced the original, now defunct tube with a standard tube. After this modification Cs2 is still slightly more stable than Cs1. The random-walk uncertainties of Cs2 and Cs1 are given in Eq. 1, and the round-trip approach improves the uncertainty by a factor $\sqrt{2}$ (assuming identical outward and return journeys). We have confirmed this by simulations with real data.

We wish to note that the systematic frequency error is not important. Even though a negligible frequency bias would make calculations easier, it has no effect on uncertainty. The average drifts of our clocks during the last year are 1.2 ns/day for Cs1 and 0.2 ns/day for Cs2.

2.2 Schedule of the comparison

Tables 3 and 4 below show the schedule and estimated uncertainty (1σ) of the transportable clock during time comparison campaigns in Baltic countries and Sweden.

Table 3. Schedule of time comparisons in Baltic countries. Here METRO is Metrosert A/S in Tallinn, and LATMB (LT) and VMT (LV) are national laboratories in Latvia and Lithuania, respectively.

MJD	Elapsed days	Laboratory	Cs1 error ns	UTC Time	Travel t. h:min
54745.13		MIKE	0.0	03:00	
54745.31	0.18	METRO 1	1.3	07:20	04:20
54745.39	0.26	METRO 2	1.5	09:15	
54745.60	0.48	LV 1	2.1	14:30	05:15
54746.23	1.11	LV 2	3.2	05:35	
54746.48	1.35	LT 1	3.5	11:25	05:50
54747.25	2.13	LT 2	3.6	06:05	
54747.44	2.31	LV 3	3.4	10:30	04:25
54748.26	3.13	LV 4	2.0	06:10	
54748.45	3.33	METRO 3	1.5	10:50	04:40
54748.53	3.41	METRO 4	1.3	12:50	
54748.72	3.59	MIKE	0.0	17:10	04:20

Numbers after the abbreviated laboratory name mean instants of arrival (odd) and departure (even). The transportable clock was continuously compared with each master clock during the entire stay in every laboratory. Comparison with a High Stability Cs-clock in LATMB verifies our assumption of untroubled behaviour of MIKES Cs1 during transport.

Table 4. Schedule of time comparisons in Sweden.

MJD	Elapsed d	Laboratory	UTC hour	Travel time	Cs2 e. est 2*sqrt(T)
54772.59		MIKES	14.17		
54773.26	0.67	STUPI 1	6.35	16:11	1.6
54773.30	0.71	STUPI 2	7.10		1.7
54773.50	0.91	SP 1	11.92	04:49	1.9
54774.31	1.72	SP 2	7.53		2.6
54774.39	1.80	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	

In Sweden we visited three laboratories in less than three days. Stupi AB is a private laboratory in Stockholm, operating several atomic clocks, including hydrogen masers, and a continuous GPS common view link to SP in Borås. SP is the national laboratory of Sweden, and Onsala Space Observatory is an IGS Reference Frame station. At Stupi AB and Onsala we spent the shortest possible time, approximately one hour. Onsala was the turning point of the trip. The longest distance without access to any time reference was from MIKES to Stupi AB over the sea.

2.3 Linear phase model – parameters

We use a simple linear model to predict the phase evolution of the clock during transport and estimate the respective uncertainty assuming random-walk of the phase, as described above. This approach requires detailed knowledge on the statistical properties of the transportable clock, phase immediately before departure, and phase immediately after arrival. Statistical properties of the transportable clock are, a priori, known and the remaining task is to measure the phase relation to the local clock with least uncertainty. As the phase-noise of the transportable clock has random-walk nature, averaging does not improve uncertainty. Nevertheless, to allow some averaging, to avoid coarse mistakes, and to verify expected behaviour of the measured phase we collected data for at least one hour in most laboratories. The approach is depicted in Fig. 2, which shows an example in which five data points (50 min) at the end of a time series are used to find the initial phase of the linear phase model.

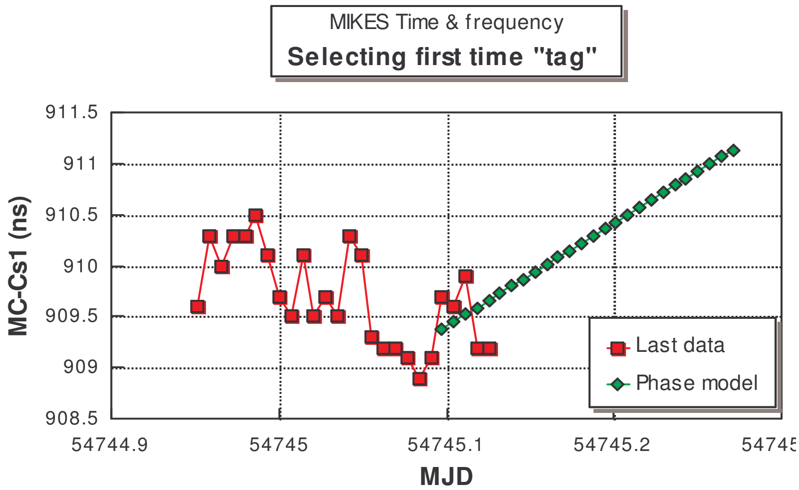

Figure 2. Finding the initial phase of the linear phase model.

2.4 Verification of the validity of linear phase model

During transport it was impossible to neither control nor monitor the phase of the transportable clock. However, it is still possible to calculate the average rate (ns/day) of the clock during transport, which allows us to evaluate the validity of the linear phase model. The linear phase model can be considered valid if the observed rate is within the associated rate uncertainty of the transportable clock, that can be calculated from Eq. 1 by dividing it with the elapsed time *T*:

(2) $$dT / T = \frac{4 \text{ ns}}{\text{day}} \cdot \frac{1}{\sqrt{T}} \text{ for Cs1 and } dT / T = \frac{3 \text{ ns}}{\text{day}} \cdot \frac{1}{\sqrt{T}} \text{ for Cs2.}$$

We have done this verification independently for each leg of the comparison, including measurement periods in the laboratories. As the historical data of all clocks participating the comparison is not available to us, we have assumed, for simplicity, that local clocks have negligible contribution to the rate uncertainty (except for Metrosert A/S that is not included in the evaluation), leading to total rate uncertainty given by Eq. 2.

From the results given in Table 5 we can observe that in LATMB (Latvia) clock rate was within uncertainty, but in VMT (Lithuania) the rate deviated statistically significantly from the linear model. The rate uncertainty predicted by Eq. 2 for 0.74 day comparison is 6.5 ns/day, but the observed deviation from the linear model is approximately 15 ns/day, or 2.3 standard deviations. However, the Cs-clock in VMT has also a standard tube. Assuming that the performance of the local clock and the transportable clock are approximately similar, the combined rate uncertainty and gravity correction (1 ns/day) together make the observed rate consistent with the linear model within 1.5 standard deviations. Nevertheless, the high rate uncertainty affects the comparison uncertainty. Table 6 reports the observed clock rate changes and round trip residuals in Sweden. Results are generally consistent with Eq. 2, which is expected as local clocks were hydrogen masers.

Table 5. Observed behaviour of the transportable clock during Baltic comparison. Clock rate at Metrosert A/S was not calculated due to large uncertainty caused by the local GPS controlled rubidium clock and the relatively short comparison time. In LATMB the local Cs-clock has a high performance tube with low random walk whereas in VMT a similar clock with standard tube is used.

Cs1 rate changes during the trip in Baltic

	Phase change ns	days	rate ns/d	Cs1 noise 4/sqrt(T)
Whole trip	32.10	3.59	8.9	
Tallin 1	2.20	0.07		
Riga 1	7.4	0.61	12.1	5.1
Vilna	-4.1	0.74	-5.5	6.5
Riga 2	9.9	0.81	12.2	4.4
Tallin 2	3.70	0.06		
Labs. sum	19.10	2.30	8.3	2.6
On the road	13.00	1.29	10.1	

Table 6. Observed behaviour of the transportable clock during comparisons in Sweden.

Cs2 changes during the trip in Sweden

	Phase change ns	elapsed days	rate ns/d	Residual SD ns	Cs2 exp. 3/sqrt(T) ns
whole trip	-1.50	2.76	-0.5		1.8
STUPI 1	-0.12	0.03	-3.9	0.30	17.0
SP	-0.45	1.03	-0.4	0.84	3.0
Onsala	0.84	0.04	21.0	0.15	15.0
STUPI 2	1.57	0.03	49.1	0.29	16.8
Lab. sum	1.84	1.13	1.6		2.8
On the road	-3.34	1.63	-5.0		2.3

Phase readings do not include local clock drifts.

Closing errors (ns, pp) :

MIKE-STUP	0.9
MIKE- SP	0.6
MIKE-Onsal	0.9

The calculated clock rate was significantly higher during transport than in the laboratories. On the other hand, all round-trip differences are small compared to the apparent clock rate during transport, which leads to an assumption that the round-trip phase changes incidentally compensate each other. An outlier is the last comparison at Stupi AB, which deviates from the linear model approximately by three standard deviations. We do not have an explanation for this, but the integration time was very short, making the apparent clock rate sensitive to even small contribution from white phase noise or transients caused by change in the ambient conditions of the transportable clock. All other measurements are consistent with the linear model.

3. Results

3.1 Corrections

The most significant correction is obtained from the linear regression method to calculate UTC-UTC(Lab), as explained in section 1.2. Other corrections are multiplexer delay, cable delay and pulse rise-time correction. The reference point in the comparison was defined to be at the BNC-connector of a 5 meter long coaxial cable connected to the pps tick output of the transportable Cs-clock. Due to the finite rise-time of the pulse, a correction is necessary if trigger level is changed. The pps pulse has a rise time of 3 ns with 2.5 V amplitude into a 50 Ω load. If possible, we used 1 V trigger level in the time-interval counter. In SP, however, the trigger level setting was 1.5 V, causing 0.4 ns correction. In SP (Sweden) and MIKES (Finland) the reference time, UTC-UTC(Lab), was defined to be at the start input of the time interval counter. A device under measurement, in this case the transportable clock, is connected to the counter via multiplexer and one has to take into account the multiplexer delay. In SP this delay is 19 ns and in MIKES 24.5 ns. In the Baltic countries (Metrosert A/S, VMT, and LATMB) the definition of UTC-UTC(lab) was different. The time was simply defined to be at the tick output of the master clock, making the cable delay between tick output and start input of the time interval counter significant. In Metrosert A/S this delay was 5 ns, In LATMB 10.2 ns and in VMT 40.6 ns. These values were obtained from the laboratory files.

3.2 Outcome of the comparison

Table 8 gives results of the time comparison campaign in Sweden. Round-trip differences are surprisingly small yielding closing errors (calculated as the difference of the round-trip measurement and given below the adopted value) less than 0.5 ns. Although the small closing errors increase our confidence that the comparison was technically successful, uncertainty of the comparison (1σ) has to be calculated from Eq. 2, as given in Tables 3 and 4.

Table 8. Results of time comparisons in Sweden.

Round trip data, Sweden

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

(1) uncorrected stupi data, mike trust on above mentioned gps1 delay
(2) UTC-UTC(SP) 22.78 ns, then UTC-UTC(STUPI) 9.5 ns

The comparison provides MIKES with a new GPS delay setting for which we use the adopted value of 164.1 ns given in Table 8 (SP-MIKE) and an uncertainty of 2 ns (1σ), see Table 3 and Eq. 1. Our previous estimate of was 177.9 ns, based on calibration at SP in 2005. This difference is significant and we assume that the multiplexer delay was accidentally omitted in 2005. At that time we did not realize, that a small relay box may cause significant delay. For Stupi AB, only raw readings are used, as measured value for multiplexer delay is not available. The best estimate for multiplexer delay is 6.9 ns, but this is not used as correction to avoid confusion.

In Baltic countries the achievable uncertainties were affected by the local clocks. Metrosert A/S operates two commercial GPS controlled rubidium clocks (Fluke 910R). The specified short-term time uncertainty of these clocks is 20 ns, which is consistent with the result of the comparison. In LATMB results were within the estimated statistical variation of the transportable clock (Cs1). In VMT the results can not be explained by statistics of the transportable clock alone, but we have to take into account the statistics of the local clock also, as the local clock and the transportable clock have approximately similar performance.

Table 9. Results of time comparisons in the Baltic countries.

Round trip data, Baltic countries

	First-last point differences (ns)			All difference data	
Trip course	Comment	data (ns)	MIKE- Lab	Average	SD
MIKE-METROSERT	gpsrub.	-34.0	-44.7	-33.8	0.5
METROSERT-MIKE		-55.4	+/- 10	-53.6	1.0
MIKE-LV	High perf.	5.8	3.6	7.6	2.5
LV-MIKE	Cs	1.4	+/- 2.2	3.9	1.2
MIKE-LT	Standard	-11.9	-6.5	-7.5	2.9
LT-MIKE	Cs	-1.2	+/- 5.4		
LV -LT	LT-LV time	18.8	10.8	Direct comparison	
LT - LV	difference	3.5	+/- 7.3	with Cs1	

Uncertainty of UTC-UTC(MIKE) is estimated to be +/- 2 ns, ref. SP time

4. Conclusion

Our initial goal to reach 1 ns uncertainty was too optimistic for a comparison with a transportable commercial Cs-beam clock. Random walk of the transportable clock and, in some cases, also the local time uncertainty limits the attainable accuracy. Uncertainty of the comparison could be further reduced with a more stable clock or shorter travel times. However, we conclude that the comparison was successful and demonstrates that local timescales in Nordic and Baltic countries are appropriately maintained.