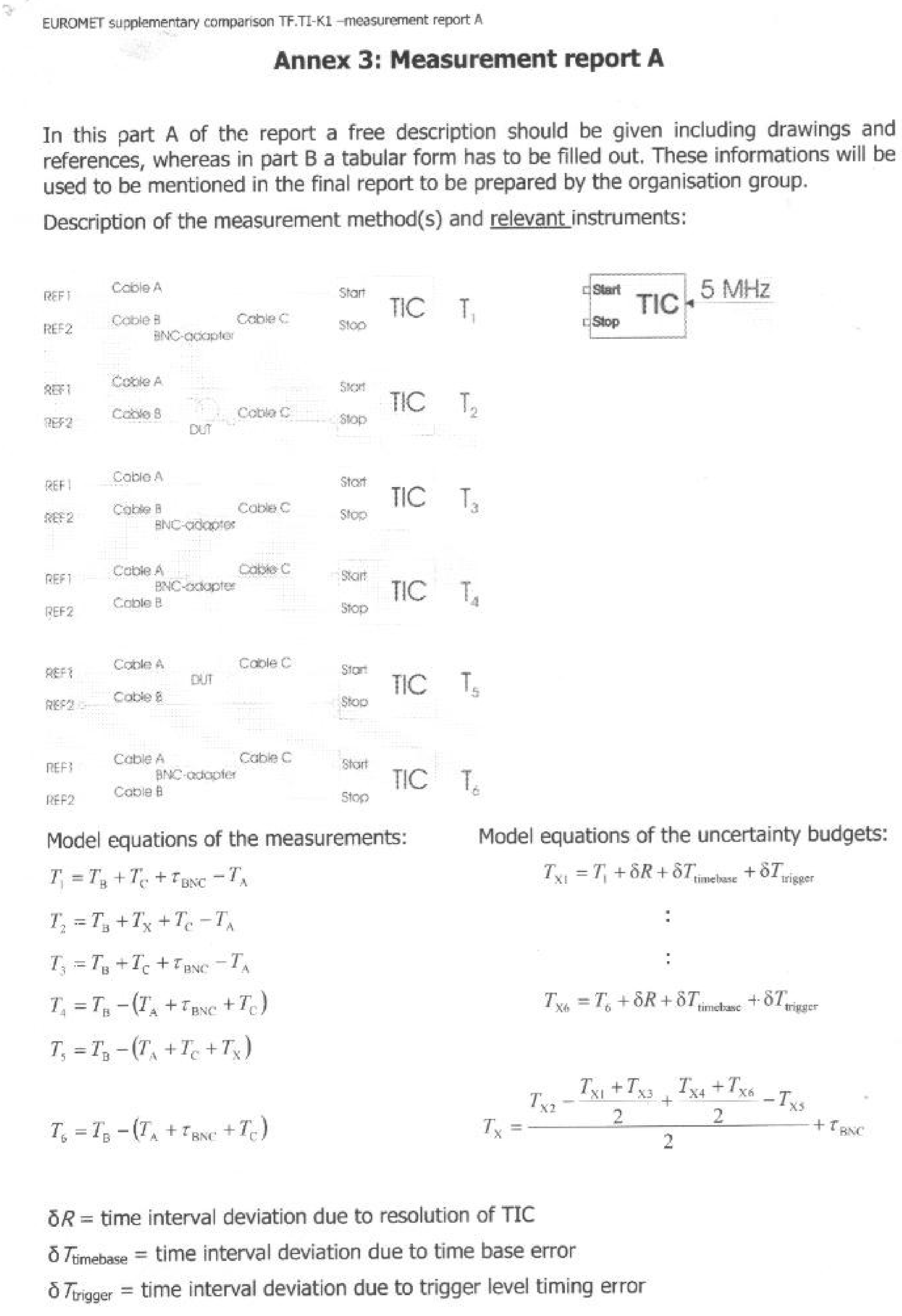
Appendix A: Measurement Reports

Appendix A.PTB



EUROMET supplementary comparison TF.TI-K1 –measurement report A

Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organisation group.

Description of the measurement method(s) and relevant instruments:

Model equations of the measurements:

$$T_1 = T_B + T_C + \tau_{BNC} - T_A$$

$$T_2 = T_B + T_X + T_C - T_A$$

$$T_3 = T_B + T_C + \tau_{BNC} - T_A$$

$$T_4 = T_B - (T_A + \tau_{BNC} + T_C)$$

$$T_5 = T_B - (T_A + T_C + T_X)$$

$$T_6 = T_B - (T_A + \tau_{BNC} + T_C)$$

Model equations of the uncertainty budgets:

$$T_{X1} = T_1 + \delta R + \delta T_{\text{timebase}} + \delta T_{\text{trigger}}$$

$$\vdots$$

$$\vdots$$

$$T_{X6} = T_6 + \delta R + \delta T_{\text{timebase}} + \delta T_{\text{trigger}}$$

$$T_X = \frac{T_{X2} - \frac{T_{X1} + T_{X3}}{2} + \frac{T_{X4} + T_{X6}}{2} - T_{X5}}{2} + \tau_{BNC}$$

δR = time interval deviation due to resolution of TIC

$\delta T_{\text{timebase}}$ = time interval deviation due to time base error

$\delta T_{\text{trigger}}$ = time interval deviation due to trigger level timing error

Participating laboratory: Physikalisch-Technische Bundesanstalt (PTB)
AG 4.42, Time Transfer
Bundesallee 100, D-38116 Braunschweig, Germany

Date: 2005-04-26

Signature Thomas

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	SRS Model SR620
Is the TIC independent of other national measurement laboratory (NML) ?	yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	

2. Measuring method

Counter settings	time, A-B, trigger level 1 V, t_{meas}= 100 s, external timebase 5 MHz
Reference parameter	U_{pp}=2.75 V; risetime = 3.5 ns
Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in °C	23
Ambient humidity in the room in %	35

Participating laboratory: Physikalisch-Technische Bundesanstalt (PTB)
AG 4.42, Time Transfer
Bundesallee 100, D-38116 Braunschweig, Germany

Date: 2005-04-26

Signature

Annex 5: Measurement results for traveling standard no: BEV01

Measurand: time interval $T_X(l)$ for measuring cable lengths:

All figures are in ns.

cable length	$T_X(l)$	combined standard uncertainty $u(T_X)$	eff. degree of freedom ν_{eff}
3 m	*20.509*	*0.047*	*180*
10 m	*48.735*	*0.041*	*240*
35 m	*175.344*	*0.068*	*130*

Appendix A.SYRTE

EUROMET supplementary comparison TF.TI-K1

Measurement report

Comparison of time interval (cable delay) measurement at SYRTE French laboratory

28th February – 13th March 2005

Jean-Yves Richard, David Valat, LNE-SYRTE Time Metrology Team
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This document resumes the measurements of time delay of three BNC cables used for time interval comparison between different National Institute of Metrology in Europe Community. This project was proposed during Euromet Time and Frequency meeting held in Ljubljana 3rd and 4th April 2003.

The Annex numbers are in consistency with the reference document EUROMET_TF_Technical protocol.doc:

Annex 3: Measurement report A
Description of measurements, uncertainties budget Type A and Type B

Annex 4: Measurement report B
Conditions of measurements

Annex 5: Measurement results for travelling standard no: BEV01
Syntheses of time interval $T_X(i)$ for measuring cable lengths

Annex 6: Uncertainty budget for TX

References

Annex 3: Measurement report A

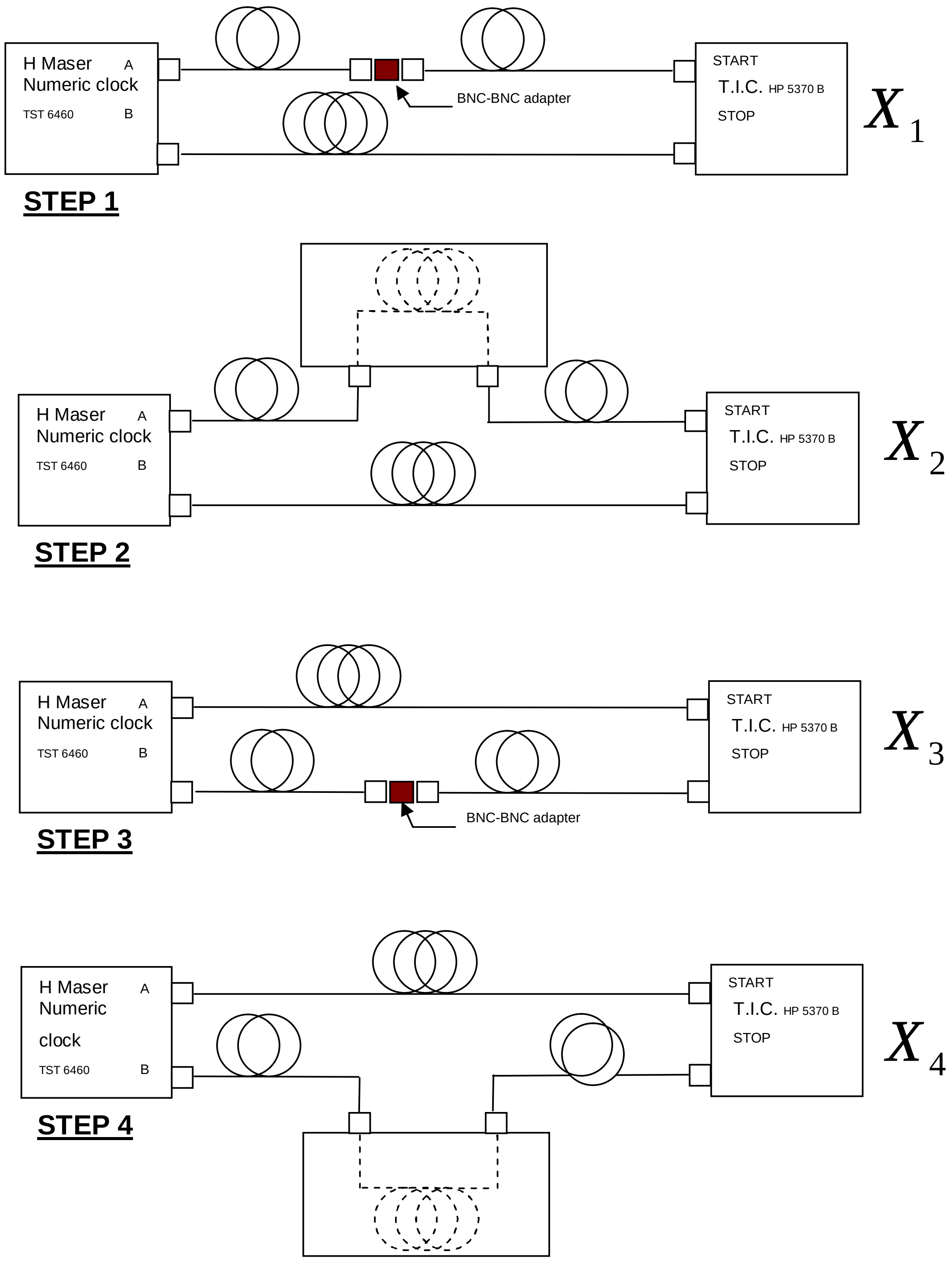

Figure 1: schematic of the step measurements

$$T_x = \left(\frac{X_4 - X_2}{2}\right) - \left(\frac{X_3 - X_1}{2}\right) - X_{Corr} \qquad (1)$$

Measurement and uncertainty of measurement

The time delay of the cable T_x and the uncertainty budget on the cable delay measurement is evaluated by the equation (1) and rewritten with systematic uncertainties considered for each X_j measurement (see tables on annex 6) as:

$$\begin{aligned} T_x = & \frac{1}{2}\left(X_1 + d_c + d_d + d_j + d_{es}\right) \\ & -\frac{1}{2}\left(X_2 + d_c + d_d + d_j + d_{es}\right) \\ & -\frac{1}{2}\left(X_3 + d_c + d_d + d_j + d_{es}\right) \\ & +\frac{1}{2}\left(X_4 + d_c + d_d + d_j + d_{es}\right) \\ & -(X_{Corr} + d_{Corr}) \end{aligned} \tag{2}$$

Each X_j with $j \in \{1, 2, 3, 4\}$ is evaluated with $n=100$ measurements. Average value and uncertainties Type A and Type B of each X_j are evaluated by the equation given bellow.

- Number of observation: $n = 100$
- Mean estimation $\langle X_j \rangle = \frac{\sum_{i=1}^{n} X_{j_i}}{n}$ for i $\in$ *[1,n]*
- **Type A** uncertainty on the mean $u_{A(X_j)} = \sqrt{\frac{\mathrm{var}(X_j)}{n}}$

  with $\mathrm{var}(X_j) = \frac{\sum_{i=1}^{n} (X_{j_i} - \langle X_j \rangle)^2}{n-1}$ gives

$$u_{A(X_j)} = \sqrt{\frac{\sum_{i=1}^{n} (X_{j_i} - \langle X_j \rangle)^2}{n\,(n-1)}} \tag{3}$$

Type A uncertainty on T_X is then calculated by

$$u_{A(T_X)} = \sqrt{C_{A(X_1)}{}^2\, u_{A(X_1)}{}^2 + C_{A(X_2)}{}^2\, u_{A(X_2)}{}^2 + C_{A(X_3)}{}^2\, u_{A(X_3)}{}^2 + C_{A(X_4)}{}^2\, u_{A(X_4)}{}^2} \tag{4}$$

With sensitivity coefficients $C_{A(X_j)}$ =1/2 and $u_{A(X_j)}$ given in tables Annex 6

$$u_{A(T_X)} = \sqrt{\frac{1}{4}u_{A(X_1)}^{\ 2} + \frac{1}{4}u_{A(X_2)}^{\ 2} + \frac{1}{4}u_{A(X_3)}^{\ 2} + \frac{1}{4}u_{A(X_4)}^{\ 2}} \qquad (5)$$

- **Type B** evaluation of standard uncertainty: $u_{B(X_j)}$ for *j Є {1, 2, 3, 4}* is given by

$u_{B(T_X)} =$

$$\sqrt{C_{B(\delta_c)}^{\ 2}\,\delta_c^{\ 2} + C_{B(\delta_d)}^{\ 2}\,\delta_d^{\ 2} + C_{B(\delta_j)}^{\ 2}\,\delta_j^{\ 2} + C_{B(\delta_l)}^{\ 2}\,\delta_l^{\ 2} + C_{B(\delta_{es})}^{\ 2}\,\delta_{es}^{\ 2} + C_{B(\delta_{Corr})}^{\ 2}\,\delta_{Corr}^{\ 2}} \qquad (6)$$

with sensitivity coefficients:

$C_{B(\delta_c)} := 2$, $C_{B(\delta_d)} := 2$, $C_{B(\delta_j)} := 2$, $C_{B(\delta_l)} := 2$, $C_{B(\delta_{es})} := 2$, $C_{B(\delta_{Corr})} := 1$

it gives:

$$u_{B(T_X)} = \sqrt{4\,\delta_c^{\ 2} + 4\,\delta_d^{\ 2} + 4\,\delta_j^{\ 2} + 4\,\delta_l^{\ 2} + 4\,\delta_{es}^{\ 2} + \delta_{Corr}^{\ 2}} \qquad (7)$$

With the different contribution detailed bellow:

- Time base error extracted from TIC constructor performance $\delta_c = 0.67\ 10^{-11}\ TI$ with TI is the max Time Interval of the open gate set between the start and stop entrance pulse command of the Time Interval Counter. This max Time Interval of open gate is either the propagation delay on the longest cable length L≈15m that is given appreciatively by the propagation delay of 5ns/m and gives about 75ns, or the time interval between two join pulses that is 1s.
For $TI = 1$ second, that gives $\delta_c = 0.67\ 10^{-11}$ second

- Resolution is given by the technical TIC performance using the equation $\delta_d = \frac{100}{3}\,\frac{1}{\sqrt{n}\,\sqrt{12}}$ *ps*. With $n := 100$ that gives $\delta_d = 0.9622\ 10^{-12}$ second.
- Trigger jitter (command pulse time instability): the constructor of the TIC gives a estimation of $\delta_j = 35\ ps$ typically
- Trigger level Timing Error (hysteretic of trigger level) the constructor of the TIC gives a estimation of $\delta_l = \frac{25\ mv}{S}$ with S the slew rate at trigger point evaluated at 1 *V/ns*, that gives $\delta_l = 0.25\ 10^{-10}$ second.
- Systematic error for relative time measurement is given by the constructor $\delta_{es} = 0.30\ 10^{-10}$ second.
- The delay of BNC F-F adaptation X_{Corr} is estimated at 100 *ps* with a confidence interval of ±50*ps.* The uncertainty of X_{Corr} is evaluated with its limit

values a_+ =150ps and a_- =50ps. $X_{Corr} = \frac{1}{2}(a_+ + a_-)$. The rectangular law distribution of X_{Corr} between a_+ and a_- have a variance $\mathrm{var}(X_{Corr}) = \frac{1}{12}(a_+ - a_-)^2$ and so $d_{Corr} = \frac{1}{\sqrt{12}}\sqrt{(a_+ - a_-)^2}$ and gives $\delta_{Corr} = 0.2887\ 10^{-10}$ second.

Budget of each cable delay measurement T_X

$$T_X = \frac{1}{2}X_1 - \frac{1}{2}X_2 - \frac{1}{2}X_3 + \frac{1}{2}X_4 - X_{Corr} \tag{8}$$

The effective number of degrees of freedom is calculated by the Welch-Satterhwaite formula with summation over the 10 parameters for T_X definition (see tables on Annex 6):

$$\nu_{eff} := \frac{\mathrm{u}(T_X)^4}{\displaystyle\sum_{i=1}^{10} \frac{\mathrm{u}(T_{X_i})^4}{\nu_i}} \tag{9}$$

with $$\mathrm{u}(T_X) = \sqrt{u_A(T_X)^2 + u_B(T_X)^2} \tag{10}$$

Equation (9) rewritten with explicit denominator is:

$$\nu_{eff} := \sqrt{u_{\mathrm{B}(X_j)}{}^2 + u_{\mathrm{A}(X_j)}{}^2}^{\,4} \Bigg/ \left(\frac{C_{A_{X_1}}{}^4 u_{A_{X_1}}{}^4}{\nu_{X_1}} + \frac{C_{A_{X_2}}{}^4 u_{A_{X_2}}{}^4}{\nu_{X_2}} + \frac{C_{A_{X_3}}{}^4 u_{A_{X_3}}{}^4}{\nu_{X_3}} + \frac{C_{A_{X_4}}{}^4 u_{A_{X_4}}{}^4}{\nu_{X_4}} + \frac{C_{\mathrm{B}(\delta_c)}{}^4 \delta_c{}^4}{\nu_{\delta_c}} + \frac{C_{\mathrm{B}(\delta_d)}{}^4 \delta_d{}^4}{\nu_{\delta_d}} + \frac{C_{\mathrm{B}(\delta_j)}{}^4 \delta_j{}^4}{\nu_{\delta_j}} + \frac{C_{\mathrm{B}(\delta_l)}{}^4 \delta_l{}^4}{\nu_{\delta_l}} + \frac{C_{\mathrm{B}(\delta_{es})}{}^4 \delta_{es}{}^4}{\nu_{\delta_{es}}} + \frac{C_{\mathrm{B}(\delta_{Corr})}{}^4 \delta_{Corr}{}^4}{\nu_{\delta_{Corr}}} \right) \tag{11}$$

The different values of degree of freedom used are listed bellow:
For each X_j the degree of freedom is evaluated by ν = n-1, n being the number of observation and here equal to 100, so ν_X=99
$\nu_{X_1} := 99$, $\nu_{X_2} := 99$, $\nu_{X_3} := 99$, $\nu_{X_4} := 99$,

For the degree of freedom of type B uncertainty, we used the hypothesis that $\Delta(\delta_k)/\delta_k = 0{,}25$ and the approximation

$$\nu_k \approx \frac{1}{2}\left[\frac{1}{\left(\frac{\Delta(d_k)}{d_k}\right)^2}\right]$$ (see ref[2] Annex G § G.4.2) (12)

and so ν_k=8 for systematic effects $\nu_{\delta_c} := 8$, $\nu_{\delta_d} := 8$, $\nu_{\delta_j} := 8$, $\nu_{\delta_j} := 8$, $\nu_{\delta_l} := 8$, $\nu_{\delta_{es}} := 8$,

Last parameter concern the degree of freedom of X_{Corr} for which we consider that its value is at a level of 100% of the confidence interval of ±50*ps*, and so $\nu_{\delta_{Corr}} := \infty$

This parameter allows evaluating the confidence interval for each mean estimation $<T_X>$:

$$\langle T_X\rangle_{max} = \langle T_X\rangle + t_p(\nu_{eff})\sqrt{{u_{A(X_j)}}^2 + {u_{B(X_j)}}^2}$$ (13)

$$\langle T_X\rangle_{min} = \langle T_X\rangle - t_p(\nu_{eff})\sqrt{{u_{A(X_j)}}^2 + {u_{B(X_j)}}^2}$$ (14)

with the value of $t_p(\nu_{eff})$ corresponds to the value of the distribution law $t = \frac{T_X - \langle T_X\rangle}{u_{T_X}}$ into a confidence interval of p:

$$p = \mathrm{Prob}(T_X - t_p(\nu)\, u_{T_X}) < T_X < \mathrm{Prob}(T_X + t_p(\nu)\, u_{T_X})$$ (15)

Value of confidence interval is less or equal to 1 and corresponds to the cumulative Student *t* distribution function:

$$p = \int_{-t_p(\nu)}^{t_p(\nu)} \mathrm{f}(t, \nu)\, dt$$ (16)

with $\mathrm{f}(t, \nu)$ as the Student *t* distribution function. We find the $t_p(\nu)$ value in table (see ref[1] & ref[2]).

For example if we choose a confidence interval of 95%, p=0,95 and for $\nu_{eff} = 45$, $t_p(\nu) = 2.0141$ that corresponds to the wide uncertainty of T_X : $T_X \pm 2.0141\, u_{Tx}$ (see Table IV Appendix I of [ref.1]). For a confidence interval of 68,27%, p=0,6827 and for the same $\nu_{eff} = 45$, $t_p(\nu) = 1.0113$ that corresponds to the wide uncertainty of T_X : $T_X \pm 1.0113\, u_{Tx}$ (see Table G.2 Appendix G of [ref.2]). This is resumed by

p = 68,27 % è $T_X \pm 1.0113\, u_{Tx}$
p = 95 % è $T_X \pm 2.0141\, u_{Tx}$

All tables of Annex 6 are filled with computation given above for uncertainties and degree of freedom..

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Hewlett Packard 5370 B
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	/

2. Measuring method

	Double Weight
Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in °C	22,0 ± 0,2 °C
Ambient humidity in the room in %	25 ± 5 %

Participating laboratory: SYRTE - Observatoire de Paris

Date: 7th June 2005

Signature

Annex 5: Measurement results for travelling standard no: BEV01

Measurand: time interval $\boldsymbol{T}_\mathrm{X}(i)$ for measuring cable lengths:

cable length	$<\boldsymbol{T}_\mathrm{X}>$	combined standard uncertainty $\boldsymbol{u}_{\boldsymbol{T}\mathbf{x}}$	eff. degree of freedom n_eff
4 m	20,473E-9	51,457E-12	278
10 m	48,666E-9	51,981E-12	289
35 m	175,624E-9	52,316E-12	296

The average of T_X is calculated by the weighted mean over the six measurement series (see Annex 6):

$$\langle T_X \rangle = \frac{\sum_{i=1}^{6} \frac{\langle T_X(i) \rangle}{u^2_{T_X(i)}}}{\sum_{i=1}^{6} \frac{1}{u^2_{T_X(i)}}} \tag{17}$$

The uncertainty is calculated over the six measurement series by the expression:

$$u_{T_X} = \sqrt{\frac{1}{\sum_{i=1}^{6} \frac{1}{u^2_{T_X(i)}}}} \tag{18}$$

The degree of freedom is calculated by the Welch-Satterthwaite formula over the six measurement series:

$$\nu_{eff} = \frac{\left(\sum_{i=1}^{6} u^2_{T_X(i)} \right)^2}{\frac{u^4_{T_X(1)}}{\nu_{eff_{T_X(1)}}} + \frac{u^4_{T_X(2)}}{\nu_{eff_{T_X(2)}}} + \frac{u^4_{T_X(3)}}{\nu_{eff_{T_X(3)}}} + \frac{u^4_{T_X(4)}}{\nu_{eff_{T_X(4)}}} + \frac{u^4_{T_X(5)}}{\nu_{eff_{T_X(5)}}} + \frac{u^4_{T_X(6)}}{\nu_{eff_{T_X(6)}}}} \tag{19}$$

Annex 6: Uncertainty budget for T_X

Measuring cable length: 4 m travelling standard: BEV01

MES_1

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,922E-9	60,536E-12	A	0,5	30,268E-12	99
X_2	-51,252E-9	57,271E-12	A	0,5	28,635E-12	99
X_3	31,685E-9	46,286E-12	A	0,5	23,143E-12	99
X_4	52,188E-9	58,644E-12	A	0,5	29,322E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	20,517E-9	123,110E-12				42,3

MES_2

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,926E-9	81,254E-12	A	0,5	40,627E-12	99
X_2	-51,276E-9	64,026E-12	A	0,5	32,013E-12	99
X_3	31,690E-9	47,438E-12	A	0,5	23,719E-12	99
X_4	52,059E-9	64,534E-12	A	0,5	32,267E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	20,459E-9	127,686E-12				48,7

Annex 6: Uncertainty budget for T_X

Measuring cable length: 4 m travelling standard: BEV01

MES_3

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,904E-9	63,710E-12	A	0,5	31,855E-12	99
X_2	-51,238E-9	67,499E-12	A	0,5	33,750E-12	99
X_3	31,695E-9	51,747E-12	A	0,5	25,874E-12	99
X_4	52,066E-9	66,032E-12	A	0,5	33,016E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	20,452E-9	126,245E-12				46,6

MES_4

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,920E-9	67,784E-12	A	0,5	33,892E-12	99
X_2	-51,252E-9	58,760E-12	A	0,5	29,380E-12	99
X_3	31,758E-9	48,816E-12	A	0,5	24,408E-12	99
X_4	52,153E-9	67,201E-12	A	0,5	33,600E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	20,464E-9	125,543E-12				45,6

Annex 6: Uncertainty budget for T_X

Measuring cable length: 4 m travelling standard: BEV01

MES_5

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,950E-9	68,141E-12	A	0,5	34,070E-12	99
X_2	-51,323E-9	78,900E-12	A	0,5	39,450E-12	99
X_3	31,825E-9	48,690E-12	A	0,5	24,345E-12	99
X_4	52,218E-9	63,890E-12	A	0,5	31,945E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	20,483E-9	127,886E-12				49,0

MES_6

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,962E-9	71,971E-12	A	0,5	35,985E-12	99
X_2	-51,311E-9	64,727E-12	A	0,5	32,363E-12	99
X_3	31,806E-9	42,859E-12	A	0,5	21,429E-12	99
X_4	52,178E-9	64,522E-12	A	0,5	32,261E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	20,461E-9	125,964E-12				46,2

Annex 6: Uncertainty budget for T_X

Measuring cable length: 10 m travelling standard: BEV01

MES_1

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,918E-9	67,921E-12	A	0,5	33,961E-12	99
X_2	-79,428E-9	90,509E-12	A	0,5	45,255E-12	99
X_3	31,686E-9	43,974E-12	A	0,5	21,987E-12	99
X_4	80,336E-9	61,200E-12	A	0,5	30,600E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	48,680E-9	129,018E-12				50,6

MES_2

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,942E-9	67,362E-12	A	0,5	33,681E-12	99
X_2	-79,502E-9	81,951E-12	A	0,5	40,975E-12	99
X_3	31,737E-9	45,310E-12	A	0,5	22,655E-12	99
X_4	80,328E-9	57,579E-12	A	0,5	28,790E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	48,676E-9	127,201E-12				48,0

Annex 6: Uncertainty budget for T_X

Measuring cable length: 10 m travelling standard: BEV01

MES_3

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,953E-9	66,465E-12	A	0,5	33,232E-12	99
X_2	-79,507E-9	78,133E-12	A	0,5	39,066E-12	99
X_3	31,842E-9	40,785E-12	A	0,5	20,392E-12	99
X_4	80,344E-9	68,198E-12	A	0,5	34,099E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	48,628E-9	127,412E-12				48,3

MES_4

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,947E-9	71,008E-12	A	0,5	35,504E-12	99
X_2	-79,475E-9	67,561E-12	A	0,5	33,781E-12	99
X_3	31,802E-9	44,173E-12	A	0,5	22,086E-12	99
X_4	80,321E-9	59,646E-12	A	0,5	29,823E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	48,623E-9	125,712E-12				45,9

Annex 6: Uncertainty budget for T_X

Measuring cable length: 10 m travelling standard: BEV01

MES_5

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,925E-9	71,781E-12	A	0,5	35,890E-12	99
X_2	-79,545E-9	76,942E-12	A	0,5	38,471E-12	99
X_3	31,767E-9	62,181E-12	A	0,5	31,090E-12	99
X_4	80,299E-9	56,032E-12	A	0,5	28,016E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	48,676E-9	128,624E-12				50,1

MES_6

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,925E-9	68,468E-12	A	0,5	34,234E-12	99
X_2	-79,505E-9	73,997E-12	A	0,5	36,999E-12	99
X_3	31,711E-9	45,422E-12	A	0,5	22,711E-12	99
X_4	80,351E-9	57,266E-12	A	0,5	28,633E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	48,710E-9	126,099E-12				46,4

Annex 6: Uncertainty budget for T_X

Measuring cable length: 35 m travelling standard: BEV01

MES_1

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,907E-9	66,220E-12	A	0,5	33,110E-12	99
X_2	-206,328E-9	95,449E-12	A	0,5	47,724E-12	99
X_3	31,770E-9	48,179E-12	A	0,5	24,089E-12	99
X_4	207,349E-9	52,248E-12	A	0,5	26,124E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	175,600E-9	129,078E-12				50,7

MES_2

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,924E-9	62,963E-12	A	0,5	31,481E-12	99
X_2	-206,342E-9	84,892E-12	A	0,5	42,446E-12	99
X_3	31,773E-9	48,609E-12	A	0,5	24,305E-12	99
X_4	207,286E-9	59,118E-12	A	0,5	29,559E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	175,566E-9	127,600E-12				48,5

Annex 6: Uncertainty budget for T_X

Measuring cable length: 35 m travelling standard: BEV01

MES_3

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,960E-9	64,901E-12	A	0,5	32,450E-12	99
X_2	-206,444E-9	76,381E-12	A	0,5	38,191E-12	99
X_3	31,786E-9	42,936E-12	A	0,5	21,468E-12	99
X_4	207,404E-9	59,954E-12	A	0,5	29,977E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	175,651E-9	126,078E-12				46,4

MES_4

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,913E-9	71,000E-12	A	0,5	35,500E-12	99
X_2	-206,345E-9	88,413E-12	A	0,5	44,207E-12	99
X_3	31,678E-9	44,247E-12	A	0,5	22,124E-12	99
X_4	207,289E-9	64,440E-12	A	0,5	32,220E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	175,622E-9	129,486E-12				51,4

Annex 6: Uncertainty budget for T_X

Measuring cable length: 35 m travelling standard: BEV01

MES_5

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,880E-9	70,043E-12	A	0,5	35,021E-12	99
X_2	-206,324E-9	94,263E-12	A	0,5	47,132E-12	99
X_3	31,766E-9	44,907E-12	A	0,5	22,454E-12	99
X_4	207,388E-9	65,223E-12	A	0,5	32,611E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	175,633E-9	130,538E-12				52,9

MES_6

Quantity X_i	Estimate x_i [s]	Standard uncertainty $u(X_i)$ [s]	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(T_x)$	Degree of freedom ν_i
X_1	-30,924E-9	70,856E-12	A	0,5	35,428E-12	99
X_2	-206,430E-9	73,854E-12	A	0,5	36,927E-12	99
X_3	31,799E-9	44,659E-12	A	0,5	22,330E-12	99
X_4	207,430E-9	56,888E-12	A	0,5	28,444E-12	99
X_{corr}	100,000E-12	29,000E-12	B	1	29,000E-12	∞
∂_C	0	6,700E-12	B	2	13,400E-12	8
∂_d	0	1,000E-12	B	2	2,000E-12	8
∂_j	0	35,000E-12	B	2	70,000E-12	8
∂_l	0	25,000E-12	B	2	50,000E-12	8
∂_{es}	0	30,000E-12	B	2	60,000E-12	8
T_x	175,668E-9	126,297E-12				46,7

References

[ref. 1] : C.F. DIETRICH Uncertainty, Calibration and Probability (Adam Hilger Second edition 1991

[ref. 2] : Guide pour l’incertitude des mesures (GUM) édition 1995.

Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organiosation group.

Description of the measurement method(s) and relevant instruments:

Relevant instruments used:

1. HP33250A Signal generator with external 10MHz reference
2. Fluke 6681R Counter with external 10MHz reference
3. 10MHz reference signals from HP5071A Cesium clocks steered to UTC
4. Connecting cables A, B of approximately 3 ns delay.

Measuring procedure:
The time delay of the traveling standard was measured with the insertion method. As shown in the following figure, first the time delay of the connecting cables was measured (Fig. 1) and then the time delay with the traveling standard inserted was measured (Fig. 2). This dual measurement was repeated 6 times.

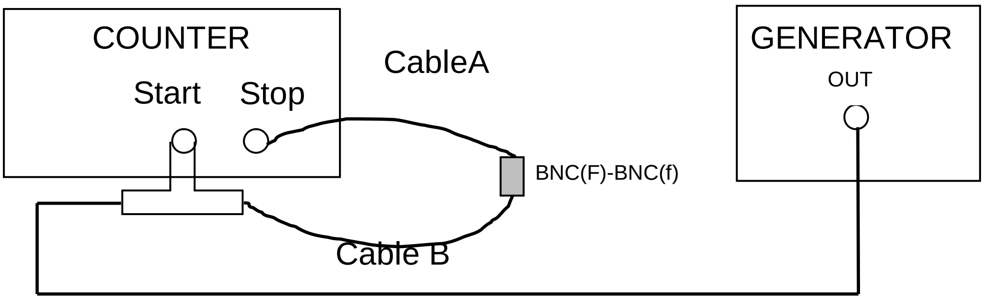

Fig. 1

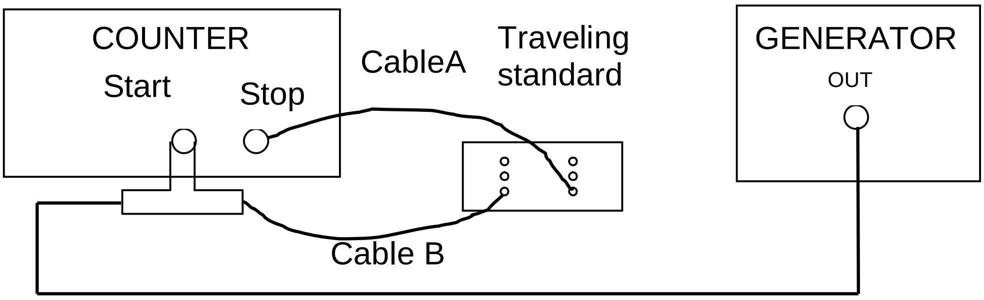

Fig. 2

The Time delay of cable *i* is given by:

$T_i = T_2 - T_1 + T_c$, where

T_1: The time delay of the first setup (Fig. 1),

T_2: The time delay of the second setup (Fig. 1) and

T_c: The time delay set by the BNC(F)-BNC(F) connector

The average value is given by

$$T_x(i) = \frac{\sum_{j=1}^{6} T_j}{6}$$, where

T_j is given above and the combined standard uncertainty is given by

$$u(T_x) = \sqrt{\sum c_i{}^2 u^2(x_i)}$$, where

$u^2(x_i)$: the standard uncertainties of the following terms:

-Quantization error and noise trigger error of the counter

-Trigger level timing error of the counter

-Channel mismatch error of the counter

-Time base error

The number of total effective degrees of freedom is calculated from

$$v_{eff} = \frac{u^4(T_x)}{\sum_{i=1}^{n} \frac{u_i^4(T_x)}{v_i}}.$$

Participating laboratory: Hellenic Institute of Metrology (EIM)

Date: 22/4/2005

Signature

Myrto Holiastou

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Fluke PM6681R
Is the TIC independent of other national measurement laboratory (NML) ?	YES
If **not** independent, please give the name of NML	
Date of last measurement in the NML	2/2/2005

2. Measuring method

Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in ^{o}C	24^{o}C ± 0.5^{o}C
Ambient humidity in the room in %	34% ± 5%

Participating laboratory: Hellenic Institute of Metrology (EIM)

Date: 22/4/2005

Signature

Myrto Holiastou.

Annex 5: **Measurement results for traveling standard no: BEV01**

Measurand: time interval $\boldsymbol{T}_\mathbf{X}(i)$ for measuring cable lengths:
All figures are in ns.

cable length	$\boldsymbol{T}_\mathbf{X}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_\mathbf{X})$	eff. degree of freedom n_{eff}
3 m	20.200	0.100	10249
10 m	48.407	0.100	10249
35 m	174.908	0.100	10249

Appendix A.SMD

EUROMET

Supplementary comparison TF.TI-K1

Comparison of time interval (cable delay) measurements

Report of SMD (Belgium)

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Directorate General Quality and Safety
Metrology Division - Calibration Service
BE 1000 BRUSSELS Belgium
Phone : +32 2 206 46 87 (J. NICOLAS)
Phone : +32 2 206 46 86 (H. VERBEECK)
Fax: +32 2 206 57 45

Executed by: J. NICOLAS
H. VERBEECK

1. Introduction:

The need for a comparison of time interval was discussed during the EUROMET Expert Meeting on Time and Frequency held at the Metrology Institute of the Republic of Slovenia (MIRS) in Ljubljana on 3-4 April 2003.

2. Measuring conditions :

All the measurements have been carried out in a room located under the ground level at a temperature of (23 ± 1) °C, at a relative humidity of (45 ± 10) % and at an atmospheric pressure of (1013,25 ± 20) hPa. All the measuring instruments were connected to an uninterruptible power supply at 50 Hz with a nominal voltage of 230 x (1 ± 0,01) V and a total harmonic distortion < 1,5 %.

3. Measuring Equipment :

The main frequency standards of SMD are the following:

- 3(three) Caesium Frequency Standard – Agilent - 5071A + opt. 001.
- 1 (one) Caesium Frequency Standard – Hewlett-Packard 5071A + opt. 001.
- 1(one) Caesium Frequency Standard – Hewlett-Packard – 5061B/5071A.
- 1(one) Ultra-Clean Phase-locked Oscillator – Timing Solutions Inc. - TSC 4145B.
- 1(one) Frequency Comparator – TimeTech GmbH –
- 1(one) GPS receiver – GPS 2K – K + K.
- 1(one) GPS receiver – TTS-2 – EMDE Electronics.
- 1(one) GPS receiver – TTR6 – AOA.

For this comparison, the following equipment was used:

- 2(two) Universal Counter – Hewlett-Packard – 53 132A with opt. 03 up 12,4 GHz
- 2(two) Time interval Counter – Stanford Research Scientific – SR620 – up 1,3 GHz
- 1(one) Time interval Counter – Pendulum – CNT90 – upgraded up to 20 GHz.
- 1(one) Digital Sampling oscilloscope – Agilent – model 54 852A - bandwidth : 2 GHz – sampling rate up to 10 GHz/s.
- 1(one) Rubidium frequency standard – XL Microwave
- 2(two) line delays - Huber + Suhner - 4,8 ns/23,7 ns/94 ns and 19,0 ns/47,3 ns/165,1 ns.

4. Measurement method :

The frequency output of the caesium frequency standard – 5071A – opt. 001 is connected to an ultra-clean phase-locked oscillator with an Allan deviation lower than 2 x 10^{-13} between 1 Hz and 100 Hz. One of the 10 MHz outputs of this ultra-clean oscillator is connected to the external reference input of the time interval counter (TIC). The 1 pps pulse was supplied by a rubidium frequency standard of which the rise time and the amplitudes at the inputs A and B were previously measured by means of a digital sampling oscilloscope for each cable length.

The delay is given by the following relation :

$$Tx = T2 - T1 + \delta T \qquad (1)$$

- T2 is the displayed value in phase 2 (with the device under test inserted)
- T1 is the displayed value in phase 1 (with the short inserted)
- δT is the estimated delay due to the BNC female short.

The trigger levels were adjusted at about 50 % at the inputs A and B.

4.a. Measurement of T2

The 1 pps output of rubidium frequency standard is applied simultaneously to the input of the device under test (DUT) and to the input A of the TIC . The output of the DUT is connected to the input B of the TIC. One measurement consists of 100 times the measurements of the time intervals between pulses successively received by the inputs A and B of the TIC.

4.b. Measurement of T1

The cables are unchanged and a BNC female short replaces the DUT.

5. Measurement uncertainties

The relation (1) could be extended in order to take into account the different uncertainties, which could result from the used measurement method:

$$T_x = (T2 \times (1 + dTBt2) + dRT2 + dTstT2 + dTspT2 + dTrT2) - (T1 \times (1 + dTBt1) + dRT1 + dTstT1 + dTspT1 + dTrT1) + dTsh + dmet$$

where :

- **T2** = Mean value of the different measurement values displayed by the TIC when the DUT is inserted in the circuit. That is the time interval between the pulse entering the DUT and the pulse coming out of the cable when the DUT is inserted.
- d**TB**t**2** = Fractional time base uncertainty for T2.
- d**RT2** = Resolution of the TIC – measurement of T2.
- d**TstT2** = Start trigger timing uncertainty for T2.
- d**TspT2** = Stop trigger timing uncertainty for T2.
- d**TrT2** = Trigger level timing uncertainty for T2.
- **T1** = Mean value of the different measurement value displayed by the TIC when the DUT is replaced by a BNC female short.
- d**TB**t**1** = Fractional time base uncertainty for T1.
- d**RT1** = Resolution of the TIC – measurement of T1.
- d**TstT1** = Start trigger timing uncertainty for T1.
- d**TspT1** = Stop trigger timing uncertainty for T1.
- d**TrT1** = Trigger level timing uncertainty for T1.
- d**Tsh** = Time interval delay due to the BNC female short.
- d**met** = Uncompensated uncertainty due to the used method (e.g.: interpolating method, reversing the channels A and B,…).

6. Measurement results and uncertainty budgets.

Measurements where performed with different measuring instruments [1], [2]. These repeated measurements was for us also the way to validate some measurements. At the end, we have decided for many practical and technical reasons to only communicate the measurement results obtained by means of the CNT-90 manufactured by Pendulum despite its lower single shot resolution [3]. Differences were registered when reversing channels A and B with this TIC but these differences were found non significant with respect the calculated combined uncertainties for the three cable lengths. The uncertainties indicated in the tables below are given for k=1.

6.a. 3 m length cable

Quantity	**Value**	**Standard Uncertainty**	**Degrees of Freedom**	**Distribution**	**Sensitivity Coefficient**	**Corr.-Coeff.**	**Index**
T2	24.24500 ns	$3.21\cdot10^{-3}$ ns	4	normal	1.0	0.02	0.0 %
δTBτ2	0.0 ns	$57.7\cdot10^{-6}$ ns	∞	rectangular	24	0.01	0.0 %
δRT2	0.0 ns	0.0577 ns	∞	rectangular	1.0	0.27	7.4 %
δTstT2	0.0 ns	0.0272 ns	∞	rectangular	1.0	0.13	1.6 %
δTspT2	0.0 ns	0.0502 ns	∞	rectangular	1.0	0.24	5.6 %
δTrT2	0.0 ns	0.0507 ns	∞	rectangular	1.0	0.24	5.7 %
T1	3.92960 ns	$1.63\cdot10^{-3}$ ns	4	normal	-1.0	-0.01	0.0 %
δTBτ1	0.0 ns	$5.77\cdot10^{-3}$ ns	∞	rectangular	-3.9	-0.11	1.1 %
δRT1	0.0 ns	0.0577 ns	∞	rectangular	-1.0	-0.27	7.4 %
δTstT1	0.0 ns	0.0292 ns	∞	rectangular	-1.0	-0.14	1.9 %
δTspT1	0.0 ns	0.0213 ns	∞	rectangular	-1.0	-0.10	1.0 %
δTrT1	0.0 ns	0.0121 ns	∞	rectangular	-1.0	-0.06	0.3 %
δTsh	0.1050 ns	0.0289 ns	∞	rectangular	1.0	0.14	1.8 %
δTmet	0.0 ns	0.173 ns	∞	rectangular	1.0	0.81	66.2 %
Tx	**20.420 ns**	**0.213 ns**	**¥**				

6.b. 10 m length cable

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Corr.-Coeff.	Index
T2	52.35520 ns	$2.89\cdot10^{-3}$ ns	4	normal	1.0	0.01	0.0 %
δTBτ2	0.0 ns	$577\cdot10^{-6}$ ns	∞	rectangular	52	0.10	0.9 %
δRT2	0.0 ns	0.0577 ns	∞	rectangular	1.0	0.18	3.4 %
δTstT2	0.0 ns	0.0275 ns	∞	rectangular	1.0	0.09	0.8 %
δTspT2	0.0 ns	0.0462 ns	∞	rectangular	1.0	0.15	2.2 %
δTrT2	0.0 ns	0.0368 ns	∞	rectangular	1.0	0.12	1.4 %
T1	3.92840 ns	$2.01\cdot10^{-3}$ ns	4	normal	-1.0	-0.01	0.0 %
δTBτ1	0.0 ns	$5.77\cdot10^{-3}$ ns	∞	rectangular	-3.9	-0.07	0.5 %
δRT1	0.0 ns	0.0577 ns	∞	rectangular	-1.0	-0.18	3.4 %
δTstT1	0.0 ns	0.0292 ns	∞	rectangular	-1.0	-0.09	0.9 %
δTspT1	0.0 ns	0.0213 ns	∞	rectangular	-1.0	-0.07	0.5 %
δTrT1	0.0 ns	0.0121 ns	∞	rectangular	-1.0	-0.04	0.2 %
δTsh	0.1050 ns	0.0289 ns	∞	rectangular	1.0	0.09	0.9 %
δTmet	0.0 ns	0.289 ns	∞	rectangular	1.0	0.92	85.1 %
Tx	**48.532 ns**	**0.313 ns**	**¥**				

6.c. 35 m length cable

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Corr.-Coeff.	Index
T2	178.7388 ns	0.0283 ns	7	normal	1.0	0.06	0.3 %
δTBτ2	0.0 ns	$289\cdot10^{-6}$ ns	∞	rectangular	180	0.11	1.1 %
δRT2	0.0 ns	0.0577 ns	∞	rectangular	1.0	0.12	1.4 %
δTstT2	0.0 ns	0.0272 ns	∞	rectangular	1.0	0.06	0.3 %
δTspT2	0.0 ns	0.0502 ns	∞	rectangular	1.0	0.10	1.1 %
δTrT2	0.0 ns	0.0507 ns	∞	rectangular	1.0	0.11	1.1 %
T1	3.93063 ns	$5.65\cdot10^{-3}$ ns	7	normal	-1.0	-0.01	0.0 %
δTBτ1	0.0 ns	$5.77\cdot10^{-3}$ ns	∞	rectangular	-3.9	-0.05	0.2 %
δRT1	0.0 ns	0.0577 ns	∞	rectangular	-1.0	-0.12	1.4 %
δTstT1	0.0 ns	0.0292 ns	∞	rectangular	-1.0	-0.06	0.4 %
δTspT1	0.0 ns	0.0213 ns	∞	rectangular	-1.0	-0.04	0.2 %
δTrT1	0.0 ns	0.0121 ns	∞	rectangular	-1.0	-0.03	0.0 %
δTsh	0.1050 ns	0.0289 ns	∞	rectangular	1.0	0.06	0.4 %
δTmet	0.0 ns	0.462 ns	∞	rectangular	1.0	0.96	91.9 %
Tx	**174.913 ns**	**0.482 ns**	**¥**				

7. Conclusions

This comparison was useful due the fact that it provides us a deeper knowledge about time interval measurements, due to the variety of methods and set-ups used. That was a good occasion for us to have a better look on the technical literature in this field. We also better know the limits of some measuring instruments and what are the points we can still improve.

8. Bibliography

[1] J. Kalisz : *Review of methods for time interval measurements with picosecond resolution, Metrologia*, vol. 41, 2004, pp. 1-16.
[2] S. Y. Yurish, F. Reverter and R. Pallàs-Areny : *Measurement error analysis and uncertainty reduction for period- and time-interval-to-digital converter based on microcontrollers*, Meas. Sci; Technol., 16 (2005), pp. 1660-1666.
[3] CNT-90 – Technical manual.

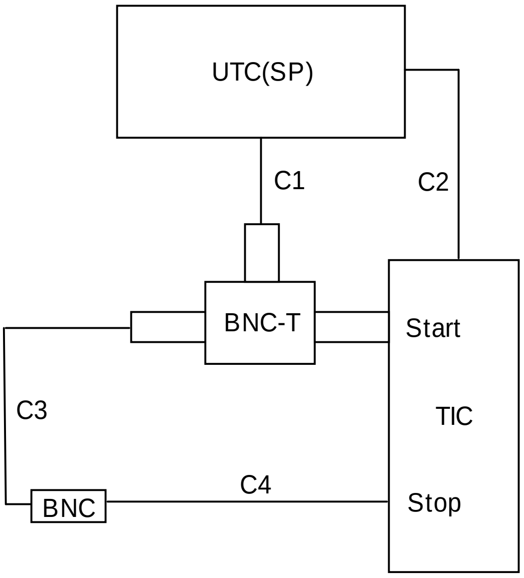
* * *

Annex 3: Measurement report A

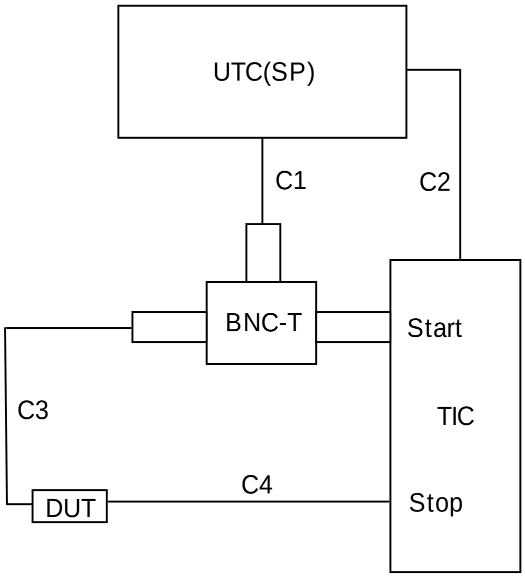
In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organiosation group.

Description of the measurement method(s) and relevant instruments:
The delay, T1, in the connecting cables C3 and C4 and the BNC and BNC-T was first measured as shown in the “SETUP”. The BNC was then replaced with the DUT, and the delay, T2, was measured again as shown in “DUT”. The final result was taken as T2-T1-DTBNC. The delay in the BNC, DBNC, was estimated by measurements to 100 ps.

SETUP



DUT



C1 1-pps (5V TTL 50 Ohm) to BNC-T
C2 10 MHz (1 V rms) to counter

The 1-pps was 3 V at Start and Stop. 1 V trigger level was chosen on the TIC, DC-coupling and 50 Ohm input impedance.

Participating laboratory: SP

Date: May 20, 2005

Signature:
Kenneth Jaldehag

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Fluke/Philips PM6681
Is the TIC independent of other national measurement laboratory (NML) ?	YES
If **not** independent, please give the name of NML	
Date of last measurement in the NML	

2. Measuring method

	Time delay using pulses
Number of repeated measurements:	6 (100 measurements in each)

3. Measurement condition

Ambient temperature in the room in ^{o}C	23 ± 1 degrees Celcius
Ambient humidity in the room in %	20 ± 5 %

Participating laboratory: SP

Date: May 20, 2005

Signature:

Kenneth Jaldehag

Annex 5: **Measurement results for traveling standard no: BEV01**

Measurand: time interval $\boldsymbol{T}_\mathbf{X}(i)$ for measuring cable lengths:
All figures are in µs.

cable length	$\boldsymbol{T}_\mathbf{X}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_\mathbf{X})$	eff. degree of freedom n_{eff}
3 m	*20.4 ns*	*0.5 ns (1-sigma)*	*102*
10 m	*48.5 ns*	*0.5 ns (1-sigma)*	*102*
35 m	*174.9 ns*	*0.5 ns (1-sigma)*	*102*

Participating laboratory: SP

Date: May 20, 2005

Signature:
Kenneth Jaldehag

Appendix A.GUM

EUROMET supplementary comparison TF.TI-K1 –measurement report A

Measurement report A

Description of the measurement method and <u>relevant</u> instruments:
In measurement of cable delays in GUM (Central Office of Measures - Poland) a method of three time interval measurements was applied according to Fig.1. All measurements were performed in air-conditioned room (stabilized temperature and humidity) and after the initial period for stabilizing temperature of DUT after transport.

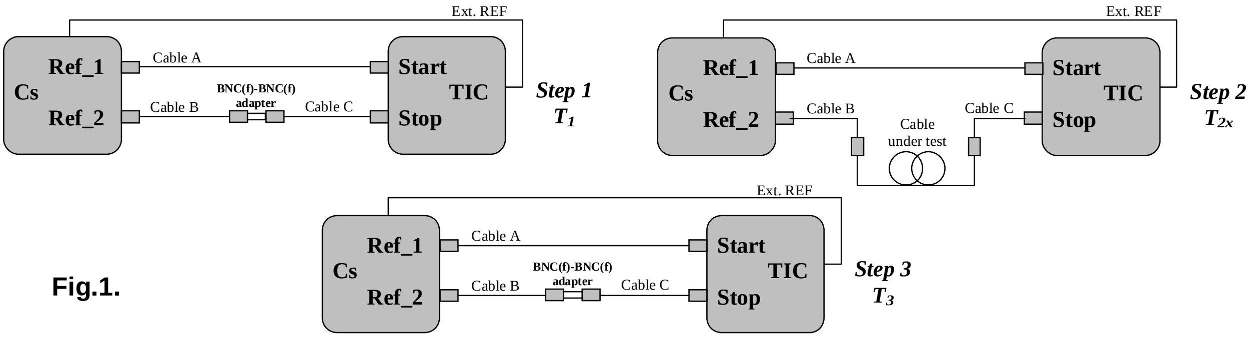


Fig.1.

As a source of reference pulse signals (Ref_1 and Ref_2) was used cesium time and frequency standard HP5071A with offset frequency < $1\cdot10^{-13}$, taking part in determination of TAI and UTC, namely 1pps outputs of HP5071A were Ref_1 and Ref_2. As a time interval counter was used digital time/frequency counter CNT-81 synchronized by a standard signal from the same cesium clock.
The delays of the cables under test were calculated using the following formula:

$$T_x = T_{2x} - \frac{T_1 + T_3}{2} + t_{AD} + d_{TB} + d_{\mathrm{Re}s} + d_{Rnd(TIC)} + d_{TLTError}\ ,$$

where: T_x - the delay of cable under test,

T_1, T_{2x}, T_3 - the results of consecutive measurements respectively as in Fig. 1.,

t_{AD} - the delay of the BNC(f)-BNC(f) adapter determined experimentally,

d_{TB} - correction due to short term stability of time base frequency,

$d_{\mathrm{Re}s}$ - correction due to finite resolution of TIC,

$d_{Rnd(TIC)}$ - correction due to total random uncertainty of TIC (including quantization error, start trigger error and stop trigger error),

$d_{TLTError}$ - correction due to slow changes in values of trigger level timing error (a part of trigger level timing error non-compensated by applied method determined experimentally) including also jitter between Ref_1 and Ref_2 outputs.

Participating laboratory: **Central Office of Measures (GUM, Poland)**

Date: **25.04.-8.05.2005**

Signature:

Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	CNT 81/356, serial No. SM847754, of Pendulum Instruments AB company
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	

2. Measuring method

Simple inserting cable method	
Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in ^{o}C	(21,2 ± 0,6) ^{o}C
Ambient humidity in the room in %	(50 ± 10) %

Participating laboratory: **Central Office of Measures (GUM, Poland)**

Date: **25.04.-8.05.2005**

Signature:

Measurement results for traveling standard no: BEV01
Serial No. 01

Measurand: time interval $T_X(i)$ for measuring cable lengths:
All figures are in µs.

cable length	$T_X(i)$	combined standard uncertainty $u(T_X)$	eff. degree of freedom n_{eff}
3 m	0,0204021	0,0000038	195
10 m	0,0484737	0,0000039	140
35 m	0,1745988	0,0000041	83

Uncertainty budgets of measurement T_x (according to EA-4/02):
Note: bellow all figures are in ps

a) for cable length 3 m

Quantity X*i*		*Estimate* x*i*	*Standard uncertainty u(x*i*)*	Probability distribution / method of evaluation(A,B)	*Sensitivity coefficient* c*i*	*Uncertainty contribution u*i*(T*x*)*	Degree of freedom ν*i*
	T_{2x}		0,613	Normal/A	1	0,613	999
	T_1		0,582	Normal/A	$-1/2$	- 0,291	999
	T_3		0,586	Normal/A	$-1/2$	- 0,293	999
$T_{2x}-\frac{T_1+T_3}{2}$		20275,987	1,162	Normal/A	1	1,162	5
t_{AD}		126,130	1,672	Normal/B	-1	-1,672	107,53
d_{TB}		0	<0,0002	Normal/B	1	<0,0002	∞
d_{Res}		0	0,0004	Rectangular/B	1	0,0004	∞
$d_{Rnd(TIC)}$		0	1,937	Normal/B	1	1,937	∞
$d_{TLTError}$		0	2,411	Normal/B	1	2,411	56
T_x		20402,117	3,776				$n_{eff}=195{,}17$

b) for cable length 10 m

Quantity X_i	*Estimate* x_i	*Standard uncertainty* $u(x_i)$	Probability distribution / method of evaluation(A,B)	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$	*Degree of freedom* ν_i
T_{2x}		0,602	Normal/A	1	0,602	999
T_1		0,589	Normal/A	$-1/2$	- 0,295	999
T_3		0,611	Normal/A	$-1/2$	- 0,306	999
$T_{2x}-\frac{T_1+T_3}{2}$	48347,605	1,474	Normal/A	1	1,474	5
t_{AD}	126,130	1,672	Normal/B	-1	-1,672	107,53
d_{TB}	0	<0,0002	Normal/B	1	<0,0002	∞
d_{Res}	0	0,0004	Rectangular/B	1	0,0004	∞
$d_{Rnd(TIC)}$	0	1,937	Normal/B	1	1,937	∞
$d_{TLTError}$	0	2,411	Normal/B	1	2,411	56
T_x	48473,735	3,883				$n_{eff}=140{,}27$

c) for cable length 35 m

Quantity X_i	*Estimate* x_i	*Standard uncertainty* $u(x_i)$	Probability distribution / method of evaluation(A,B)	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$	*Degree of freedom* ν_i
T_{2x}		0,575	Normal/A	1	0,575	999
T_1		0,588	Normal/A	$-1/2$	- 0,294	999
T_3		0,588	Normal/A	$-1/2$	- 0,294	999
$T_{2x}-\frac{T_1+T_3}{2}$	174472,699	1,891	Normal/A	1	1,891	5
t_{AD}	126,130	1,672	Normal/B	-1	-1,672	107,53
d_{TB}	0	<0,0002	Normal/B	1	<0,0002	∞
d_{Res}	0	0,0004	Rectangular/B	1	0,0004	∞
$d_{Rnd(TIC)}$	0	1,937	Normal/B	1	1,937	∞
$d_{TLTError}$	0	2,411	Normal/B	1	2,411	56
T_x	174598,829	4,054				$n_{eff}=83{,}60$

Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organiosation group.

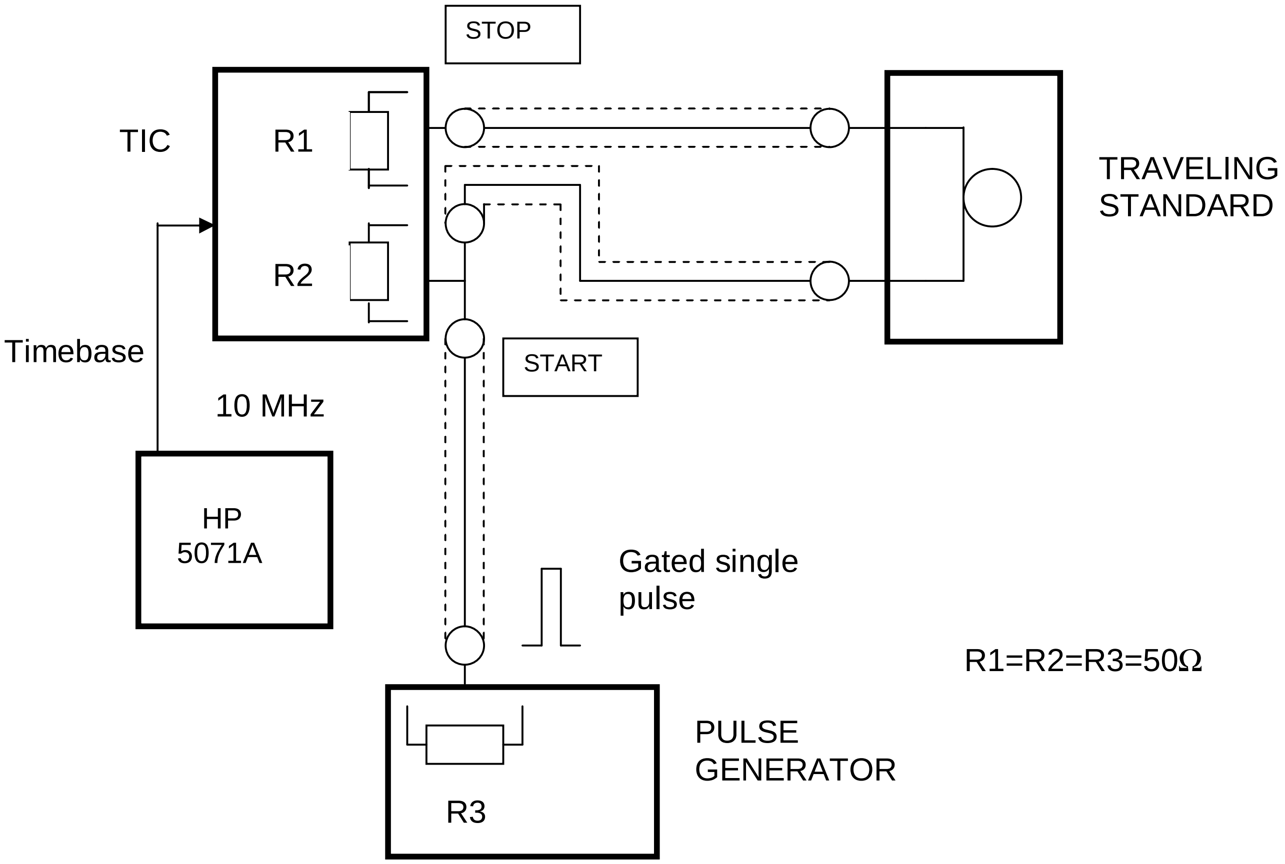
Description of the measurement method(s) and <u>relevant </u>instruments:

The rise edge of the pulse from impulse generator starts the time interval counter. This pulse through the connection cables and the traveling standards (cable#1or cable#2 or cable#3) stops the time measurement.

The features of the pulse: rise up time: 2,5 ns, level: +3V width: 50 ns.

The source impedance is 50 Ω and the gates of the TIC terminal are 50 Ω resistors. The pulses are manually initiated.

The time base of the TIC is our National Time and Frequency Standard (HP 5071A Cesium beam oscillator) 10 MHz.



Participating laboratory: Országos Mérésügyi Hivatal (OMH)
National Office of Measures-Hungary

Date: Budapest 06 June, 2005.06.06. Signature: Endre Szentirmai

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Agilent 53132A
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If not independent, please give the name of NML	
Date of last measurement in the NML	25 April, 2005

2. Measuring method

Number of repeated measurements:	80

3. Measurement condition

Ambient temperature in the room in oC	23 ± 1 °C
Ambient humidity in the room in %	20%-40%

Participating laboratory: Országos Mérésügyi Hivatal (OMH)
National Office of Measures-Hungary

Date: 06 June, 2005.06.06

Signature: Endre Szentirmai

Annex 5: **Measurement results for traveling standard no: BEV01**

Measurand: time interval $\boldsymbol{T}_{\mathrm{X}}(i)$ for measuring cable lengths:
All figures are in µs.

cable length	$\boldsymbol{T}_{\mathrm{X}}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_{\mathrm{X}})$	eff. degree of freedom n_{eff}
3 m	*0,02043*	*0,00035*	*79*
10 m	*0,04846*	*0,00034*	*79*
35 m	*0,17479*	*0,00036*	*79*

Participating laboratory: Országos Mérésügyi Hivatal (OMH)
National Office of Measures-Hungary
Date: Budapest 06 June, 2005.06.06.

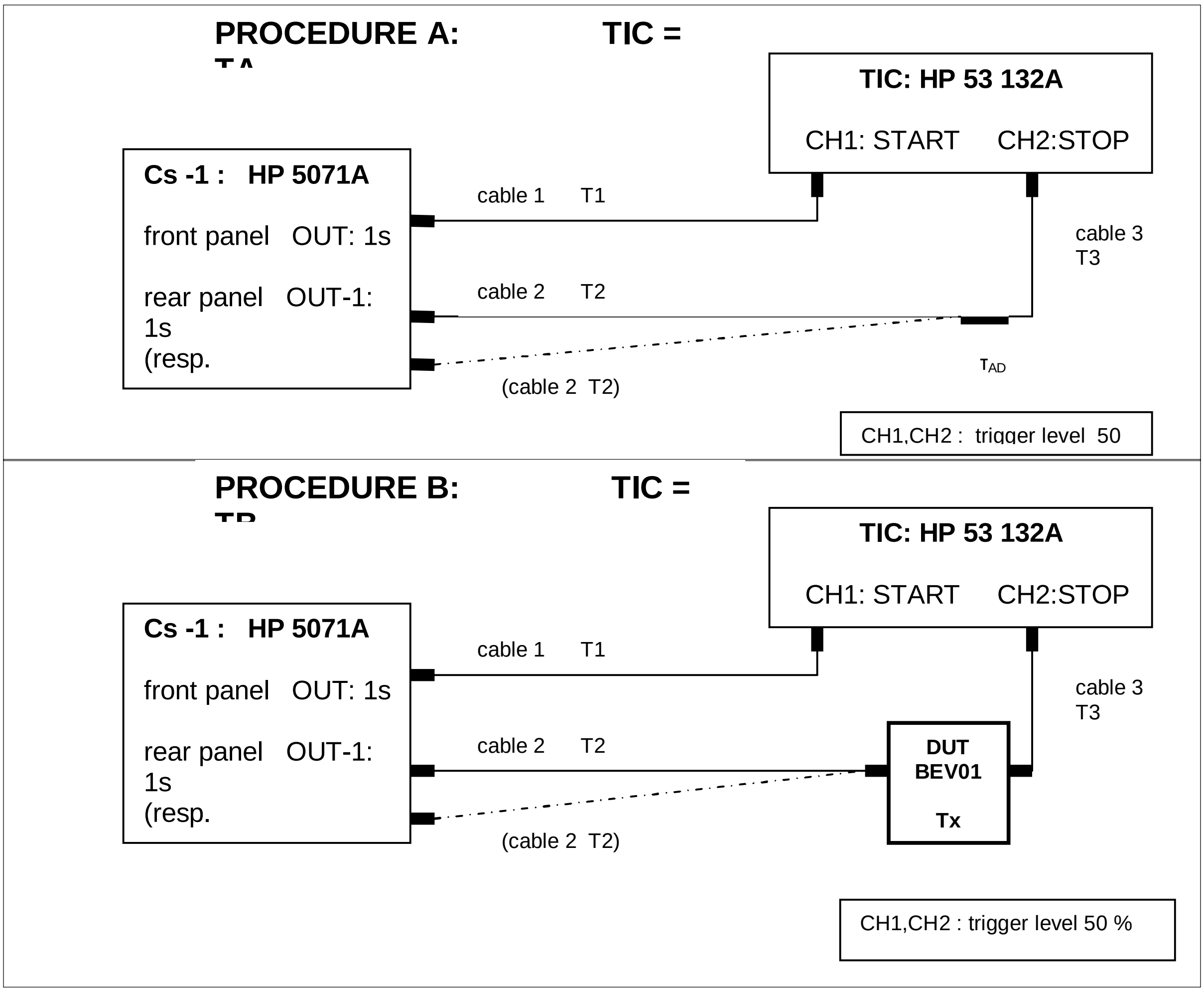
Signature: ....
Endre Szentirmai

Appendix A.SMU

ANNEX 3: MEASUREMENT REPORT A

Description of measurement method and relevant instrument:

- Every measurement consists of two steps.
- Signal TTL $U_{max} = 4$ V from *front* panel of Cs HP 5071A is connected by cable 1 (delay time T1) to START input (Chanel 1) of Time Interval Counter (TIC).
- Signal TTL 4 V from Cs *rear panel OUT-1* by cable 2 (delay T2) and via BNC(f) / BNC(f) Adaptor and cable 3 – delay T3 to STOP (Ch2) TIC.
- Procedure B is the same like A only instend BNC(f)/BNC(f) adaptor is connected DUT: BEV01 box.. Cable 2 (T2) and cable 3 (T3) was the same as in step 1.
- Procedure B was repeated with output signal of Cs I from OUT-2, too.
- Procedure A and with output rear panel OUT-1 and OUT-2 was repeated from Cs-2 HP 5071A (laboratory TF SMU has two Cs HP in operation).
- One result Tx consist of 6 measurements: $A_1B_1A_2B_2A_3B_3A_4B_4A_5B_5A_6B_6\,A_7$: 6x(ABA)



$TA = T2 + \tau_{AD} + T3 - T1 \qquad (TA = 0{,}5.\,(TA_{i+1} + TA_i))$ (1)

$TB = T2 + Tx + T3 - T1$ (2)

$\mathbf{Tx = TB - TA + \tau_{AD}}$ (3)

Participating laboratory: SMU Bratislava, Slovakia
Date: 20. 07. 2005 Signature: P. Doršic

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Hewlett Packard HP 53132A
Is the TIC independent of other national measurement laboratory (NML) ?	YES
If **not** independent, please give the name of NML	(SMU Bratislava T&F: the same laboratory)
Date of last measurement in the NML	direct connected 10MH from Cs standard ($Ext.f_{ref}$ TIC) wich is compared via GPS to BIPM Circul.T
Source of measuring pulses:	Cs I or Cs II , START front panel output 1 s, STOP rear OUT 1 or OUT 2 1s $U_{max.} = 4$ V, $U_{ref.} = 2$ V $t_{LH} = 3$ ns / 4V / 50 Ω

2. Measuring method

Simple insertion method (TA –TB –TA) *Two time reference signals from one common source – cesium standard HP 5071A* *REF1 – from front panel of Cs stand.* *REF2 – rear panel OUT1 or OUT2 (two results)* *and for 2 pc. of Cs standards (2x2 results)*	$Tx = TB – (0,5\ (TA_{i+1} + TA_i)) + \tau_{AD}$ (3)
Number of repeated measurements:	6 x 4

3. Measurement condition

Ambient temperature in the laboratory (°C)	22,3 to 22,7
Ambient humidity in the laboratory in (%)	45 – 55

Participating laboratory: SMU Bratislava, Slovakia / Doršic

Date: 20- 07. 2005

Signature P. Doršic

Annex 5: Measurement results for travelling standard no: BEV01

Measurand: time interval $T_X(i)$ for measuring cable lengths:
All figures are in ns.

cable length	T_X (ns)	**combined standard uncertainty** $u(T_X)$ **(ns)**	**eff. degree of freedom** n_{eff}
3 m	***20. 712***	***0.135***	***9596***
10 m	***48. 762***	***0.085***	***9346***
35 m	***175. 271***	***0.106***	***9428***

When $v_{eff} > 50$ *then* $k = 2$ *for evaluation of exp. uncertainty U, (95 % prob.)*

Participating laboratory: SMU Bratislava, Slovakia / Doršic

Date: 20- 07. 2005

Signature P. Doršic

Source of corrections and uncertainties for measurement results.

The model of equation to determine time delay interval T_x of each length of the cable is given by:

$\mathbf{T_x = (TB - TA) + \tau_{AD} + \delta T_j + \delta T_L}$

1. **(TB – TA)** correction and uncertainty of final result for two measuring TB and TA for various source of pulses: Cs I / Cs II and OUT 1s: Port 1 / Port 2 .

   $u_B = k_N . s / \sqrt{4}$, (k_N = 1,7 for N = 4)

2. $\boldsymbol{\tau_{AD}}$ correction and uncertainty of BNC(f) / BNC(f) adaptor

   τ_{AD} = **0,138 ns**, u_B = 1.s = **0,014 ns** n = 9
   (measured in SMU)

3. $\boldsymbol{\delta T_j}$ correction and uncertainty of source of outputs pulse-to-pulse jitter, external source and input amplifier jitter and noise (trigger jitter):

   Trigger error = $(E_{input}^2 + E_{signal}^2)^{1/2}$ / input signal slew rate

   (T_{jitter} = 1 ns … Cs out 1 s, manual Cs: HP 5071A) , n=100 ,
   $E_{signal} = E_{source\ Cs}$ = (1/0,75 V/ns) . 1 ns / $\sqrt{100}$ = 0,13 V SR= 0,75 ns/V)

   E_{input} = 1 mV from manual TIC: HP 530132A
   E_{signal} = 130 mV
   SR = 0,75 ns / V (input signal slew rate, Cs output 1s)
   t_{res} = 2 x 0,15 ns = 0,3 ns (manual TIC: HP 53 132A)

   Trigger error = $(0{,}001^2 + 0{,}13)^{½} / 1{,}3.10^9$ = **0,1 ns**

   $\boldsymbol{\delta T_j}$ = $(t_{res}^2$ + trigger error START^2 + trigger error STOP$^2)^{½}$ =

   = $(0{,}3^2 + 0{,}1^2 + 0{,}1^2)^{½}$ = **0,33 ns**

   Note: time interval deviation due to resolution of TIC is t_{res} and is into δT_j

4. $\boldsymbol{\delta T_L}$ correction and uncertainty due to trigger level timing error, this error results from a deviation of actual trigger level from specified (indicated) level = 2 V for both channel. (Manual IC: HP 53 132A)

   δT_L = 2 x (15 mV + 1 % START and STOP trigger level) / SR
   = 2 . (0,015 + 2/100) / 1,3 . 10^9 = 2 . 0,03 / 1,3.10^9 = **0,046 ns**

   (Slew rate = 1/(0,75 ns/V)

FINAL TABLE OF PARTIAL RESULTS

no.	date	T (°C)	R.H. (%)	CABLE #1		CABLE #2		CABLE #3		TIC: HP 53 132A	
				T_x (ns)	**1.s (ns) n=6**	**T_x (ns)**	**1.s (ns) n=6**	**T_x (ns)**	**1.s (ns) n=6**	**START** **Ch.1**	**STOP** **Ch.2**
1	13.6.05	22.3	54	20.835	0.008	48.676	0.016	175.292	0.021	CsII fr.	CsII P1
2	13.6.05	22.2	59	20.833	0.025	48.744	0.015	175.410	0.016	CsII fr.	CsII P2
3	14.6.05	22.6	62	20.558	0.040	48.850	0.009	175.193	0.012	CsI fr.	CsI P2
4	14.6.05	22.2	60	20.622	0.011	48.779	0.011	175.188	0.014	CsI fr.	CsI P1
										trigger level for both channel = 2 V (Umax=4V pulse, t_{LH} = 3 ns/4V)	
				20.712	0.143	**48.762**	0.073	**175.271**	0.105		
				u_A =	**0.121**	u_A =	**0.062**	u_A =	**0.089**		

$T_x = (TB - TA) + \tau_{AD}$ $u_A = 1.7 \times 1.s / \sqrt{4}$ 1.s for N=6

UNCERTAINTY BUDGET FOR T_x CABLE #1 (3 m)

Quantity X_i	*Estimate* x_i (ns)	*Standard uncertainty* $u(x_i)$ (ns)	*Probability distribution / method of evaluation(A,B)*	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$ (ns)	*Degree of freedom* ν_i
TB – TA	20.574	0.121	normal	1	0.121	3
τ_{AD}	0.138	0.014	normal	1	0.014	8
$d\mathrm{T}_\mathrm{J}$	*0*	0.033	normal	1	0.033	*oo*
$d\mathrm{T}_\mathrm{L}$	*0*	0.046	normal	1	0.046	*oo*
						oo
T_X	*20.712*				*0.135*	9596

UNCERTAINTY BUDGET FOR T_x CABLE #2 (10 m)

Quantity X_i	*Estimate* x_i (ns)	*Standard uncertainty* $u(x_i)$ (ns)	*Probability distribution / method of evaluation(A,B)*	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$ (ns)	*Degree of freedom* ν_i
TB – TA	48.624	0.062	normal	1	0.062	3
τ_{AD}	0.138	0.014	normal	1	0.014	8
$d\mathrm{T}_\mathrm{J}$	*0*	0.033	normal	1	0.033	*oo*
$d\mathrm{T}_\mathrm{L}$	*0*	0.046	normal	1	0.046	*oo*
						oo
T_X	*48.762*				*0.085*	135582

UNCERTAINTY BUDGET FOR T_x CABLE #3 (35 m)

Quantity X_i	*Estimate* x_i (ns)	*Standard uncertainty* $u(x_i)$ (ns)	*Probability distribution / method of evaluation(A,B)*	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$ (ns)	*Degree of freedom* ν_i
TB – TA	175.133	0.089	normal	1	0.089	3
τ_{AD}	0.138	0.014	normal	1	0.014	8
$d\mathrm{T}_\mathrm{J}$	*0*	0.033	normal	1	0.033	*oo*
$d\mathrm{T}_\mathrm{L}$	*0*	0.046	normal	1	0.046	*oo*
						oo
T_X	*175.271*				*0.106*	*32212*

Participating laboratory: SMU Bratislava, Slovakia / Doršic

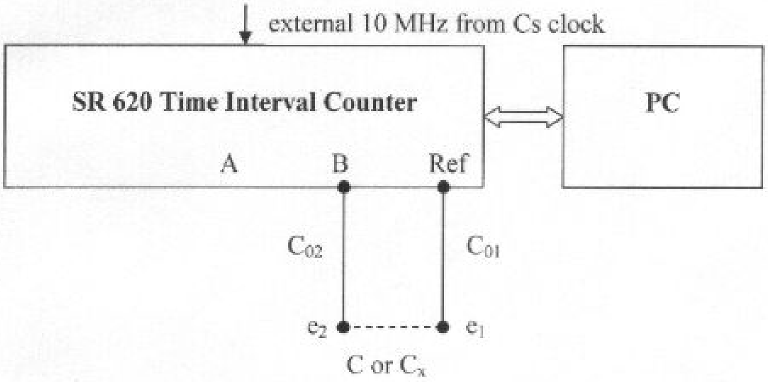
Date: 20- 07. 2005

Signature P. Doršic

Annex 3: Measurement report A

Description of the measurement method(s) and relevant instruments:

1. Definition of the measurand (cable time delay): *Time from the pulse entering the cable to time when the same instant of the pulse appears at the output of the cable* (in this Technical Protocol 2.3.1). In our measurement "the instant" is defined at 25% of the peak-to-peak voltage level where the cable responses have about the maximum slope.
2. Schematic of the measuring system

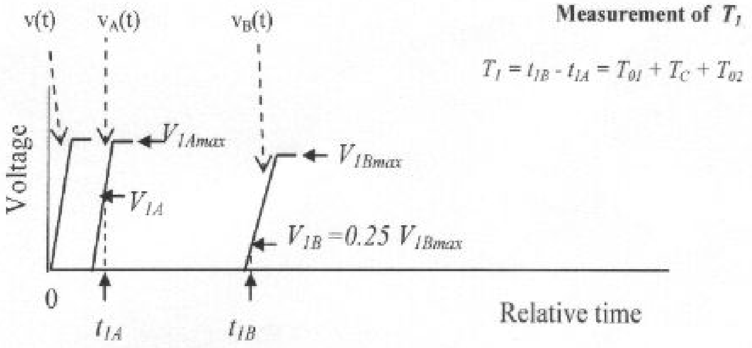


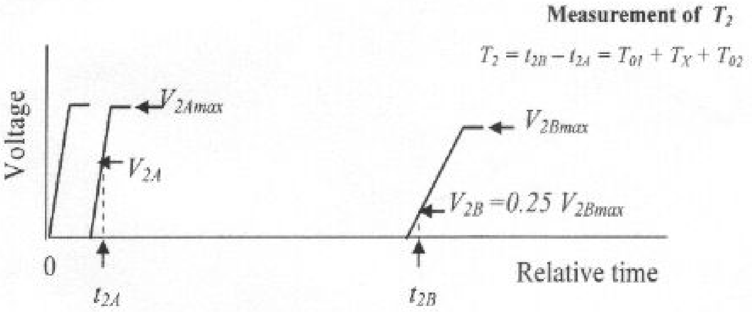
C_{01}, C_{02}	short auxiliary cables with delays T_{01}, T_{02}, respectively
C	female-to-female BNC coupler with known delay T_C
C_x	unknown cable with delay T_x

The measurement was carried out with the SR620 time interval counter serial number 4521. As a test signal, we used 1 kHz pulses from counter's REF output. The test pulse amplitude and shape were measured by a HP54615B oscilloscope with 500 MHz bandwidth (with 0.7 ns rise time). The counter start source was set to REF in which mode the test pulse is split in such a way that it goes internally directly to the counter gate logic bypassing the input A (thus the start trigger level is not known), and in parallel it is available at the REF output. The counter was connected to 10 MHz external time base from a high-performance HP5071A cesium clock. Before the measurement, the auto-calibration procedure was run. The counter was controlled by PC via GPIB. Input B (stop input) was set to 50 Ω, DC, and positive slope.

We have used a simple substitution method based on measurements of two time intervals: 1) of the time interval T_1 with the coupler C between points e_1 and e_2, and 2) of the time interval T_2 with the unknown cable C_x that substitutes the coupler.

Diagram of voltage to time relations during the measurement



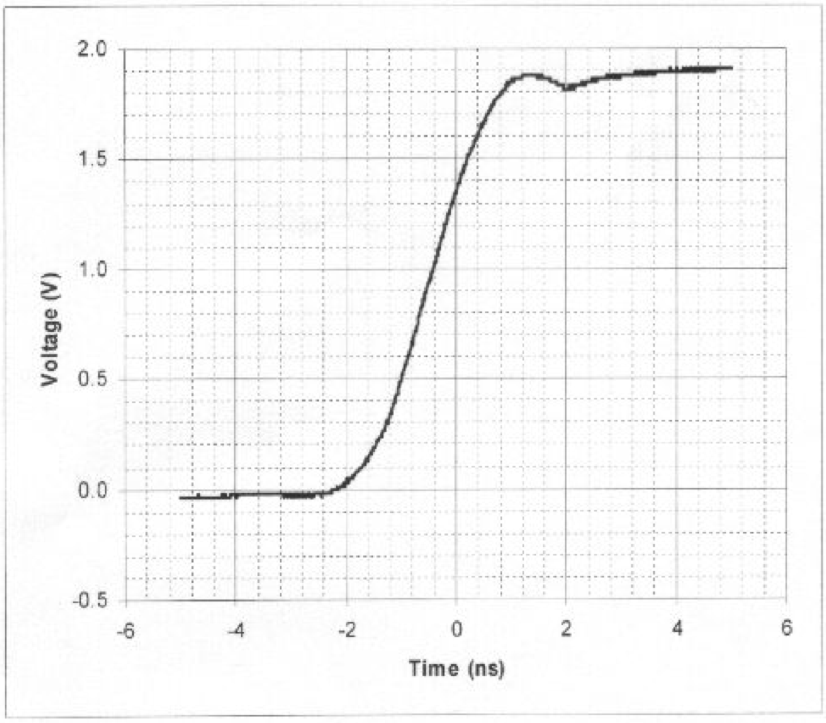


v(t)	original test pulse
$v_A(t)$	response at start input (in REF mode at gate logic)
$v_B(t)$	response at stop input (B)

Note: There is a dead time between both measurements.

3. Test pulse specification

1 kHz TTL from the SR620-counter reference output with nominal values Vmin = 0 V, Vmax = 2 V at 50 Ω. The test pulse from the counter sn 4521 is shown below (measured by the HP54615B oscilloscope).



4. The delay T_x of the unknown cable is obtained from the relation

$$T_x = T_2 - T_1 + \delta T_C + \delta T_{2J} + \delta T_{2L} - \delta T_{1J} - \delta T_{1L} + \delta T_Q + \delta T_N + \delta T_T + \delta T_O$$

where

T_1 - time interval measured with the BNC coupler

T_2 - time interval measured with the unknown cable

δT_C - correction for coupler delay

δT_{1J} - correction for fast variations in T_1

δT_{2J} - correction for fast variations in T_2

δT_{1L} - correction for trigger level in measurement of T_1

δT_{2L} - correction for trigger level in measurement of T_2

δT_Q - correction for quantization error

δT_N - correction for differential non-linearity

δT_T - correction for temperature effects on cable

δT_O - correction for other error contributions

Note: All quantities in the above relation are time quantities.

5. **Coupler delay (δT_C):** The coupler delay correction has been calculated from the relation $\delta T_C = L\,\varepsilon_r^{1/2}/c$, where L is the mechanical length, ε_r is the relative dielectric constant, and c is the speed of light. Assuming for Teflon $\varepsilon_r = 2.1 \pm 0.1$, the mechanical length L = 26.6 mm ± 1 mm, and a uniform distribution, we obtain $\delta T_C = 128 \pm 4$ ps (type B uncertainty).
6. **Fast variations (δT_{1J}, δT_{2J}):** These variations include the combined effect of trigger jitter and short-term frequency instability of time base, and give the standard deviation of 7 ps from 1000 samples for T_1 and T_2 for cables C_1 (the shortest) and C_2, and 8 ps for cable C_3 (type A uncertainty).
7. **Trigger level correction (δT_{1L}, δT_{2L}):** The trigger level timing error is a combination of imperfect scaling of the HP54615B oscilloscope used for the measurement of pulse amplitude, and imperfect trigger level of the counter. From the oscilloscope specification of voltage measurement we have ±1.2% of full scale ±0.5% of position value, and from the counter specification we have ±15 mV ± 0.5% of setting which gives in total the timing uncertainty of ± 30 mV/ slope; the slopes of individual responses are shown in Measurements (type B uncertainty).
8. **Differential nonlinearity (δT_N):** Specifies the maximum time error for any given relative measurement. In the SR620 counter, the dependence of δT_N, on the measured interval has approximately a sine-wave form with zero mean and the timing-error amplitude of 20 ps for measured intervals (type B uncertainty).
9. **Quantization (δT_Q):** In the averaging mode the counter has ± 0.5 ps error, which gives the total contribution of 0.5 ps for both measurement (type B uncertainty).
10. **Temperature variations (δT_T):** Since the cables are unknown, it is impossible to determine this correction. A guess can be made, however. The measured delays in cables C_2 and C_3 and the assumed length of 10 m and 35 m fit with Teflon as dielectric. From the measurement on a Teflon cable of our own, we have obtained the temperature coefficient of -0.16 ps/°C/m which gives $\delta T_T = \pm 2$ ps for C_2 (10 m) and ± 6 ps for C_3 (35 m) due to ±1°C variations. In the case of cable C_1 the guess is even more difficult. The cable is assumed to be 3 m but for that length and the measured delay of 20.4 ns delay we could not find any common dielectric. The measured delay, however, well fits with a cable of 4 m based on solid polyethylene (PE). So we have measured two types of PE cables and we obtained two different coefficients: -2.4 ps/°C/m and -1.2 ps/°C/m. Taking the larger coefficient and assuming that the cable is of 4 m length, we get ±10 ps due to ±1°C variations (type B uncertainty).
11. **Other variations (δT_O):** Evidently, there are other uncertainty contributions such as connections instability, temperature effects on the counter, humidity effects, reproducibility, and perhaps some other effects not known to us during the measurement. Since we have no experimental support to quantify these contributions as of the writing of this report, we have covered them by ± 20 ps within a uniform distribution (type B uncertainty).
12. **Correlation**: We assume that none of the input quantities are correlated to any significant extent.

13. **Measurement environment**: Temperature 25°C ± 1 °C, relative humidity 76% ± 5%.

    Note: The temperature in the room where the measurement was carried out could not been set to recommended 23°C because it is bound to the temperature maintained in the room with our cesium clocks (24.5°C).

14. **Measurements (T_j):** The time interval T_j, $j=1,2$ was measured as an average of 1000 samples with accompanied standard deviation. The measurement was repeated at seven trigger levels at input B: $V_{jB}(k) = V_j(0) + k*10\ mV$, $k= -3,2, ...+3$, where $V_j(0)$ is the closest discrete value to the 25% level, V_{jB}.

No.	Trg level	T_1	Trg level	$T_2(1)$	Trg level	$T_2(2)$	Trig level	$T_2(3)$
1	23.54%	3.339 ns	23.23%	23.597 ns	23.42%	51.667 ns	23.41%	177.704 ns
2	24.05%	3.352 ns	23.75%	23.612 ns	23.94%	51.682 ns	23.93%	177.724 ns
3	24.56%	3.365 ns	24.26%	23.626 ns	24.46%	51.699 ns	24.45%	177.746 ns
4	25.08%	3.38 ns	24.78%	23.642 ns	24.98%	51.716 ns	24.97%	177.767 ns
5	25.59%	3.393 ns	25.30%	23.658 ns	25.50%	51.733 ns	25.49%	177.789 ns
6	26.10%	3.407 ns	25.81%	23.674 ns	26.02%	51.748 ns	26.01%	177.811 ns
7	26.61%	3.424 ns	26.33%	23.686 ns	26.54%	51.763 ns	26.53%	177.831 ns

linear regression value at 25.0% trigger level:

T_1 = 3.378 ns
$T_2(1)$ = 23.649 ns
$T_2(2)$ = 51.716 ns
$T_2(3)$ = 177.769 ns

slope at 25.0% trigger level:

$sl(T_1)$ = 0.71 V/ns
$sl(T_2(1))$ = 0.68 V/ns
$sl(T_2(2))$ = 0.62 V/ns
$sl(T_2(3))$ = 0.46 V/ns

15. **Uncertainty budget ($T_x(1)$):**

quantity X_i	estimate x_i	standard uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$	degree of freedom ν_i
T_1	3.378 ns					
T_2	23.649 ns					
δT_C	0.128 ns	0.004 ns	rectangular	1.0	0.004 ns	∞
δT_{1J}	0 ns	0.0003 ns	normal	-1.0	0.0003 ns	999
δT_{1L}	0 ns	0.043 ns	rectangular	-1.0	0.043 ns	∞
δT_{2J}	0 ns	0.0003 ns	normal	1.0	0.0003 ns	999
δT_{2L}	0 ns	0.045 ns	rectangular	1.0	0.045 ns	∞
δT_Q	0 ns	0.0005 ns	rectangular	1.0	0.0005 ns	∞
δT_N	0 ns	0.015 ns	U-shaped	1.0	0.015 ns	∞
δT_T	0 ns	0.006 ns	rectangular	1.0	0.006 ns	∞
δT_O	0 ns	0.012 ns	rectangular	1.0	0.012 ns	∞
$T_x(1)$	20.399 ns				0.066 ns	∞

Uncertainty budget ($T_x(2)$):

quantity X_i	estimate x_i	standard uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$	degree of freedom ν_i
T_1	3.378 ns					
T_2	51.716 ns					
δT_C	0.128 ns	0.004 ns	rectangular	1.0	0.004 ns	∞
δT_{1J}	0 ns	0.0003 ns	normal	-1.0	0.0003 ns	999
δT_{1L}	0 ns	0.043 ns	rectangular	-1.0	0.043 ns	∞
δT_{2J}	0 ns	0.0003 ns	normal	1.0	0.0003 ns	999
δT_{2L}	0 ns	0.049 ns	rectangular	1.0	0.049ns	∞
δT_Q	0 ns	0.0005 ns	rectangular	1.0	0.0005 ns	∞
δT_N	0 ns	0.015 ns	U-shaped	1.0	0.015 ns	∞
δT_T	0 ns	0.002 ns	rectangular	1.0	0.002 ns	∞
δT_O	0 ns	0.012 ns	rectangular	1.0	0.012 ns	∞
$T_x(2)$	48.466 ns				0.069 ns	∞

Uncertainty budget ($T_x(3)$ **):**

quantity X_i	estimate x_i	standard uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$	degree of freedom ν_i
T_1	3.378 ns					
T_2	177.769 ns					
δT_C	0.128 ns	0.004 ns	rectangular	1.0	0.004ns	∞
δT_{1J}	0 ns	0.0003 ns	normal	-1.0	0.0003 ns	999
δT_{1L}	0 ns	0.043 ns	rectangular	-1.0	0.043 ns	∞
δT_{2J}	0 ns	0.0003 ns	normal	1.0	0.0003 ns	999
δT_{2L}	0 ns	0.066 ns	rectangular	1.0	0.066 ns	∞
δT_Q	0 ns	0.0005 ns	rectangular	1.0	0.0005 ns	∞
δT_N	0 ns	0.015 ns	U-shaped	1.0	0.015 ns	∞
δT_T	0 ns	0.004 ns	rectangular	1.0	0.004 ns	∞
δT_O	0 ns	0.012 ns	rectangular	1.0	0.012ns	∞
$T_x(3)$	174.519 ns				0.082 ns	∞

Participating laboratory: Institute of Radio Engineering and Electronics, Czech Academy of Sciences (CMI Associated Laboratory)

Date: August 16, 2005

Signature Jan Čermák

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Stanford Research SR620
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	

2. Measuring method

	Substitution method
Number of repeated measurements:	7

3. Measurement condition

Ambient temperature in the room in °C	25°C ± 1°C
Ambient humidity in the room in %	76 ± 5

Participating laboratory: Institute of Radio Engineering and Electronics, Czech Academy of Sciences (CMI Associated Laboratory)

Date: August 16, 2005

Signature Jan Čermák

Annex 5: Measurement results for traveling standard no: BEV01

Measurand: time interval $T_X(i)$ for measuring cable lengths:
All figures are in µs.

cable length	$T_X(i)$	combined standard uncertainty $u(T_X)$	eff. degree of freedom ν_{eff}
3 m	*0.020399*	*0.000066*	∞
10 m	*0.048466*	*0.000069*	∞
35 m	*0.174519*	*0.000082*	∞

Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These information will be used to be mentioned in the final report to be prepared by the organisation group.

Description of the measurement method(s) and <u>relevant </u>instruments:

The method adopted at IEN for the time interval cable delay measurement is the “Double Weight Method” (DWM). This method, suggested by BIPM for the GPS calibration campaigns, has the capability to compensate for different asymmetries of the cables and of the counter; it follows the five steps procedure reported in Fig. 1.

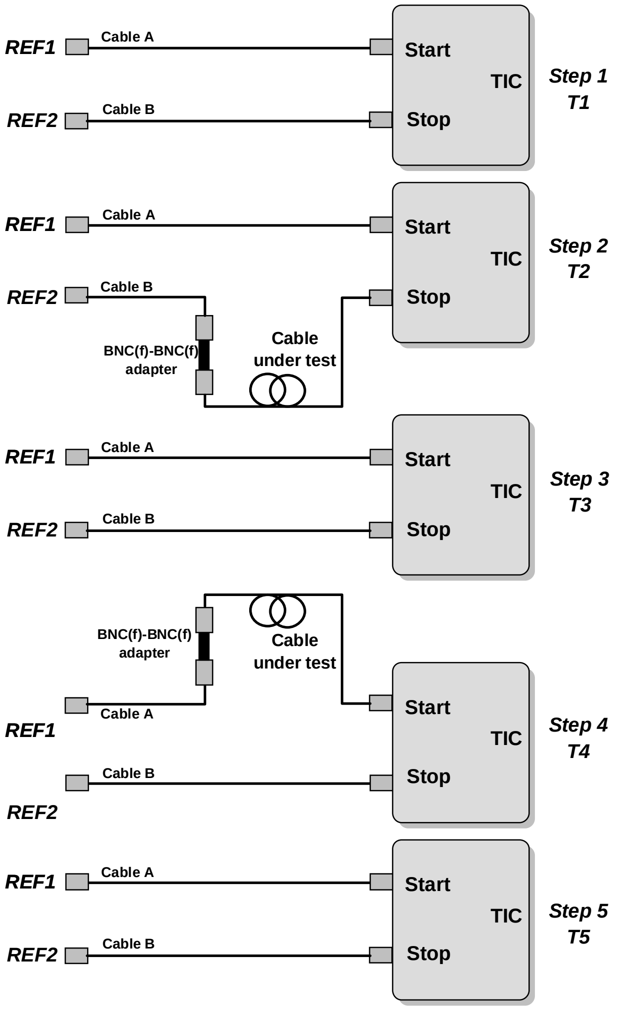


Fig. 1 – block diagram of the DWM method

Using the five time interval measurements T1, T2, T3, T4 and T5, it has been computed the delay of the cable under test T_x , being Ω_{AD} the delay of the BNC_F/BNC_F adapter (Jack/Jack adapter), as:

$$T_x = \frac{T_2 - \frac{T_1 + T_3}{2} + \frac{T_3 + T_5}{2} - T_4}{2} + t_{AD} \qquad (1)$$

Where the auxiliary cable delays (A and B), the unknown phase difference between REF1 and REF2 and the counter asymmetries cancel out thanks to the relative method.

In Fig. 2 is reported the used experimental set-up. The reference *1PPS* signals are obtained from two outputs of a distribution amplifier supplied with UTC(IEN). The time base of the time interval counter is a 10 MHz signal from UTC(IEN), the impedance of the A and B inputs are of 1 MΩ, while the signals are connected to the counter using two 50 Ω feed through matching devices.

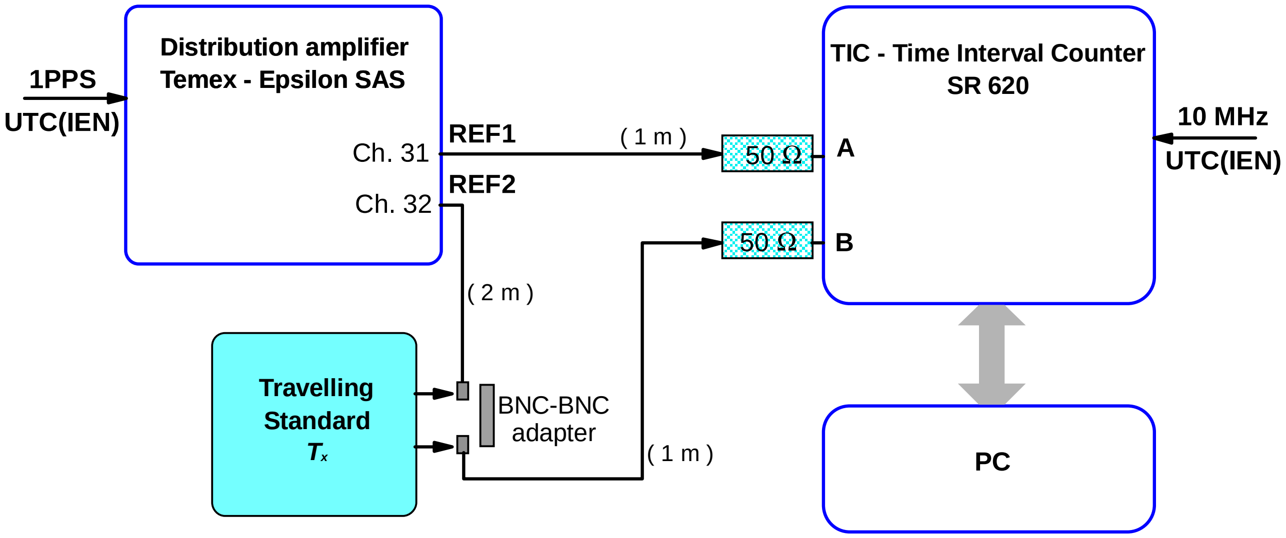


Fig. 2 – IEN experimental set-up

The scheme of Fig. 2 represents the cases of steps 1, 2 and 3 of Fig. 1, where the *Stop* cable is split into two parts allowing to insert both a BNC_F/BNC_F adapter or the cable under test; during the steps 4 and 5 of Fig. 1, the adapter or the device under test are inserted on the *Start* cable.

Amplitude of the 1PPS reference signals:	(from 0,02 to 3,95) V
Counter trigger level (A and B):	+1 V
Slew rate of the input signals (around 1 V):	0,46 V/ns
Delay of the BNC_F/BNC_F adapter:	(0,148±0,010) ns
Averaged readings per measurement:	10

The selected trigger levels of the *Start* and *Stop* channels (1 V) were about ¼ of the signals amplitude, but for the *Stop* channel, the trigger level has been reduced, when a cable under test was inserted, according to the attenuation of the cable itself to guarantee the same percentage versus the total amplitude as for the *Start*. For the Cable #1, this change was lower than the trigger settability of the counter (10 mV), for the Cables #2 and #3, the chosen trigger levels were of 0,99 V and 0,97 V respectively.

The delay of the BNC_F/BNC_F adapter used, has been experimentally evaluated measuring the total delay of a couple of $BNC_F/BNC_F + BNC_M/BNC_M$ adapters, as for a normal cable delay measurement, and computing the single delays, BNC_F/BNC_F and BNC_M/BNC_M, proportionally to the electric length of the single adapters.

The evaluation of the cable delays has been repeated 9 times (9 sessions), distributed over seven days, in order to evaluate the repeatability of the results.

Participating laboratory: IEN - Torino

Date: July 18, 2005

Signature: Valerio Pettiti

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Stanford Research Systems, Inc. – SR620 s/n 3680
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	July 13, 2005

2. Measuring method

Number of repeated measurements:	Mean values over 10 measurements with a 1 s repetition rate; 5 steps per session; one measurement delay per session and per cable according to expression (1); 9 sessions distributed over 7 days.

3. Measurement condition

Ambient temperature in the room in ^{o}C	(25 ± 1) °C
Ambient humidity in the room in %	From 45 to 55 %

Participating laboratory: IEN - Torino

Date: July 18, 2005

Signature: Valerio Pettiti

Annex 5: Measurement results for travelling standard no: BEV01

Measurand: time interval $\boldsymbol{T}_{\mathbf{X}}(i)$ for measuring cable lengths:
All figures are in ns.

cable length	$\boldsymbol{T}_{\mathbf{X}}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_{\mathbf{X}})$	eff. degree of freedom n_{eff}
3 m	20,45	0,06	>100
10 m	48,43	0,06	>100
35 m	174,88	0,06	>100

The uncertainty budget for the IEN measurements is reported in the following table.

Quantity X_i	*Estimate* x_i	*Standard uncertainty* $u(x_i)$	Probability distribution / method of evaluation(A,B)	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$	*Degree of freedom* ν_i
T_2	58,836					
T_1	10,450					
$\partial TB(\tau)$	0,000	0,010	normal (A)	1	0,010	10
dR	0,000	0,025	normal (B)	$1/\sqrt{10}$	0,008	¥
dT_J	0,000	0,001	normal (B)	$\sqrt{2}/\sqrt{10}$	0,001	¥
dT_L	0,000	0,043	normal (B)	$\sqrt{2}$	0,061	¥
dT_1	0,148	0,010	normal (A)	1	0,010	10
T_X	48,534				0,063	n_{eff} > 100

To investigate on the repeatability of the measured delays, a set of measurement sessions has been collected over o period of about seven days. In the following table is reported a summary of this investigation.

cable length	$\boldsymbol{T}_X(i)$	Standard uncertainty on repeated meas.	Number of meas. sessions
3 m	20,45	0,02	9
10 m	48,43	0,02	9
35 m	174,88	0,03	9

Final Remarks

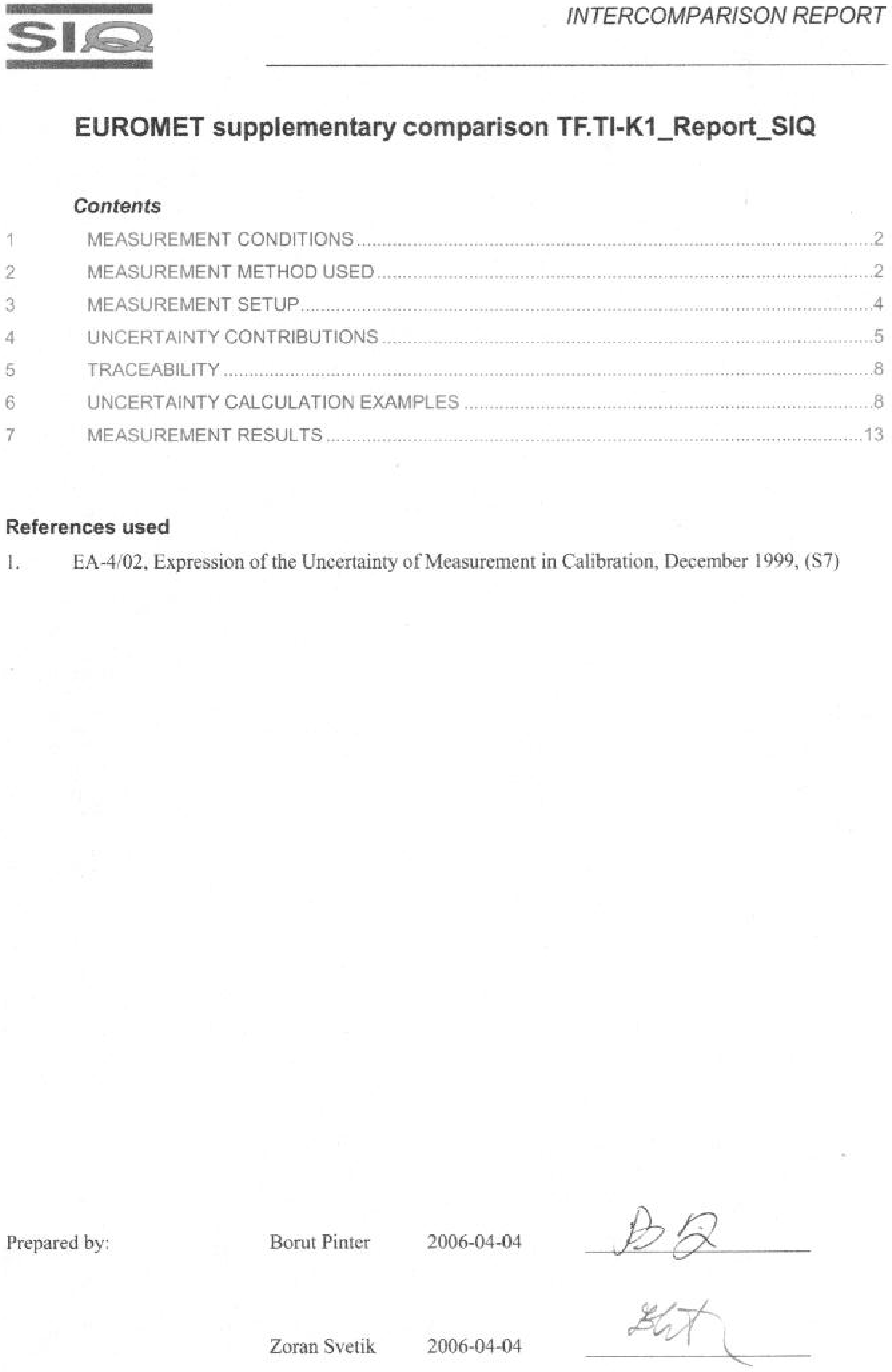
The uncertainty budget evaluated for this time delay measurement campaign (0,06 ns), is lower than the IEN calibration measurement capabilities (1 ns) published on the KCDB – Appendix C. This result, if confirmed by this supplementary comparison, could be used to upgrade the IEN CMCs.

Participating laboratory: IEN - Torino

Date: July 18, 2005

Signature: Valerio Pettiti

Appendix A.SIQ



EUROMET supplementary comparison TF.TI-K1_Report_SIQ

Contents

1 MEASUREMENT CONDITIONS 2
2 MEASUREMENT METHOD USED 2
3 MEASUREMENT SETUP 4
4 UNCERTAINTY CONTRIBUTIONS 5
5 TRACEABILITY 8
6 UNCERTAINTY CALCULATION EXAMPLES 8
7 MEASUREMENT RESULTS 13

References used

1. EA-4/02, Expression of the Uncertainty of Measurement in Calibration, December 1999, (S7)

Prepared by: Borut Pinter 2006-04-04

Zoran Svetik 2006-04-04

1 Measurement conditions

All measurements were performed in the period from 18 July 2005 to 29 July 2005 under following environmental conditions:

Temperature:	23 °C ± 1 °C
Relative humidity:	50 % ± 20 %

Actual temperature at the measured item is given along the measurement results.

Before commencing measurements connectors were inspected.

2 Measurement method used

The following system was used for determinig the cable time delay. A HP8161A programable pulse generator was used for generation of pulses. Pulse setting were as follows:

Period	10 μs
Width	1 μs
Rise time	1 ns
High Level	5 V
Low Level	0 V

It's output impedance is 50 Ω. The pulses from this generator were divided by means of a precizion 50 Ω microwave power splitter Weinchel model 1870A. After the pulses are split into two cables their high level is aproximately 2,5 V at both ports of the splitter. All cables used in the system were RG223U 50 Ω coaxial BNC cables. One port of the splitter was connected with a BNCm-BNCm cable to the channel 1 of the time interval counter which was used as a start gate for the time interval measurement. The other port of the splitter was connected to the channel 2 of the time interval counter which was used as a stop gate for the time interval measurement, trough two BNCm-BNC-m cables connected toghether in the middle with a BNCf-BNCf adapter. The time interval counter used for the measurements was a Stanford Researh SR620. Then residual time delay of this setup was measured. To exclude the time delay of the BNCf-BNCf adapter from the final measurement a 1 to 3 adapter method was used. First time delay with one BNCf-BNCf adapter inserted into system was measured, and then a combination of two BNCf-BNCf adapters and one BNCm-BNCm adapters were inserted into the system. All of these adapters had same length so we estimated that the time delay trough three adapters is three times of the time delay trough one adapter. With this assumption the residual time delay of the system T_1 without the adapter can be calculated using the following formula:

$$T_1 = \frac{3 \cdot T_{1A} - T_{3A}}{2}$$

where:

T_{1A} Time interval measured with one adapter inserted

T_{3A} Time interval measured with three adapters inserted

Then the measured cables were inserted into the system and time delays with each one of them inserted were measured. Then the time delay of the cables Td_x was calculated using the following formula:

$$Td_x = T_{2x} - T_1$$

where:

T_{2x}	Time interval measured with the cable x inserted where x stands for 1, 2 or 3 as a designation for the three cables measured.
T_1	Residual time delay of the system

During the measurements it was seen that longer the cable measured worse was its bandwidth. Due to that fact the rise time of the pulse coming out of the cable was substantialy degraded so that systematic drift was observed for longer cables. Due to that fact low trigger level (0,5 V) was selected so that the counter wasn't triggered by the noise and so that the systematic drift due to different rise times of the pulses for start and stop trigger was minimized. Due to this fact additional uncertainty was added to the final results. The detailed explanation of this effect is given with uncertainty budget calculation.

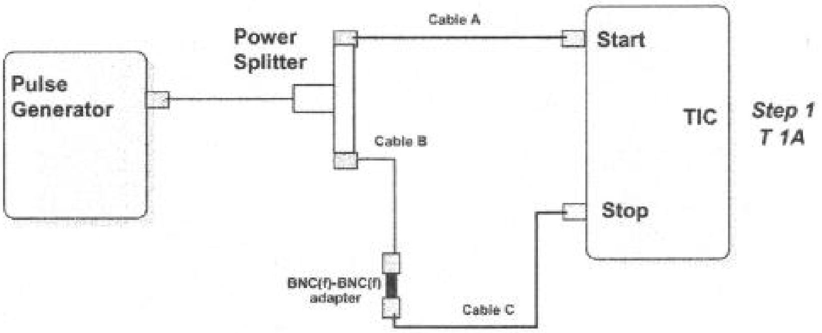
For a single measurement of the time delay of one cable three time intevals were measured with the counter. Each of these time intervals T measured had the following mathemathical model for estimating the uncertainty:

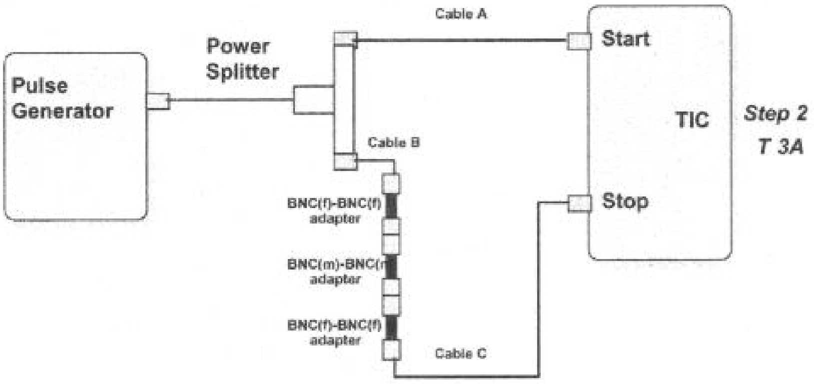
$$T = T_R + \delta RMS + \delta TBE + \delta StartTLE + \delta StopTLE + \delta RT$$

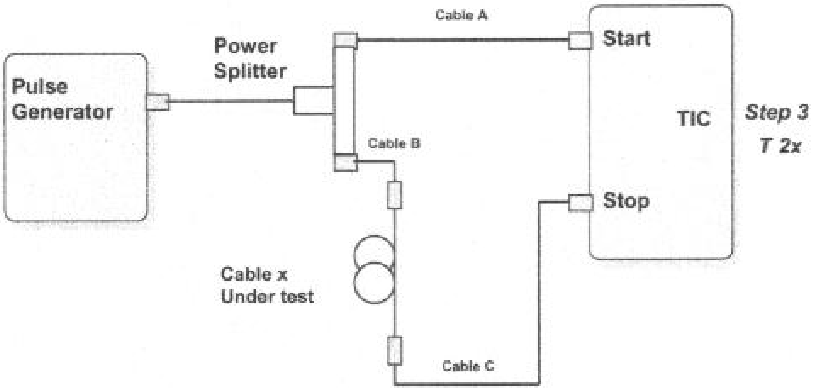
where:

T_R	Time interval reading from the counter
δRMS	Correction due to the RMS resolution of the time interval counter
δTBE	Correction due to the time base error of the counter
$\delta StartTLE$	Correction due to the start trigger level error
$\delta StopTLE$	Correction due to the stop trigger level error
δRT	Correction due to the rise time degradation of the stop pulse

3 Measurement setup







4 Uncertainty contributions

Time delay measured with one adapter inserted (T_{1A})

Uncertainty of this value is calculated using the uncertainty calculation for time interval measurements which is given later. The sensitivity coefficient for this value is 1,5. This uncertainty contribution is assumed to have normal probability distribution.

Time delay measured with three adapter inserted (T_{3A})

Uncertainty of this value is calculated using the uncertainty calculation for time interval measurements which is given later. The sensitivity coefficient for this value is 0,5. This uncertainty contribution is assumed to have normal probability distribution.

Time interval measured with the cable x inserted where x stands for 1, 2 or 3 as a designation for the three cables measured (T_{2x})

Uncertainty of this value is calculated using the uncertainty calculation for time interval measurements which is given later. The sensitivity coefficient for this value is 1. This uncertainty contribution is assumed to have normal probability distribution.

Residual time delay of the system (T_l)

Uncertainty cantribution of this value is calculated as shown earlier in the text. The sensitivity coefficient for this value is 1. This countrbution is assumed to have normal probability distribution.

Time interval reading from the counter (T_R)

This value is read from the time interval counter as a mean value of 10000 measurements taken with the time interval counter using internal time interval counters statistics. The uncertainty associates with this measurement is a STD DEV reading U_SDS from the time interval counter, which is a standard deviation of the sample of 10000 measurements taken with the counter. Therefore the standard uncertainty contribution U_TR of this value is taken to be the standard deviation of the mean and is calculated as:

$$U\_T_R = \frac{U\_SDS}{\sqrt{N}}$$

where:

N Number of samples set on the time interval counter for mean and std dev calculation (usualy 10000).

This uncertainty contribution is assumed to have normal probability distribution.

Correction due to the RMS resolution of the time interval counter (δRMS)

This value is estimated to be 0 ns, with associated uncertainty $U\_\delta RMS$ calculated using the following formula as stated in time interval counter specifications:

$$U\_\delta RMS = \sqrt{\frac{t_{res}^2 + TBS^2 + StartTriggJitt^2 + StopTriggJitt^2}{N}}$$

where:

t_{res}	time resolution of the time interval counter (0,025 ns for SR620)
TBS	time base short term stability
$StartTriggJitt$	start trigger jitter of the time interval counter
$StopTriggJitt$	stop trigger jitter of the time interval counter

Time base short term stability is taken from cezium clock specifications to be $1*10^{-10} * T_R$.

Trigger jitter is calculated using the following formula as stated in time interval counters specifications:

$$TriggJitt = \frac{\sqrt{E_{in}^2 + E_{sig}^2}}{SR}$$

where:

E_{in}	RMS noise of the input amplifier (typicaly 0,35 mVrms)
E_{sig}	RMS noise of the input signal (typicaly 1 mVrms for the setup used)
SR	Input signal slew rate at trigger point

RMS noise of the input amplifier is given in time interval counters specifications and is estimated to be 0,35 mVrms.

RMS noise of the input signal is also estimated to be no more than 1 mVrms.

Input signal slew rate at trigger point is calculated using following formula:

$$SR = \frac{U_{peak}}{RT}$$

U_{peak}	Peak amplitude of the pulse at the input of the time interval counter
RT	Rise time of the pulse at the input of the time interval counter

If calculated slew rate is higher than 1,7 V/ns then the value of 1,7 V/ns is used, because the bandwidth of the internal circuitry of the time interval counter limits the slew rate to this value. This was usualy the case when measuring residual time delay of the system and for all start trigger events. For all measurements of the time intervals when pulse that was used for stop trigger which traveled trough the cable this value was smaller due to the degradation of the rise time when traveling trough the cable. Slew rate used for calculation of uncertasinty for the first cable was taken to be 1 V/ns, for cable 2 this value was 0,5 V/ns and for cable 3 0,2 V/ns. This uncertainty contribution is assumed to have rectangular probability distribution.

Correction due to the time base error of the counter (*δTBE*)

During all the measurements the time interval counter was connected to the cezium clock 10 MHz output which was used as counters reference time base. This correction is estimated to be 0 ns with asociated uncertainty taken from cezium clock specifications which is $2 * 10^{-12} * T_R$. This uncertainty contribution is assumed to have rectangular probability distribution.

Correction due to the start trigger level error (*δStartTLE*)

This correction is estimated to be 0 ns with associated uncertainty, which is calculated using the following formula:

$$U\_TLE = \frac{0{,}015V + 0{,}005 \cdot TrigLevel}{SR}$$

where:

TrigLevel	Start trigger level (0,5 V)

Slew rate at all start trigger points is taken to be 1,7 V/ns.

This uncertainty contribution is assumed to have rectangular probability distribution.

Correction due to the stop trigger level error (*δStopTLE*)

This correction is estimated to be 0 ns with associated uncertainty, which is calculated using the following formula:

$$U\_TLE = \frac{0{,}015V + 0{,}005 \cdot TrigLevel}{SR}$$

where:

TrigLevel	Stop trigger level (0,5V)

The slew rate at stop trigger points is degraded when time intervals with longer cables inserted are measured. This uncertainty contribution is assumed to have rectangular probability distribution.

Correction due to the rise time degradation of the stop pulse (*δRT*)

This value is taken to be 0 ns. The uncertainty of this value is different for different cables inserted into the system. When residual time delay of the system is measured then the uncertainty contribution of this value is estimated to be 0,05 ns. When measuring the time interval trough cable 1 the uncertainty is estimated to be 0,2 ns, trough cable 2 the uncertainty contribution is 0,3 ns and when measurign the time interval trough cable 3 this contribution is 0,5 ns. This uncertainty is assumed to have U-shaped probability distribution. The values for this uncertainty contribution were estimated by measuring the time intervals at different trigger levels and by noting how the measured values changed.

Each of the measured time intervals has an additional systematic drift from its true value due to the differential channel error. This drift was not added to the uncertainty calculations due to the fact that it is the same in all measurements and therefore it cancels itself out when calculating the time delay of the cable by subtracting the time intervals measured.

5 Traceability

Traceability of the time interval counter used is assured trough traceable calibration, which is performed once a year in house.

6 Uncertainty calculation examples

In the following example the time delay of the system with one BNCf-BNCf adapter inserted T1A was measured.

Mathematical model of measurement:

$$T_{1A} = T_R + \delta RMS + \delta TBE + \delta StartTLE + \delta StopTLE + \delta RT$$

Trmean	6,124
St. Deviation of the sample	0,033
St. Deviation of the mean	0,0003

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
Tr	6,124 ns	0,000 ns	normal	1	1	0,000 ns	9999
dRMS	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dTBE	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dStartTLE	0 ns	0,006 ns	rectangular	1,73	1	0,006 ns	20000
dStopTLE	0 ns	0,006 ns	rectangular	1,73	1	0,006 ns	20000
dRT	0 ns	0,035 ns	U-shaped	1,41	1	0,035 ns	20000
T1a	6,124 ns				Combined uncertainty:	0,036 ns	22293

In the following example the time interval of the system with three adaptors inserted T3A was measured.

Mathematical model of measurement:

$$T_{3A} = T_R + \delta RMS + \delta TBE + \delta StartTLE + \delta StopTLE + \delta RT$$

Trmean	6,367 ns
St. Deviation of the sample	0,033 ns
St. Deviation of the mean	0,0003 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
Tr	6,367 ns	0,000 ns	normal	1	1	0,000 ns	9999
dRMS	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dTBE	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dStartTLE	0 ns	0,006 ns	rectangular	1,73	1	0,006 ns	20000
dStopTLE	0 ns	0,006 ns	rectangular	1,73	1	0,006 ns	20000
dRT	0 ns	0,035 ns	U-shaped	1,41	1	0,035 ns	20000
T3a	6,367 ns				Combined uncertainty:	0,036 ns	22293

In the following example residual time delay of the system without the adaptor inserted T1 was calculated. Values of T1A and T3A used for calculation are taken from previous examples.

Mathematical model of measurement:

$$T_1 = \frac{3 \cdot T_{1A} - T_{3A}}{2}$$

T1a	6,124 ns
U_T1a	0,036 ns
T3a	6,367 ns
U_T3a	0,036 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
T1a	6,124 ns	0,036 ns	normal	1	1,5	0,054 ns	22293
T3a	6,367 ns	0,036 ns	normal	1	0,5	0,018 ns	22293
T1	6,003 ns				Combined uncertainty:	0,057 ns	27187

In the following example the time interval of the system with cable 1 inserted T21 was measured.

Mathematical model of measurement:

$$T_{21} = T_R + \delta RMS + \delta TBE + \delta StartTLE + \delta StopTLE + \delta RT$$

Trmean	26,382 ns
St. Deviation of the sample	0,050 ns
St. Deviation of the mean	0,0005 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
Tr	26,382 ns	0,001 ns	normal	1	1	0,001 ns	9999
dRMS	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dTBE	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dStartTLE	0 ns	0,006 ns	rectangular	1,73	1	0,006 ns	20000
dStopTLE	0 ns	0,010 ns	rectangular	1,73	1	0,010 ns	20000
dRT	0 ns	0,141 ns	U-shaped	1,41	1	0,141 ns	20000
T21	26,382 ns				Combined uncertainty:	0,142 ns	20276

In the following example time delay trough cable 1 Td1 was calculated. Values for the calculation are taken from previous examples.

Mathematical model of measurement:

$$Td_1 = T_{21} - T_1$$

T21	26,382 ns
U_T21	0,142 ns
T1	6,003 ns
U_T1	0,057 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
T21	26,382 ns	0,142 ns	normal	1	1	0,142 ns	22293
T1	6,003 ns	0,057 ns	normal	1	1	0,057 ns	22293
Td1	20,379 ns				Combined uncertainty:	0,153 ns	29295

In the following example the time interval of the system with cable 2 inserted T22 was measured.

Mathematical model of measurement:

$$T_{22} = T_R + \delta RMS + \delta TBE + \delta StartTLE + \delta StopTLE + \delta RT$$

Trmean	54,392 ns
St. Deviation of the sample	0,027 ns
St. Deviation of the mean	0,0003 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
Tr	54,392 ns	0,000 ns	normal	1	1	0,000 ns	9999
dRMS	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dTBE	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dStartTLE	0 ns	0,006 ns	rectangular	1,73	1	0,006 ns	20000
dStopTLE	0 ns	0,020 ns	rectangular	1,73	1	0,020 ns	20000
dRT	0 ns	0,212 ns	U-shaped	1,41	1	0,212 ns	20000
T22	54,392 ns				Combined uncertainty:	0,213 ns	20395

In the following example time delay trough cable 2 Td2 was calculated. Values for the calculation are taken from previous examples.

Mathematical model of measurement:

$$Td_2 = T_{22} - T_1$$

T22	54,392 ns
U_T22	0,213 ns
T1	6,003 ns
U_T1	0,057 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
T22	54,392 ns	0,213 ns	normal	1	1	0,213 ns	22293
T1	6,003 ns	0,057 ns	normal	1	1	0,057 ns	22293
Td2	48,389 ns				Combined uncertainty:	0,220 ns	25470

In the following example the time interval of the system with cable 3 inserted T23 was measured.

Mathematical model of measurement:

$$T_{23} = T_R + \delta RMS + \delta TBE + \delta StartTLE + \delta StopTLE + \delta RT$$

Trmean	180,345 ns
St. Deviation of the sample	0,050 ns
St. Deviation of the mean	0,0005 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
Tr	180,345 ns	0,001 ns	normal	1	1	0,001 ns	9999
dRMS	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dTBE	0 ns	0,000 ns	rectangular	1,73	1	0,000 ns	20000
dStartTLE	0 ns	0,006 ns	rectangular	1,73	1	0,006 ns	20000
dStopTLE	0 ns	0,051 ns	rectangular	1,73	1	0,051 ns	20000
dRT	0 ns	0,354 ns	U-shaped	1,41	1	0,354 ns	20000
T23	180,345 ns				Combined uncertainty:	0,357 ns	20828

In the following example time delay trough cable 3 Td3 was calculated. Values for the calculation are taken from previous examples.

Mathematical model of measurement:

$$Td_3 = T_{23} - T_1$$

T23	180,345 ns
U_T23	0,357 ns
T1	6,003 ns
U_T1	0,057 ns

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
T23	180,345 ns	0,357 ns	normal	1	1	0,357 ns	22293
T1	6,003 ns	0,057 ns	normal	1	1	0,057 ns	22293
Td3	174,342 ns				Combined uncertainty:	0,362 ns	23429

7 Measurement results

1. Measuring system

Type of TIC used:	Stanford Research SR620
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	/
Date of last measurement in the NML	08.11.2004

2. Measuring method

Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in °C	23 +/- 1
Ambient humidity in the room in %	50 +/- 20

Measurand: time interval $\boldsymbol{T}_\mathbf{X}(i)$ for measuring cable lengths:

All figures are in µs.

cable length	$\boldsymbol{T}_\mathbf{X}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_\mathbf{X})$	eff. degree of freedom ν_{eff}
3 m	*0,02039*	*0,00015*	*29295*
10 m	*0,04840*	*0,00022*	*25470*
35 m	*0,17435*	*0,00036*	*23429*

Participating laboratory: Slovenian Institute for Quality and Metrology

Date: 04.04.2006

Signature:

Appendix A.NPL

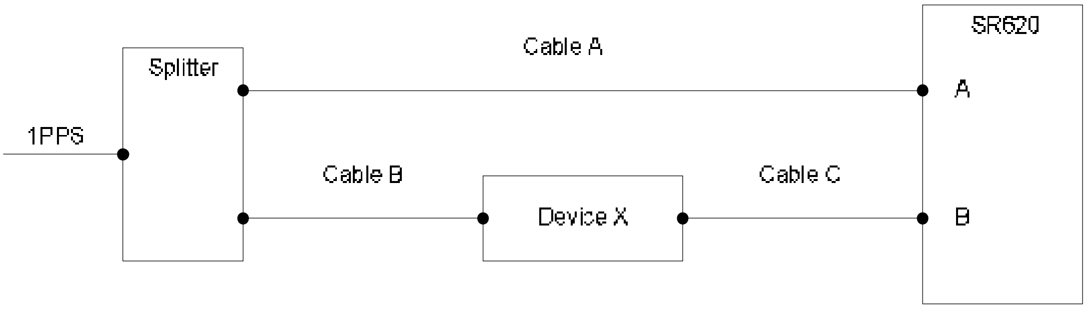
EUROMET supplementary comparison TF.TI-K1
NPL Measurement Report

Annex 3: Measurement report A

Description of the measurement method(s) and relevant instruments:

Measurement instrument: Stanford research Systems SR620 Universal Time Interval Counter.
Source of 1 pulse-per-second (1PPS) input signals: Symmetricom active hydrogen maser, via pulse generator, pulse distribution amplifier and power splitter (Mini-Circuits ZSC-2-1).
The same maser provided a reference frequency input to the SR620.

Basic principle of the measurements:



The measurements were performed as time interval measurements between inputs A and B, using as device X:

i) a BNC female – BNC female adaptor: measurement result t_1,

ii) the three test cables: measurement result t_Y for cable Y,

using 10-sample averages and repeated alternately 6 times.
The calculation of the delay T_Y of cable Y is then basically:

$$T_Y = (t_Y - t_1) + T_{AD},$$

Where T_{AD} is the delay of the BNC adaptor.
T_{AD} was determined separately using the SR620's 1 kHz square wave output and a pair of test cables, by measuring the delays of each cable separately and of both cables with the adaptor.

Participating laboratory: NPL, UK.

Date: 2006-04-12

Signature

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Stanford Research Systems SR620
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	Calibrated 2004-11-22

2. Measuring method

Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in ^{o}C	24.4 ± 1.0
Ambient humidity in the room in %	40 ± 20

Participating laboratory: NPL, UK

Date: 2006-04-12

Signature

Annex 5: **Measurement results for traveling standard no: BEV01**

Measurand: time interval $\boldsymbol{T}_{\mathbf{X}}(i)$ for measuring cable lengths:
All figures are in ns.

cable length	$\boldsymbol{T}_{\mathbf{X}}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_{\mathbf{X}})$	eff. degree of freedom n_{eff}
3 m	*20.42*	*0.50*	*5*
10 m	*48.52*	*0.50*	*5*
35 m	*174.83*	*0.50*	*5*

Uncertainty Budget

The analysis here is based on the example provided for the insertion method.

Measuring method: The time interval (t_1) between reference and sample arms of the system without the transfer standard inserted is measured with a Time Interval Counter (TIC). The transfer standard is then inserted into the sample arm and the TIC measures the changed time interval (t_Y).
The model equation to determine the time delay of the cable T_Y is given by:

$$T_Y = t_Y(1+TB(\tau)) + \delta R + \delta T_J + \delta T_L - t_1 + \delta t_1 + T_{AD} + \delta T_{AD}$$

The parameters assumed to contribute to the uncertainty of the measurement are:
$TB(\tau)$ - fractional frequency deviation due to short term (τ) stability of time base frequency.
δR - uncertainty due to resolution of TIC.
δT_J - uncertainty due to trigger jitter.
δT_L - uncertainty due to trigger level timing error.
δt_1 - uncertainty due to error in measuring residual time delay of the system.
δt_{AD} - uncertainty due to error in measuring time delay of BNC adaptor.
These parameters are assumed to be all uncorrelated.

An uncertainty budget is given for each of the sample cables.

Short (3 m) cable, with Delay T_S

Quantity X_i	*Estimate* x_i */ns*	*Standard uncertainty* $u(x_i)$ */ns*	Probability distribution / method of evaluation(A,B)	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$ /ns	*Degree of freedom* ν_i
t_S	*29.20*					
t_1	*8.88*					
T_{AD}	*0.10*					
$\partial TB(\tau)$	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δR	*0*	*0.025*	*rectangular*	*1.0*	*0.025*	*∞*
δT_J	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δT_L	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δt_1	*0*	*0.5*	*normal*	*1.0*	*0.5*	*5*
δT_{AD}	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
T_S	*20.42*	*0.50*				*5*

Medium (10 m) cable, with Delay T_M

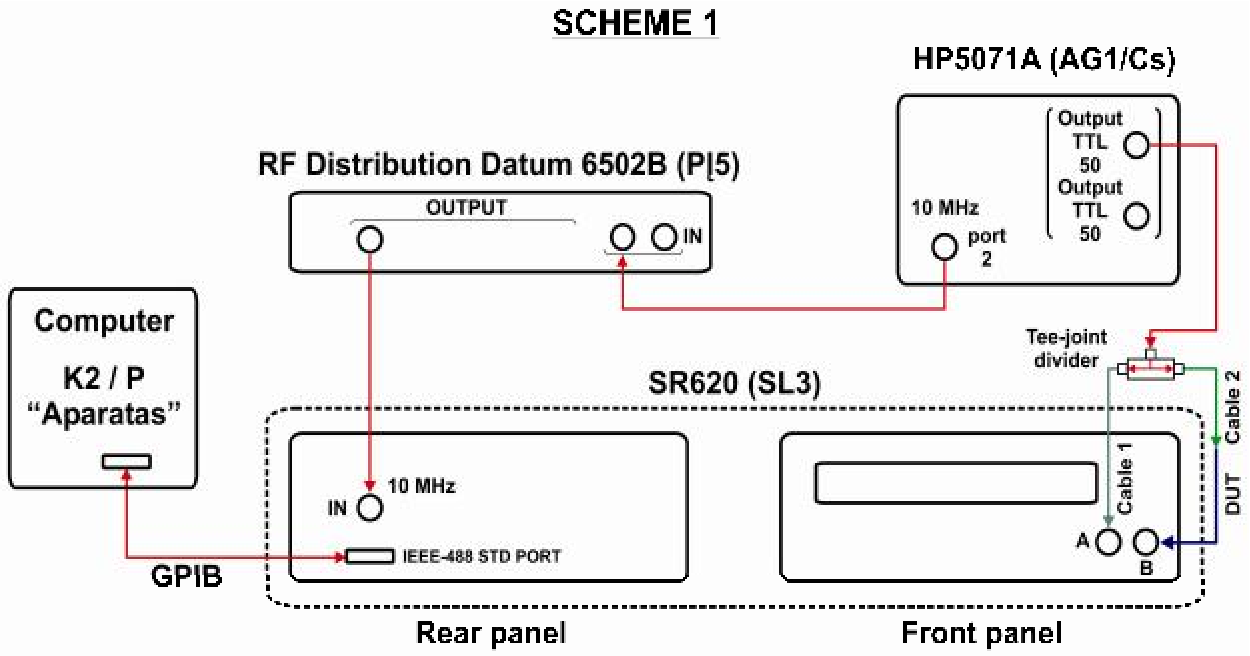
Quantity X_i	*Estimate* x_i */ns*	*Standard uncertainty* $u(x_i)$ */ns*	Probability distribution / method of evaluation(A,B)	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$ /ns	*Degree of freedom* ν_i
t_M	*57.30*					
t_1	*8.88*					
T_{AD}	*0.10*					
$\partial TB(\tau)$	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δR	*0*	*0.025*	*rectangular*	*1.0*	*0.025*	*∞*
δT_J	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δT_L	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δt_1	*0*	*0.5*	*normal*	*1.0*	*0.5*	*5*
δT_{AD}	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
T_M	*48.52*	*0.50*				*5*

Long (35 m) cable, with Delay T_L

Quantity X_i	*Estimate* x_i */ns*	*Standard uncertainty* $u(x_i)$ */ns*	Probability distribution / method of evaluation(A,B)	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$ /ns	*Degree of freedom* ν_i
t_L	*183.61*					
t_1	*8.88*					
T_{AD}	*0.10*					
$\partial TB(\tau)$	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δR	*0*	*0.025*	*rectangular*	*1.0*	*0.025*	*∞*
δT_J	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δT_L	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
δt_1	*0*	*0.5*	*normal*	*1.0*	*0.5*	*5*
δT_{AD}	*0*	*0.01*	*normal*	*1.0*	*0.01*	*∞*
T_L	*174.83*	*0.50*				*5*

Annex 3: Measurement report A

Description of the measurement method(s) and relevant instruments:



The measurements were performed using PPS pulses from the cesium atomic clock HP5071A. The pulses were fed through the tee-joint divider and cables to the channels A and B of the time interval counter SR620 (further referred to as TIC). The TIC, which time base was disciplined to the reference 10 MHz signal from the HP5071A, was to measure the time difference between the pulses – actually, the difference between the delays of the cable 1 and cable 2 plus the cable investigated (DUT). Then, DUT was removed. The delay of DUT obtained by subtracting the delay measured **without** DUT from the delay measured **with** DUT present.
For every delay, thousands of measurements were made, and the results were recorded by the computer. The standard uncertainty obtained by means of type A and type B evaluation was 100 ps.

Participating laboratory: Semiconductor Physics Institute

Date: November 23, 2005

Signature: Dr. Rimantas Miškinis

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	SR620
Is the TIC independent of other national measurement laboratory (NML) ?	Yes, it is.
If **not** independent, please give the name of NML	-
Date of last measurement in the NML	-

2. Measuring method

Number of repeated measurements for each cable delay:	3000

3. Measurement condition

Ambient temperature in the room in ^{o}C	22±1 ^{o}C
Ambient humidity in the room in %	(40±10)%

Participating laboratory: Semiconductor Physics Institute

Date: November 23, 2005

Signature: Dr. Rimantas Miškinis

Annex 5: Measurement results for traveling standard no: BEV01

Measurand: time interval $\boldsymbol{T}_{\mathrm{X}}(i)$ for measuring cable lengths:
All figures are in µs.

cable length	$\boldsymbol{T}_{\mathrm{X}}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_{\mathrm{X}})$	eff. degree of freedom n_{eff}
3 m	*0.0204*	*0.0001*	*>1000*
10 m	*0.0486*	*0.0001*	*>1000*
35 m	*0.1760*	*0.0001*	*>1000*

Participating laboratory: Semiconductor Physics Institute

Date: November 23, 2005

Signature: Dr. Rimantas Miškinis

Appendix A.METAS

Dudle Gregor 30.06.2006

EUROMET Complementary Comparison TF-TI-K1

Measurement Report from METAS

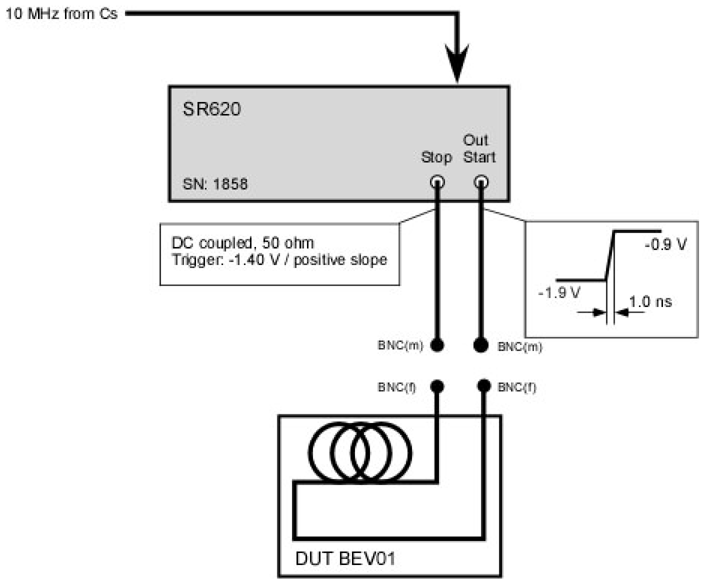
Table of content

1. Description of the measurement setup, Part A
2. Description of the measurement setup, Part B
3. Summary of the measurement results for traveling standard no: BEV01
4. Definition of the symbols and details of the computation
5. Summary cable "3 m"
6. Summary cable "10 m"
7. Summary cable "35 m"

1. Description of the measurement setup, Part A

METAS reference of the measurement setup: 119.21, Calibration of cable delay

Block diagram



Picture

Participating laboratory: METAS

Date: 22-Sept-2005

Signature

2. Description of the measurement system, Part B

1. Measuring system

Type of TIC used:	Stanford Research SR 620
Is the TIC independent of other national measurement laboratory (NML) ?	yes
If **not** independent, please give the name of NML	-
Date of last measurement in the NML	-

2. Measuring method

Number of repeated measurements:	6

3. Measurement conditions

Ambient temperature in the room in ^{o}C	(23.0 ± 1.0) °C
Ambient humidity in the room in %	50 %rH

Participating laboratory: METAS

Date: 22-Sept-2005

Signature

3. Summary of the measurement results for traveling standard no: BEV01

Measurand: time interval t_{cable} for measuring cable lengths:
All figures are in ns.

cable length	t_{cable}	combined standard uncertainty $u(t_{\text{cable}})$	eff. degree of freedom n_{eff}
3 m	*20.48*	*0.19*	*1*
10 m	*48.56*	*0.27*	*1*
35 m	*174.9*	*1.1*	*1*

4. Definition of the symbols and details of the computation

Basic equation

$$t_{\text{cable}} = (1 - y)[t_{\text{CR}} - t_{\text{offset}}]$$

with

t_{cable}	time delay of the cable
y	relative frequency offset of the time base of the TIC
t_{CR}	reading on the counter
t_{offset}	residual time delay of the system reading with a DUT-cable of length “0”

Uncertainty estimation

$\boldsymbol{y}$

The relative frequency offset of the timebase of the TIC can be neglected.

$\boldsymbol{t_{\text{CR}}}$

The reading of the counter encompasses several contributions to the uncertainty.

dt_{res}	contribution due to the resolution of the counter
dt_{tj}	contribution due to the time jitter of the trigger
dt_{tl}	contribution due to dispersion of the measurement pulse across the cable (this contribution depends on the cable length)[1]

$\boldsymbol{t_{\text{offset}}}$

The uncertainty corresponding to the residual time delay of the system when a DUT-cable of length “0” is connected is obtained by a separate experiment.

---

[1] It is assumed that the delay of the cable can not be defined with an accuracy better than the spread of the test pulse as it propagates across the cable. The spread of the pulse is defined as the difference of the rise time at the input and the rise time at the output.

5. Summary for cable “3 m”

Contributions to t_{CR}

Quantity	Estimate /ns	Standard uncertainty /ns	Probability distribution/ method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution /ns	Degrees of freedom
dt_{res}	0	0.010	rect.	1	0.003	5
dt_{tj}	0	0.025	gauss	1	0.025	5
dt_{tl}	0	0.15	gauss	1	0.15	1
t_{CR}	25.21				0.16	1

Quantity	Estimate /ns	Standard uncertainty /ns	Probability distribution/ method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution /ns	Degrees of freedom
t_{CR}	25.21	0.15		1	0.16	1
t_{offset}	4.73	0.09	A	1	0.09	1
t_{cable}	20.48				0.19	1

6. Summary for cable “10 m”

Contributions to t_{CR}

Quantity	Estimate /ns	Standard uncertainty /ns	Probability distribution/ method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution /ns	Degrees of freedom
dt_{res}	0	0.010	rect.	1	0.003	5
dt_{tj}	0	0.025	gauss	1	0.025	5
dt_{tl}	0	0.15	gauss	1	0.24	1
t_{CR}	53.29				0.25	1

Quantity	Estimate /ns	Standard uncertainty /ns	Probability distribution/ method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution /ns	Degrees of freedom
t_{CR}	53.29	0.25		1	0.25	1
t_{offset}	4.73	0.09	A	1	0.09	1
t_{cable}	48.56				0.27	1

7. Summary for cable “35 m”

Contributions to t_{CR}

Quantity	Estimate /ns	Standard uncertainty /ns	Probability distribution/ method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution /ns	Degrees of freedom
dt_{res}	0	0.010	rect.	1	0.003	5
dt_{tj}	0	0.025	gauss	1	0.025	5
dt_{tl}	0	0.15	gauss	1	1.1	1
t_{CR}	179.66				1.1	1

Quantity	Estimate /ns	Standard uncertainty /ns	Probability distribution/ method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution /ns	Degrees of freedom
t_{CR}	179.7	1.1		1	1.1	1
t_{offset}	4.73	0.09	A	1	0.09	1
t_{cable}	174.9				1.1	1

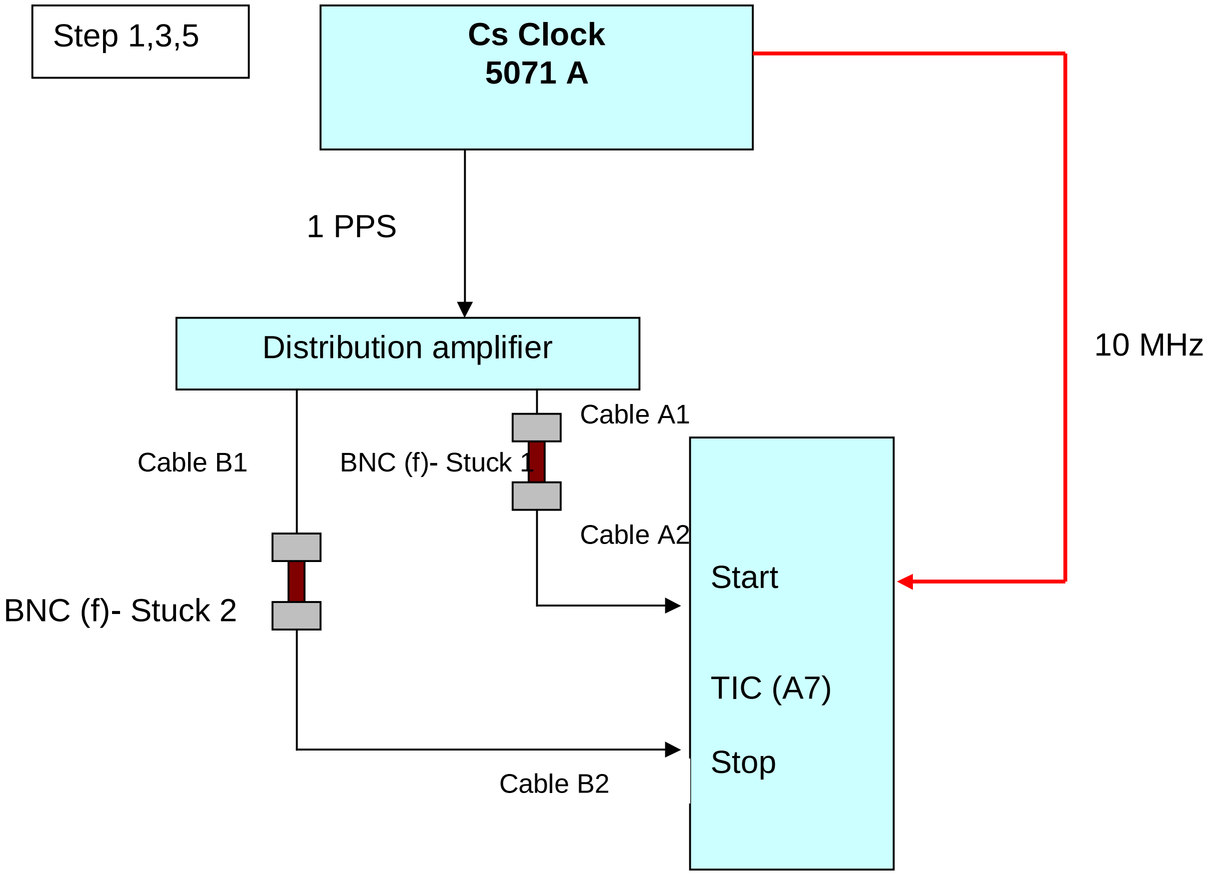
Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organiosation group.

Description of the measurement method(s) and relevant instruments:

The measurement method is directly measurement of the time delay of the cable Tx by two-channel time interval meter (counter).

The laboratory NCM uses this principle scheme:



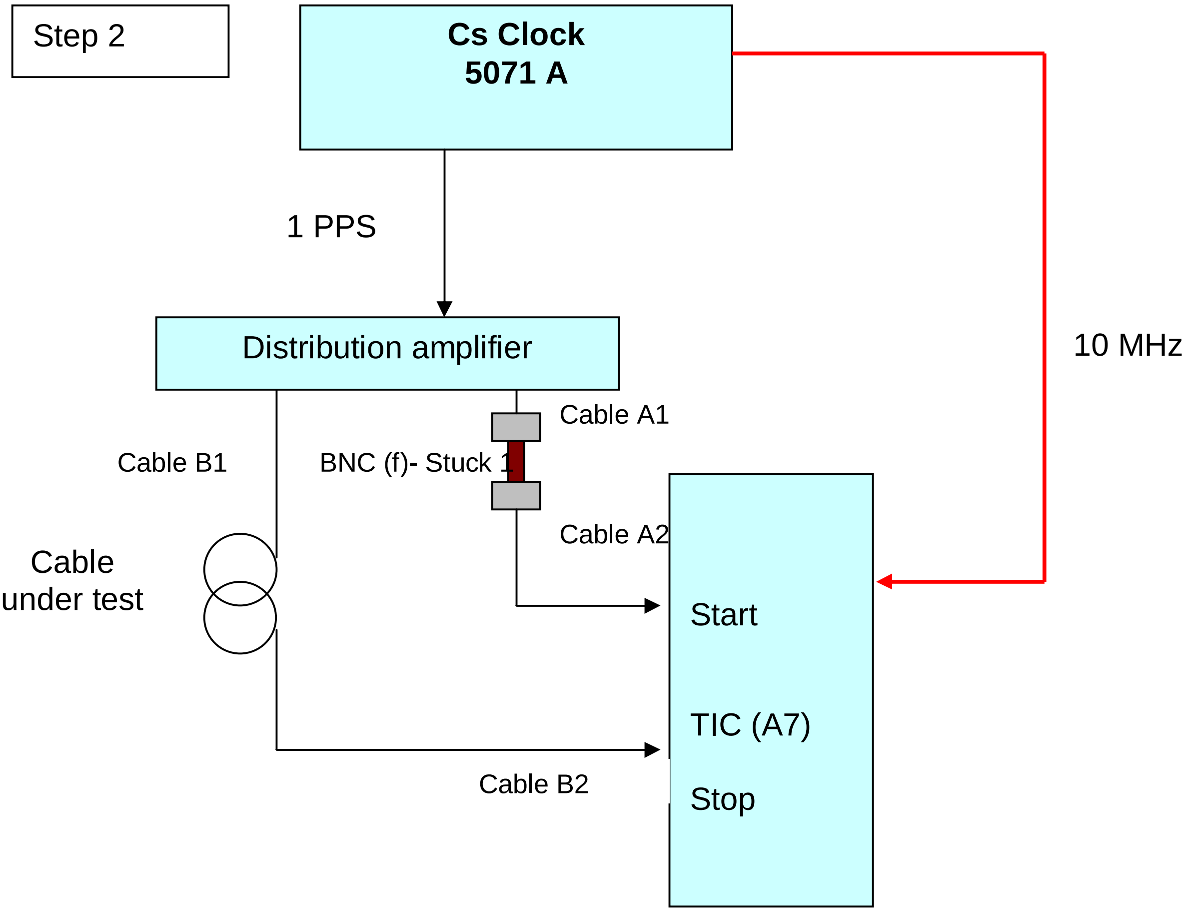
where as:

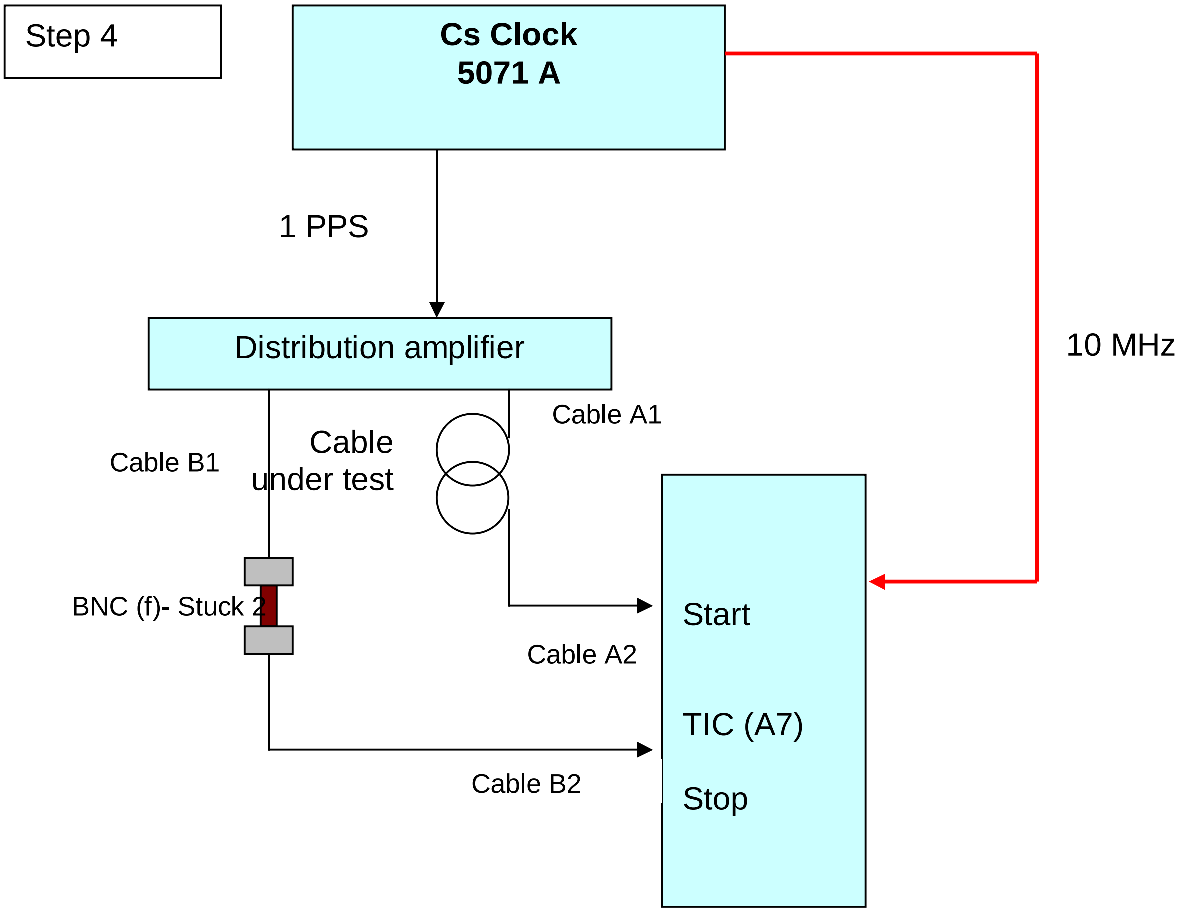
HP 5071 A is the Time and frequency national premier standard production of HEWLETT PACKARD, USA;

A 7 is a system “Frequency and Phase Comparator/calibrator with two-channel time interval counter”, production of QUARTZLOCK, UK. The two-channel time interval meter (counter) is synchronized with 10 MHz from the national premier standard;

BDA - Distribution amplifier for pulse signals

BNC (f)- Stuck for pass on of the 1PPS.


Step 2
Cs Clock
5071 A
1 PPS
10 MHz
Distribution amplifier
Cable A1
Cable B1
BNC (f)- Stuck 1
Cable A2
Cable
under test
Start
TIC (A7)
Stop
Cable B2


Step 4
Cs Clock
5071 A
1 PPS
10 MHz
Distribution amplifier
Cable A1
Cable B1
Cable
under test
BNC (f)- Stuck 2
Start
Cable A2
TIC (A7)
Stop
Cable B2

Measurement condition:

Measurements conditions are provided by air-condition and they are automatically recorded by Temperature and Humidity Recorder, digital, type “Testostor 171” production of TESTO, Austria.

Participating laboratory: NCM, Bulgaria

Date: 03.11.2005

Signature

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	A 7
Is the TIC independent of other national measurement laboratory (NML) ?	Yes, it is independent
If **not** independent, please give the name of NML	
Date of last measurement in the NML	
Date of last measurement in the NCM	26.01.2005

2. Measuring method

Number of repeated measurements:	6
Number of the measurements in one series	30

3. Measurement condition

Ambient temperature in the room in ^{o}C	22,9 ^{o}C ± 0,5 ^{o}C
Ambient humidity in the room in %	38,5 % ± 2,5 %
Temperature and Humidity Recorder, digital	type “Testostor 171”

Participating laboratory: NCM, Bulgaria

Date: 03.11.2005

Annex 5: **Measurement results for traveling standard no: BEV01**

Measurand: time interval $\boldsymbol{T}_\mathbf{X}(i)$ for measuring cable lengths:

All figures are in µs.

Level 2 V

cable length	$\boldsymbol{T}_\mathbf{X}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_\mathbf{X})$	eff. degree of freedom n_{eff}
3 m (or 4 m?)	0.02023	0.00116	infinity
10 m	0.04872	0.00116	infinity
35 m	0.17539	0.00116	infinity

Participating laboratory: NCM, Bulgaria

Date: 12/09/2006

Appendix A.NIMB

Annex 3: Measurement report A

Description of the measurement method(s) and <u>relevant</u> instruments:

The measurements of the cables delay was made using the method propose by IEN (fig.2).

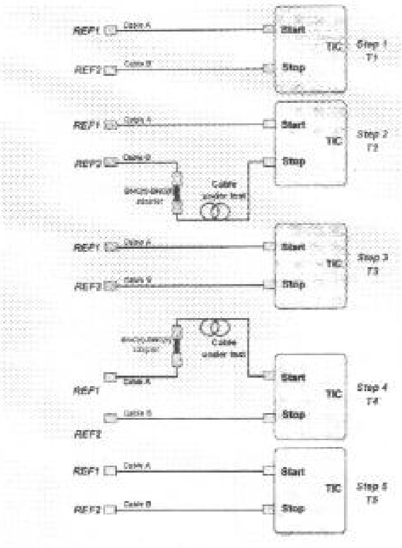


Fig. 2 – Block diagram of the DWM configuration

$$T_x = 0.5[T_2 - 0.5(T_1 + T_3) + 0.5(T_3 + T_5) - T_4)] - \tau_{adapter}$$

The references signals used were independent :

- 1pps : amplitude 2,4 V, pulse width 20 μs ± 10 ns, slew rate 1×10^9;
- 1pps : amplitude 5,0 V, pulse width 16 μs ± 1 μs, slew rate 1×10^9.

We did 6 series of repeated measurements. We estimated the adapter delay by making measurements with and without BNC(f)/BNC(f) adapter. I hope I had obtained a reliable result.
Thermohygrometer HUMLOG 10, CE 04.01-398/2004 for measuring the parameters of the ambient conditions during the measurements.

Participating laboratory: Time & Frequency Laboratory, National Institute of Metrology

Date:19.12.2005
Signature

Anca Niculescu

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	FLUKE PM 6681R
Is the TIC independent of other national measurement laboratory (NML) ?	yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	

2. Measuring method

Double Weigth Method (DWM)	
Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in °C	$23\,^{0}C \pm 1\,^{0}C$
Ambient humidity in the room in %	(34…37) %

Participating laboratory: Time & Frequency Laboratory, National Institute of Metrology

Date: 19.12.2005

Signature
Anca Niculescu

Annex 5: Measurement results for traveling standard no: BEV01

Measurand: time interval $T_x(l)$ for measuring cable lengths.

cable length	$T_x(l)$	combined standard uncertainty $u(T_x)$	eff. degree of freedom ν_{eff}
3 m	20.185 ns	0.291 ns	165431
10 m	48.319 ns	0.291 ns	165480
35 m	174.582 ns	0.290 ns	163000

Signature:

Anca Niculescu

The uncertainty budget for TIC (PM6681R)

Quantity X_i	Standard uncertainty $u(x_i)$ ns	Probability distribution/ method of evaluation	Sensitivity coefficient c_i	Uncertainty contribution $u(T_x)$ ns	Degree of freedom ν_i
$\delta T_{random\ uncert.}$	0.008	normal	1.0	0.008	∞
$\delta T_{trigger\ level\ error}$	0.016	rectangular	1.0	0.016	∞
$\delta T_{timebase\ error}$	$2.5\times10^{-10}\times TI_{measured}$	rectangular	1.0	$2.5\times10^{-10}\times TI_{measured}$	∞
$\delta T_{resolution}$	0.014	rectangular	1.0	0.014	∞
$\delta T_{channel\ mismatch}$	0.289	rectangular	1.0	0.289	∞
Standard uncertainty of TIC				0.290	∞

Standard uncertainty of the time base error is too small and it can be neglected.

The uncertainty budget for Cable 1

Quantity X_i	Estimate x_i ns	Standard uncertainty $u(x_i)$ ns	Probability distribution/ method of evaluation	Sensitivity coefficient c_i	Uncertainty contribution $u(T_x)$ ns	Degree of freedom ν_i
T_{11}	427.923	0.007	normal	- 0.25	- 0.00175	294
T_{21}	448.303	0.007	normal	+ 0.5	0.0035	294
T_{31}	427.975	0.006	normal	0	0	294
T_{41}	407.716	0.006	normal	- 0.5	- 0.003	294
T_{51}	427.940	0.007	normal	+ 0.25	0.00175	294
$T_{adapter}$	0.113	0.025	normal	-1.0	- 0.025	9
Standard uncertainty of TIC					0.290	∞
T_1	20.185				0.291	165431

Signature
Anca NICULESCU

National Institute of Metrology
Time & Frequency Laboratory

The uncertainty budget for Cable 2

Quantity X_i	Estimate x_i ns	Standard uncertainty $u(x_i)$ ns	Probability distribution/ method of evaluation	Sensitivity coefficient c_i	Uncertainty contribution $u(T_x)$ ns	Degree of freedom ν_i
T_{12}	425.471	0.007	normal	- 0.25	- 0.001873	294
T_{22}	473.997	0.009	normal	+ 0.5	0.004406	294
T_{32}	425.432	0.008	normal	0	0	294
T_{42}	377.064	0.008	normal	- 0.5	- 0.003756	294
T_{52}	425.374	0.008	normal	+ 0.25	0.002014	294
$T_{adapter}$	0.113	0.025	normal	-1.0	- 0.025	9
Standard uncertainty of TIC					0.290	∞
T_2	48.319				0.291	165480

The uncertainty budget for Cable 3

Quantity X_i	Estimate x_i ns	Standard uncertainty $u(x_i)$ ns	Probability distribution/ method of evaluation	Sensitivity coefficient c_i	Uncertainty contribution $u(T_x)$ ns	Degree of freedom ν_i
T_{13}	426.837	0.271	normal	- 0.25	- 0.068	294
T_{23}	601.741	0.304	normal	+ 0.5	0.152	294
T_{33}	426.740	0.358	normal	0	0	294
T_{43}	252.304	0.188	normal	- 0.5	- 0.094	294
T_{53}	426.743	0.202	normal	+ 0.25	0.051	294
$T_{adapter}$	0.113	0.025	normal	-1.0	- 0.025	9
Standard uncertainty of TIC					0.290	∞
T_3	174.582				0.290	163000

Signature
Anca NICULESCU

Appendix A.ZMDM

EUROMET supplementary comparison TF.TI-K1 – measurement report A

Annex 3: Measurement report A

The method for the time interval cable delay measurement, implemented at ZMDM, is the well known “Double Weight Method” (DWM) that follows the five steps procedure illustrated in Figure 1.

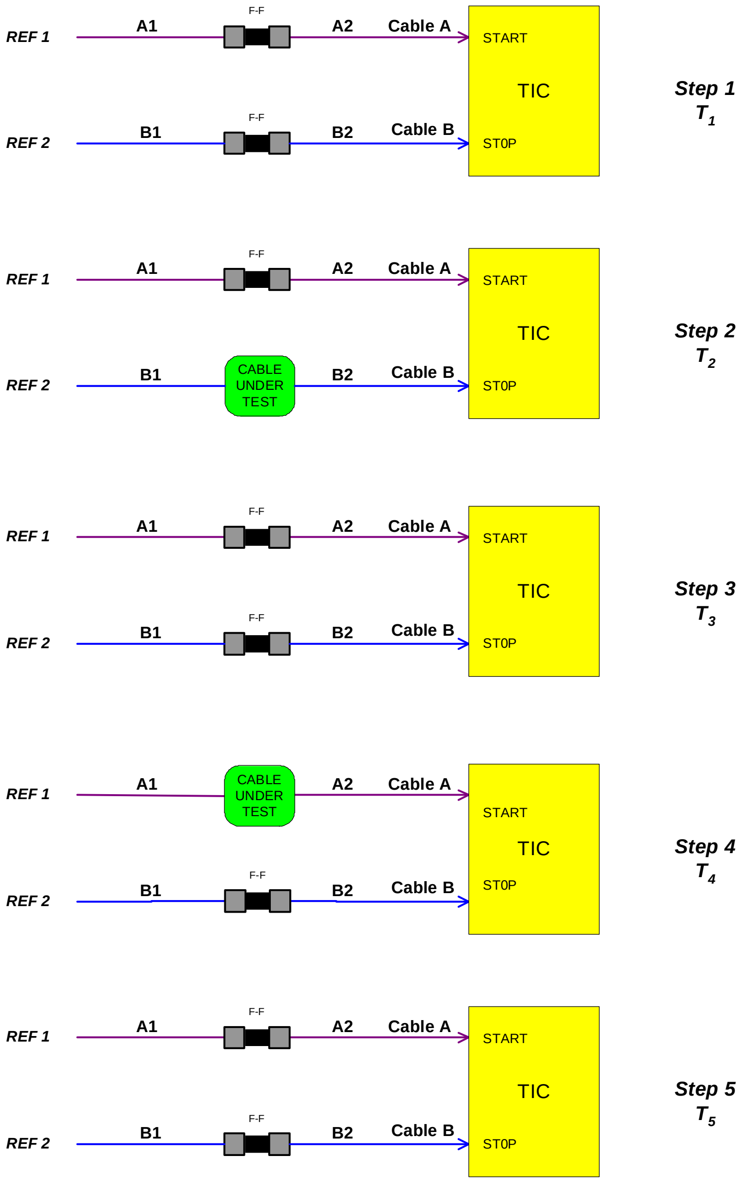


Figure 1. – Block diagram of the DWM method

The delay of the cable under test T_x, is computed from the five subsequent time interval measurements T_1, T_2, T_3, T_4 and T_5 as:

$$T_x = \frac{T_2 - \frac{T_1 + T_3}{2} + \frac{T_3 + T_5}{2} - T_4}{2} + t_{AD} \qquad (1)$$

t_{AD} being the delay of the BNC_F/BNC_F adapter.

The auxiliary cable delays (A1, A2, B1 and B2), phase difference between *REF1* and REF2 and the counter asymmetries cancel out due to the relative method.

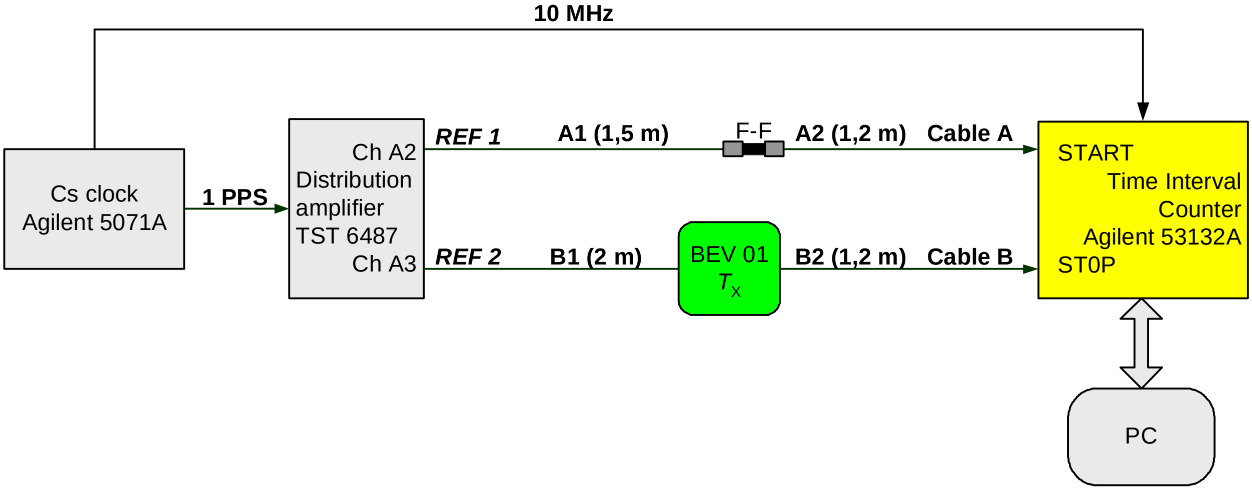


Figure 2. – Scheme of the ZMDM experimental set-up (step 2 of Figure 1).

Figure 3. Measurement equipment

The selected trigger levels of the *Start* and *Stop* channels were 54% of the signals amplitude, (about 2,5 V). In steps 2 and 4, when the cable under test was inserted, the trigger level of the *Stop* channel (step 2), i.e., *Start* channel (step 4) was reduced according to the attenuation of the cable itself, in order to preserve the same percentage of the signal amplitude. For the Cable #1, this change was equal to the trigger settability of the counter (5 mV), while for the Cables #2 and #3, it was 10 mV and 45 mV respectively.

Amplitude of the 1PPS reference signals: REF1 REF2	 from 0,00 V to 4,67 V from 0,00 V to 4,61 V
Counter trigger level (*Start* and *Stop*):	54% amplitude (about 2,5 V)
Slew rate of the input signals at trigger point:	0,9 V/ns
Input impedance:	50 Ω
Coupling:	dc
Gate time:	1 s
Averaged readings per measurement:	100
Delay of the BNC_F/BNC_F adapter:	(0,125 ± 0,010) ns

The delay of the BNC_F/BNC_F adapters was experimentally evaluated measuring the total delay of a couple of BNC_F/BNC_F + BNC_M/BNC_M adapters, using the same procedure as for cable delay measurement. Then, the single delay of the BNC_F/BNC_F adapter is computed proportionally to the electric length of the adapter. Since the reference plane of the BNC connector of the cable under test is defined at the outer end of the dielectric of BNC female connector, the electric length of *BNC_F/BNC_F* adapters is computed the same way, i.e., between ends of the dielectric.

During the period of nine days, the measurement of the cable delays has been repeated 18 times (18 sessions), to evaluate the repeatability of the results.

Participating laboratory: ZMDM - Belgrade

Date: February 16, 2006

Signature: Jadranka Marendic-Miljkovic

Annex 4: Measurement report B

1. Measuring system

Type of TIC used:	Agilent 53132A, s/n MY40001695
Is the TIC independent of other national measurement laboratory (NML) ?	YES
If **not** independent, please give the name of NML	
Reference standard (caesium clock):	Agilent 5071 Std. Opt., s/n US43452033
Pulse Distribution Amplifier:	TST 6487, s/n 8646-2186
Oscilloscope:	Tektronix, TDS 3032, s/n B018665
Date of last measurement in the NML	28.11.2005.

2. Measuring method

Number of repeated measurements:	Mean values over 100 measurements with a 1 s gate time; 5 steps per session; 18 sessions distributed over 9 days.

3. Measurement condition

Ambient temperature in the room in ^{o}C:	23 ± 0,5
Ambient humidity in the room in %:	50 ± 30
Termohygrometer type:	Cole-Parmer Ins. Co., Digi-Sense, s/n 256545

Participating laboratory: ZMDM Belgrade

Date: February 16, 2006

Signature: Jadranka Marendic-Miljkovic

Annex 5: Measurement results for travelling standard no: BEV01

Measurand: time interval $T_X(i)$ for measuring cable lengths:
All figures are in ns.

Cable length	$T_X(i)$	Combined standard uncertainty $u(T_X)$	Eff. degree of freedom n_{eff}
4 m	20,46	0,07	> 100
10 m	48,60	0,07	> 100
35 m	174,90	0,07	> 100

The uncertainty budget for the ZMDM measurements (in ns)

Quantity X_i	*Estimate* x_i	*Standard uncertainty* $u(x_i)$	*Probability distribution / method of evaluation (A, B)*	*Sensitivity coefficient* c_i	*Uncertainty contribution* $u_i(T_x)$	*Degree of freedom* ν_i
$T_{2(3)}$	177,155					
T_1	2,405					
$\partial TB(\tau)$	0,000	0,012	normal (B)	1	0,012	¥
dR	0,000	0,300	normal (B)	$1/\sqrt{100}$	0,030	¥
dT_L	0,000	0,044	normal (B)	$\sqrt{2}$	0,063	¥
dT_1	0,125	0,010	normal (A)	1	0,010	10
$T_{X(3)}$	174,875				0,072	$\nu_{eff} > 100$

The repeatability of the measured delays was investigated by making a set of measurement sessions over a period of nine days. A summary of this investigation is reported in the following table.

All figures are in ns.

Cable length	$T_X(i)$	Standard uncertainty on repeated measurements	Number of measurement sessions
4 m	20,46	0,01	18
10 m	48,60	0,02	18
35 m	174,90	0,01	18

Additional remarks

Since ZMDM has not yet submitted its CMCs, here is the explanation of the above uncertainty budget calculation.

Details of the uncertainty budget calculation

$TB(t)$	Short term (τ=1s) stability of the cesium clock 1PPS $\sigma_Y(2,\tau)= 1{,}2 \times 10^{-11}$
∂TB (τ)	$\partial TB(\tau) = T_4 \times 1{,}2 \times 10^{-11}$ = 12 ps, $T_4 \approx 1$ s. 1 s $\times 1{,}2 \times 10^{-11}$ = 12 ps
δR	Resolution of TIC, for single shot time interval measurement RES = 300 ps, (Trigger Error = ± 0,5 ps) reduced to 30 ps via averaging
δT_L	Trigger Level Timing Error= Input Hysterezis + Trigger Point Unc. due to Trigger Level Offset Input Hysterezis = $\frac{0{,}5 \times \text{Hysteresis Band}}{\text{Slew Rate at Start Trigger Point}} - \frac{0{,}5 \times \text{Hysteresis Band}}{\text{Slew Rate at Stop Trigger Point}} = 0$ Trigger Point Uncertainty due to Trigger Level offset = $\sqrt{\text{Start Trigger Level Setting Error}^2 + \text{Stop Trigger Level Setting Error}^2}$; Start Trigger Level Setting Error = Stop Trigger Level Setting Error = $\pm \frac{15\,\text{mV} \pm (1\% \times \text{Trigger Level Setting})}{\text{Slew Rate at Trigger Point}}$ = $\pm \frac{15\,\text{mV} \pm 25\,\text{mV}}{0{,}9\,\text{V/ns}}$ = ± 44 ps $\pm\sqrt{2} \times 44$ ps = ± 63 ps

$TB(t)$ - relative frequency deviation due to short term (τ) stability of time base frequency.

δR - time interval deviation due to resolution of TIC.

δT_L - time interval deviation due to trigger level timing error.

δT_1 - time interval deviation due to error in measuring residual time delay of the system

Trigger point uncertainty due to noise ($\sqrt{\text{Start Trigger Error}^2 + \text{Stop Trigger Error}^2}$) is estimated to be:

$$\pm\sqrt{2} \times \frac{\sqrt{(E_{\text{input}})^2 + (E_{\text{signal}})^2}}{\text{Slew Rate at Trigger Point}} = \sqrt{2} \times \frac{\sqrt{(0{,}35\ \text{mV})^2 + (0{,}175\,\text{mV})^2}}{0{,}9\ \text{V/ns}} = \pm\sqrt{2} \times 0{,}33\ \text{ps} = \pm 0{,}5\ \text{ps}$$

and is included in δR , according to the specification of TIC.

From January 2, 2006 year, our laboratory (with one cesium clock) is participating to TAI, and the first measurement results are included in the Circular T 217, dated February 9, 2006. According to these first results, relative frequency offset of the clock is less than 1×10^{-13}.

Participating laboratory: ZMDM Belgrade

Date: February 16, 2006

Signature: Jadranka Marendic-Miljkovic

Appendix A.UME

Measurement Report A

Cable Delay Measurement Setup is given by figure 1 and 2. Pulses from pulse generator are applied to a splitter. Outputs of splitter are connected to the channel 1 and 2 of Wide-Bandwidth Oscilloscope (WBO) in figure 1 and 2. In time interval measurements, the middle point of raised edge of the signal on channel 1 and on channel 2 are used as trigger point. The time difference between these two points is the time interval that is defined in our procedure.

The system time interval (T_1) is measured using Wide-Bandwidth Oscilloscope 86100B (WBO) with Two Channel 50 GHz Module 83484A (fig.1). Then, the time transfer standard is inserted in place of I-connector (fig.2) and each standard cable delay is measured in order. Thus first measurement is completed. In this case the model equation of the cable delay measurement system is roughly:

$$T_x = T_{2x} - T_{1x} + T_{ICON}$$

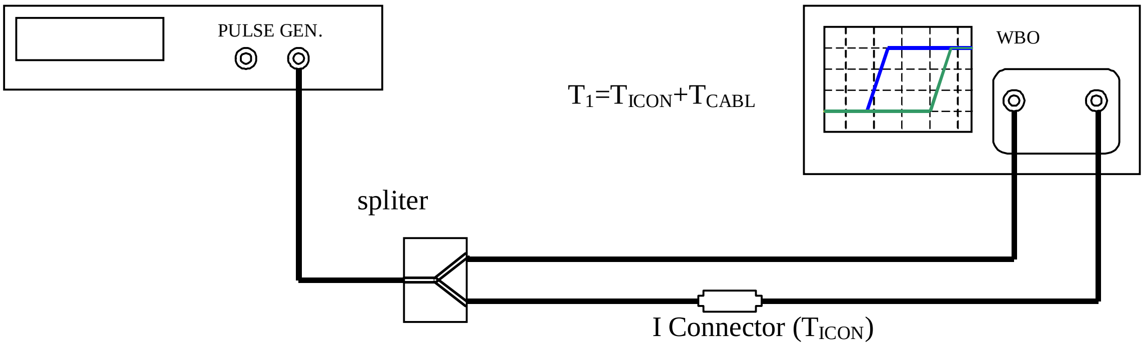


Figure 1. The Measurement Setup for T_1.

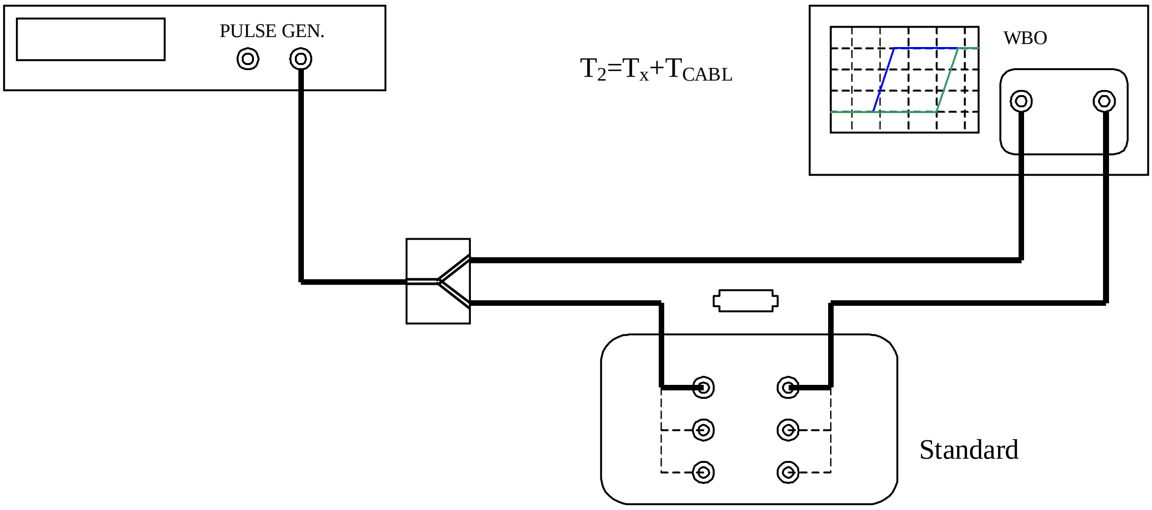


Figure 2. The Measurement Setup for T_2.

The model equation of recommended measurement system:

$$T_{1x} = T_1(1 + T_{BASE} + dT_{BASE}) + dT_{1RES}$$

$$T_{2x} = T_2(1 + T_{BASE} + dT_{BASE}) + dT_{2RES}$$

$$T_x = T_{2x} + dT_{2x} - (T_{1x} + dT_{1x}) - (T_{LCOR} + dT_{LCOR}) + (T_{ICON} + dT_{ICON})$$

The parameters in the given above model equations are demonstrated in figure 3:

T_1 : System time interval in Figure 1.
T_2 : Time interval in Figure 2.
T_{1x} : Corrected value of Time interval **T_1** in respect of **T_{BASE}.**
T_{2x} : Corrected value of Time interval **T_2** in respect of **T_{BASE}.**
T_{BASE} : Time base correction value of WBO. It's value is measured with reference frequencies.
T_{ICON} : I-connector time interval contribution. It has been measured independently.
T_{LCOR} : Level correction value. Input signal and delayed signal are trigged at same voltage level. This results from WBO. However, amplitude of input signal is bigger than delayed signal. Each signal must be trigged at the middle point of their signal amplitude. Because of WBO hasn't such a capability T_{LCOR} level correction value has been applied to T_x for each standard cable. T_{LCOR} is calculated from slew rate of **T_{1x}** with the formula:

$$T_{LCOR} = \frac{V_{2AMPL} - V_{1AMPL}}{2 \times SlewRate}$$

V_{2AMPL} **:** Amplitude of input signal.
V_{1AMPL} **:** Amplitude of delayed signal.

dT_{BASE} : Standard deviation of time base correction value of WBO.
dT_{2RES} : Resolution effect of WBO in measurement of T_2,
dT_{1RES} : Resolution effect of WBO in measurement of T_1,.
dT_{ICON} : Deviation of T_{ICON} in measurement of T_{ICON},.
dT_{LCOR} : Uncertainty of T_{LCOR} in calculation of T_{LCOR},. It also includes trigger errors.

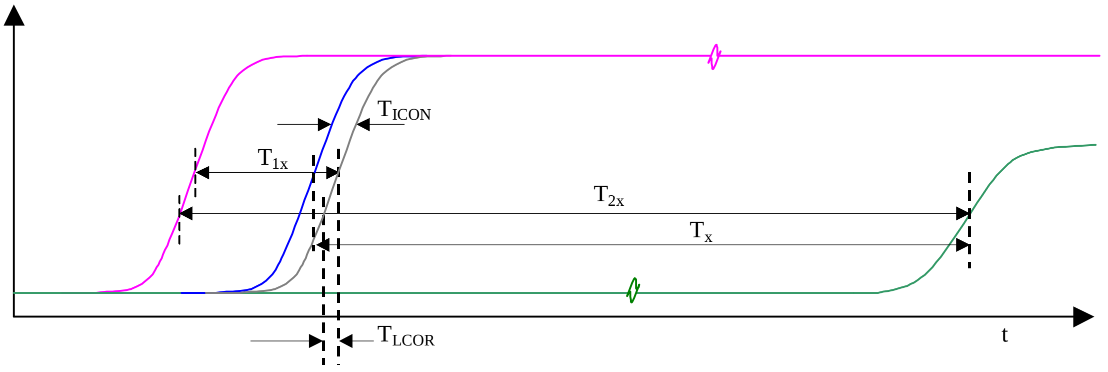


Figure 3.

Measurement Report B

1. Measuring system

Type of TIC used:	Wide-Bandwidth Oscilloscope 86100B (WBO), Two Channel 50 GHz Module 83484A
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	-
Date of last measurement in the NML	-

2. Measuring method

Wide-Bandwidth Oscilloscope and 50 GHz Module are used as TIC.	
Number of repeated measurements:	9

3. Measurement condition

Ambient temperature in the room in ^{o}C	23 ± 1 ^{o}C
Ambient humidity in the room in %	45% ± 10%

Participating laboratory: Ulusal Metroloji Enstitisu (UME)

Date:

Signature

Measurand: time interval $\boldsymbol{T}_{\mathrm{X}}(i)$ for measuring cable lengths:
All figures are in µs.

cable length	$\boldsymbol{T}_{\mathrm{X}}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_{\mathrm{X}})$	eff. degree of freedom n_{eff}
3 m	0.020404 µs	0.0000058 µs	1600
10 m	0.048485 µs	0.0000075 µs	2041
35 m	0.174766 µs	0.0000102 µs	2051

EUROMET supplementary comparison TF.TI-K1 – measurement report A

Measurement report A

<u>Equipment Used</u>: HP 5071A Primary Frequency Standard S/N US39301652; HP 5370B Universal Time Interval Counter S/N 2438A01006 (TIC); Pulse (1 PPS) Distribution Amplifier TF-3004A S/N 0000001029; Program “ReadTic”.

<u>The Method Used.</u> The delay of the cable under test was measured using the time interval counter (TIC) and two time reference signals REF1 and REF2.

The first signal REF1 (1 PPS) was taken directly from the Cs-standard output and was applied to the “START” input of the TIC.

The second signal REF2 was obtained by delay of the direct 1 PPS signal of the Cs-standard by pulse distribution amplifier. The REF2 was applied to the “STOP” input of the TIC.

The delay of the calibrated cable was estimated by the Double Weight Method (DWM). DWM is based on a five step measurement procedure. The insertion of the cable under test is performed successively on the both channels of the TIC. In this method the delay of the cable under test T_x is computed by the following formula:

$$T_x = \frac{T2 - \frac{T1+T3}{2} + \frac{T3+T5}{2} - T4}{2} - T_{ac},$$

where T1,T2,T3,T4,T5 are the five time interval measurements and every is the average of 300 measurement points; T_{ac} is the delay of the auxiliary connecting cable equal to: T_{ac} = 7.767 ns ± 0.024 ns, where 0.024 ns is the combined standard uncertainty.

Number of repeated measurements for every cable under test was 9.

Participating laboratory: **The National Physical Laboratory of Israel**

Date: 22.01.2006

Signature: Dr. Nadya Goldovsky

Measurement report B

1. Measuring system

Type of TIC used:	HP 5370B S/N 2438A01006
Is the TIC independent of other national measurement laboratory (NML) ?	The TIC is independent of other national measurement laboratory
If **not** independent, please give the name of NML	
Date of last measurement in the NML	

2. Measuring method

Double Weight Method (DWM)	
Number of repeated measurements:	9

3. Measurement condition

Ambient temperature in the room in ^{o}C	**21°C ± 1°C**
Ambient humidity in the room in %	**40% ± 10%**

Participating laboratory: **The National Physical Laboratory of Israel**

Date: 22.01.2006

Signature: Dr. Nadya Goldovsky

Measurement results for traveling standard BEV01

Measurand: time interval $\boldsymbol{T}_\mathrm{X}(i)$ for measuring cable lengths:
All figures are in µs.
Table 1.

Cable length	$\boldsymbol{T}_\mathrm{X}(i)$	Combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_\mathrm{X})$	Eff. degree of freedom n_eff
3 m	0.020 356	0.000 029	23.1
10 m	0.048 422	0.000 029	24.8
35 m	0.174 881	0.000 040	25.9

For uncertainty budget see Tables 2 – 4.

Participating laboratory: **The National Physical Laboratory of Israel**

Date: 22.01.2006

Signature: Dr. Nadya Goldovsky

Measurement results for traveling standard BEV01

Table 2. Uncertainty budget for $\boldsymbol{T}_X(1)$.

Source of uncertainty	Value u_i, s	Probability distribution	Divisor D_j	Sensitivity coefficient, C_i	Uncertainty contribution, s	V_j or V_{eff}
Short-term stability of time base frequency of the Cs-standard	4.90E-12	Normal	1.0	1.0	4.90E-11	∞
TIC resolution	2.0E-11	Rectangular	√ 12	1.0	5.77E-12	∞
Trigger jitter	2.10E-12	Normal	1.0	1.0	2.10E-12	3599
Trigger level timing error	1.17E-11	Normal	1.0	1.0	1.17E-11	8
Repeatability of the measurement results of T1	2.18E-12	Normal	1.0	1.0	2.18E-12	299
Repeatability of the measurement results of T2	1.90E-12	Normal	1.0	1.0	1.90E-12	299
Repeatability of the measurement results of T3	2.14E-12	Normal	1.0	1.0	2.14E-12	299
Repeatability of the measurement results of T4	2.05E-12	Normal	1.0	1.0	2.05E-12	299
Repeatability of the measurement results of T5	2.15E-12	Normal	1.0	1.0	2.15E-12	299
Residual time delay of the auxiliary cable Tac	2.42E-11	Normal	1.0	1.0	2.42E-11	13
Reproducibility of the measurement results of Tx(1)	2.97E-12	Normal	1.0	1.0	2.97E-12	9
Combined standard uncertainty		Normal			2.86E-11	23.1

Participating laboratory: **The National Physical Laboratory of Israel**

Date: 22.01.2006

Signature: Dr. Nadya Goldovsky

Measurement results for traveling standard BEV01

Table 3. Uncertainty budget for $\boldsymbol{T}_X(2)$.

Source of uncertainty	Value u_i, s	Probability distribution	Divisor D_j	Sensitivity coefficient, C_i	Uncertainty contribution, s	V_j or V_{eff}
Short-term stability of time base frequency of the Cs-standard	4.90E-12	Normal	1.0	1.0	4.90E-11	∞
TIC resolution	2.0E-11	Rectangular	√ 12	1.0	5.77E-12	∞
Trigger jitter	2.10E-12	Normal	1.0	1.0	2.10E-12	3599
Trigger level timing error	1.17E-11	Normal	1.0	1.0	1.17E-11	8
Repeatability of the measurement results of T1	2.18E-12	Normal	1.0	1.0	2.18E-12	299
Repeatability of the measurement results of T2	2.48E-12	Normal	1.0	1.0	2.48E-12	299
Repeatability of the measurement results of T3	2.17E-12	Normal	1.0	1.0	2.17E-12	299
Repeatability of the measurement results of T4	2.79E-12	Normal	1.0	1.0	2.79E-12	299
Repeatability of the measurement results of T5	2.13E-12	Normal	1.0	1.0	2.13E-12	299
Residual time delay of the auxiliary cable Tac	2.42E-11	Normal	1.0	1.0	2.42E-11	13
Reproducibility of the measurement results of Tx(2)	5.89E-12	Normal	1.0	1.0	5.89E-12	9
Combined standard uncertainty		Normal			2.92E-11	24.8

Participating laboratory: **The National Physical Laboratory of Israel**

Date: 22.01.2006

Signature: Dr. Nadya Goldovsky

Measurement results for traveling standard BEV01

Table 4. Uncertainty budget for $\boldsymbol{T}_{\mathrm{X}}(3)$.

Source of uncertainty	Value u_i, s	Probability distribution	Divisor D_j	Sensitivity coefficient, C_i	Uncertainty contribution, s	V_j or V_{eff}
Short-term stability of time base frequency of the Cs-standard	4.90E-12	Normal	1.0	1.0	4.90E-11	∞
TIC resolution	2.0E-11	Rectangular	√ 12	1.0	5.77E-12	∞
Trigger jitter	2.10E-12	Normal	1.0	1.0	2.10E-12	3599
Trigger level timing error	1.17E-11	Normal	1.0	1.0	1.17E-11	8
Repeatability of the measurement results of T1	2.12E-12	Normal	1.0	1.0	2.12E-12	299
Repeatability of the measurement results of T2	2.34E-12	Normal	1.0	1.0	2.34E-12	299
Repeatability of the measurement results of T3	2.33E-12	Normal	1.0	1.0	2.33E-12	299
Repeatability of the measurement results of T4	3.16E-12	Normal	1.0	1.0	3.16E-12	299
Repeatability of the measurement results of T5	2.17E-12	Normal	1.0	1.0	2.17E-12	299
Residual time delay of the auxiliary cable Tac	2.42E-11	Normal	1.0	1.0	2.42E-11	13
Reproducibility of the measurement results of Tx(3)	2.86E-11	Normal	1.0	1.0	2.86E-11	9
Combined standard uncertainty		Normal			4.04E-11	25.9

Participating laboratory: **The National Physical Laboratory of Israel**

Date: 22.01.2006

Signature: Dr. Nadya Goldovsky

Annex 3: Measurement report A

Description of the measurement method(s) and relevant instruments:

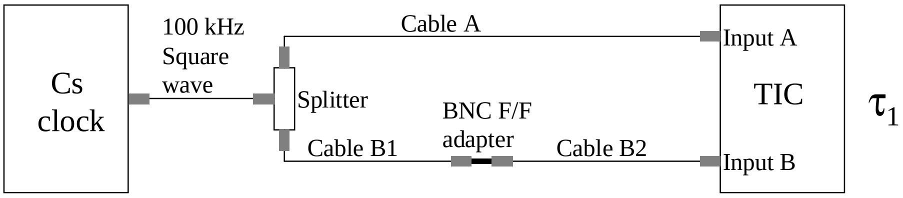
Four different measurement methods have been used to determine the cable delays, out of which methods 1 and 2 have been used as the main methods, and methods 3 and 4 have been used as supplementary methods. Delay in adapters has been measured with methods 3 and 4.

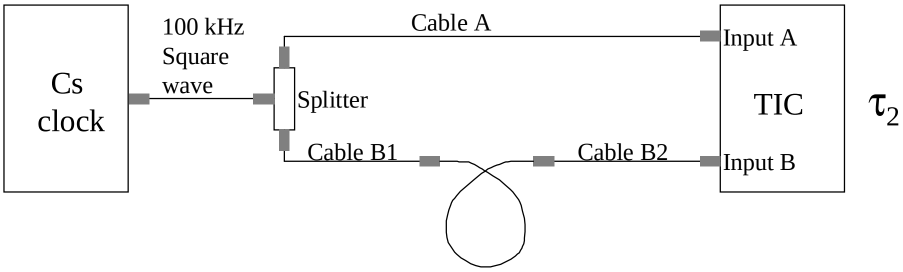
1. The simple insertion method
2. Channel reversal method
3. End reflection method
4. CW resonance method

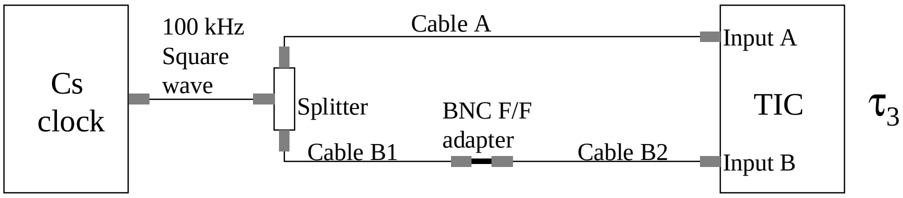
Instruments used:
Cs Clock: Datum/FTS 4065B,
Time Interval Counter: HP 5334B,
Oscilloscope: Tektronix xxxxx,
Synthesised Signal Source: Rohde&Schwarz AM300.
All cables are RG-223 with BNC connectors.

Time Interval Counter and Synthesised Signal Source have been locked to the Cs Clock.

1. Simple insertion method



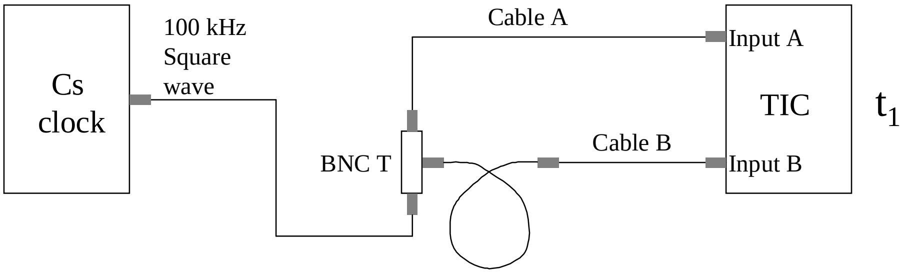


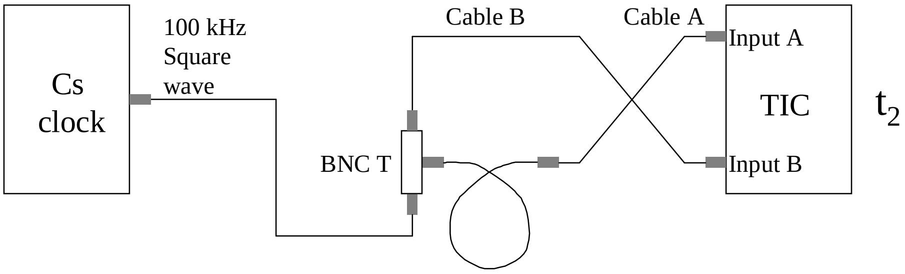


$$t = t_2 - \frac{t_1 + t_3}{2} + t_{Adapter}$$

where $t_{Adapter}$ is delay in BNC female-female adapter.

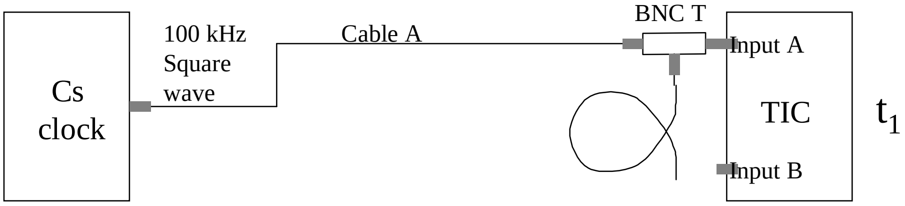
2. Channel reversal method





$t = \frac{t_1 + (T - t_2)}{2} + t_{dBNC}$, where T is period of square wave signal and t_{dBNC} is the difference in delay between two branches of BNC T. This value is estimated to be less than 20 ps, and can thus be neglected.

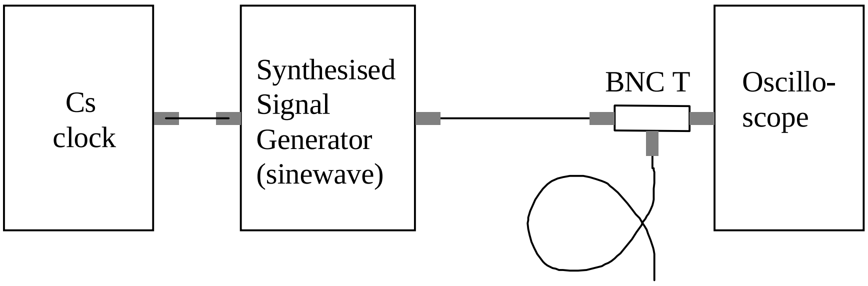
3. End reflection method



TIC input A and B connected together internally. Channel B trigger level set to trigger on reflected pulse edge.

$t = \frac{t_1}{2} - t_{BNC}$, where t_{BNC} is delay from centre to one end of BNC T.

4. CW resonance method



This method can be used to determine cable delay versus frequency. Signal source frequency f_N is tuned to make the cable under test $N*l/4$, where N is an odd integer. At these frequencies there is a minimum in the amplitude displayed on the oscilloscope. Open at far end of the cable under test is transformed into a short in the centre of the BNC T

$t = \frac{N}{4 \cdot f_N} - t_{BNC}$, where t_{BNC} is delay from centre to one end of BNC T

The cables to be measured show a significant delay variation with frequency at frequencies below about 5 MHz.

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	HP 5334B
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	N/A
Date of last measurement in the NML	N/A

2. Measuring method

Channel reversal method+ simple insertion method	
Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in ^{o}C	23 ± 1
Ambient humidity in the room in %	45 ± 5

Participating laboratory: Justervesenet, Norway

Date: March 02, 2006

Signature Kåre Lind

Annex 5: Measurement results for traveling standard no: BEV01

Measurand: time interval $\boldsymbol{T}_{\mathrm{X}}(i)$ for measuring cable lengths:
All figures are in µs.

cable length	$\boldsymbol{T}_{\mathrm{X}}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_{\mathrm{X}})$	eff. degree of freedom n_{eff}
3 m	*0,0211*	*0,0014*	*60069*
10 m	*0,0494*	*0,0014*	*38150*
35 m	*0,1761*	*0,0016*	*269748*

Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organiosation group.

Description of the measurement method(s) and relevant instruments:

Participating laboratory: MIKES, Tekniikantie 1, FIN 02150

Date:

Signature

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	Agilent 53132A
Is the TIC independent of other national measurement laboratory (NML) ?	Yes
If **not** independent, please give the name of NML	
Date of last measurement in the NML	23. 02.2006

2. Measuring method

Several methods, look report	
Number of repeated measurements:	500

3. Measurement condition

Ambient temperature in the room in ^{o}C	23
Ambient humidity in the room in %	38

Participating laboratory: MIKES, Finland

Date: 21.3.2006

Signature Kalevi Kalliomäki

Annex 5: **Measurement results for traveling standard no: BEV01**

Measurand: time interval $\boldsymbol{T}_{\mathrm{X}}(i)$ for measuring cable lengths:
All figures are in µs.

Pulse delay method, extrapolation to the beginning of the pulse

cable length	$\boldsymbol{T}_{\mathrm{X}}(i)$	combined standard uncertainty $\boldsymbol{u}(\boldsymbol{T}_{\mathrm{X}})$	eff. degree of freedom n_{eff}
3 m	*0,02037*	*0.000077*	*4*
10 m	*0,04849*	*0.000116*	*4*
35 m	*0,17446*	*0,000214*	*4*

Resonance/Phase shift method (freq. range 1...100 MHz)

Long Cable: Delay (ns) = 180.61 -5.646*log(f/MHz) +1.26*log(f/MHz) ^{2}
Medium Cable: Delay (ns) = 50.3 -1.57*log(f/MHz) +0.3*log(f/MHz) ^{2}
Short Cable Delay (ns) = 21.06 –0.66*log(f/MHz) +0.15*log(f/MHz) ^{2}

Pulse delay and phase shift methods coincide if frequency is 50 MHz

Euromet 828 “Comparison of time interval (cable delay) measurement”

Introduction

An accurate pulse delay in coaxial cable is a tricky problem if: a) the pulse itself and b) the measurement method are not carefully defined. That is the case in EUROMET 828 comparison.

The main problem is the propagation velocity dispersion. Low frequencies, e.g. 1 MHz propagate around 3 % slower than high frequencies like 100 MHz due to the skin depth. At high frequencies current flows only on the surface of any conductor. This phenomenon lowers the inductance of the center conductor in coaxial cable leading to increased phase velocity.

In practice this means, that the sharp edges of the pulses, containing high frequency components are ahead of the main pulse body. Therefore, the pulse shape is distorted. In addition, in long cables high frequency attenuation takes place, rounding the sharp edges.

Therefore, one has first to define independently the pulse shape. In our case the typical rise time of a timing pulse is 10 ns and range from 5 to 20 ns depending on the clock manufacturer and cable length. The unloaded amplitude of the pulse is from 5 to 6 V peak and from 2 to 3 V peak into 50 ohm load.

The rise times of the pulses define the required frequency band of the measurements themselves and naturally that of the measurement instruments. Minimum frequency band follows the rule of thump used in case of oscilloscopes: Rise time $t_r = 0.35 / B$. This rule leads to bandwidth of 35 MHz (10 ns pulse). However, in case of accurate measurements one has to extend the bandwidth to the most essential zero of the Fourier spectrum. i.e. $f = 1 / t_r$. Hence we concluded that 100 MHz band is quite appropriate. 1 GHz is absolutely mind-boggling.

Materials

The coaxial cables to be studied were closed to a box ("DUT"). There are three cables in the box; "Long" (≈35 m), "Medium"(≈ 10 m) and "Short"(≈ 3 m). 6 BNC-connectors are clearly marked to indicate the ends of the cables. The reference plane for delay measurements is defined to the outer end of the dielectric insulator inside the connector.

Measurement Methods

Cable resonance method.

We have earlier used with good results resonance measurements of open and short circuited cables. By measuring all resonant frequencies up to 100 MHz, we obtain both the cable delay at fixed frequencies and the delay dispersion. Because the resonances are quite sharp, the repeatability is quite good, 0,1...0,2 % rms of the delay for a single point. By combining all the results, we can easily go down to 100 ps level using this very simple method. The necessary instrumentation is a crystal controlled signal generator and an oscilloscope. Because we need only one end of the cable, we can measure delays of already installed cables.

Phase shift method

The second method we used was phase method using a crystal controlled signal generator and two channel digital oscilloscope. We simply measured all frequencies which produced zero phase difference (modulo 2□) between the ends of the cable. In this case both ends of the cable must be available. The phase error in an oscilloscope and electrical length error of connecting cables was eliminated by interchanging the channels. Thus the dominating error is "manual" zero phase detection. The error seems to be about the same as that of the resonance method. We also used carefully calibrated Network Analyzer (Agilent PNA series) to check the delays up to 1 GHz.

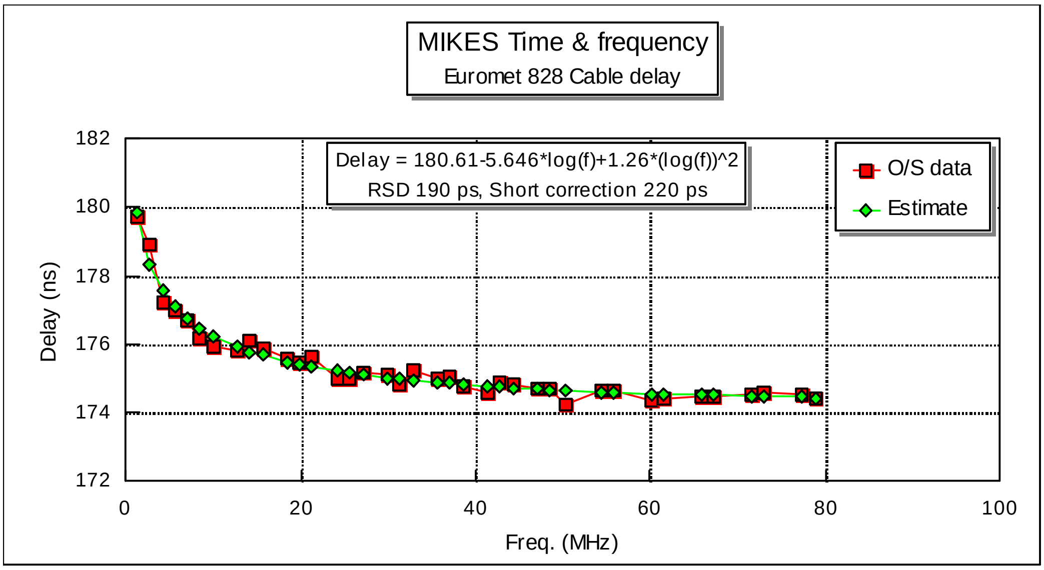


Fig. 1 Propagation delay of "long" cable as a function of frequency

Pulse delay method

Finally we tested the pulse delay method by using our automatic clock measuring system with active hydrogen maser as the main clock. After preliminary tests we had to abandon time interval methods where a separate clock was used as the pulse source because, due to random drift of a cheaper clock (like rubidium), the repeatability was worse than 100 ps.
We used the second pulse of our master clock as pulse source. The DUT was simply connected/disconnected in series with our self check channel d0 and the corresponding time change was registered automatically every second. Due to the long (~ 100m) tick cable from reference clock laboratory (underground) to the time/frequency laboratory (2nd floor), the pulse shape was nicely shaped and rounded (filtered) to fit into DUT properties, e.g. pulse shape did not change much due to the DUT anymore. Thus trigger point selection was not a problem and we could use our ordinary 1 V level.

Improving the accuracy of a time interval counter

To eliminate the nonlinearity of analog interpolators of the time interval counter (HP 53132A), we locked the counter time base to a frequency with an offset of $1\cdot10^{-9}$. This causes the counter time base to drifts 1 ns/s and the 100 ns ranges of analog interpolators are covered within 100 s. Because the measurement rate of the automatic measuring system is 1/s, we obtain 100 readings in the above-defined 100 s time. After calculating the average value of those 100 readings, the nonlinearity is compensated at any time interval value (cable delay) to be measured and the random errors are decreased by one decade. We obtained 20 ps repeatability using 300 ps rms (spec.) time interval counter.

Trigger level error

The only problem is the trigger level error, which can easily be 1000 ps in case of "Long" cable due to delay dispersion and signal attenuation.

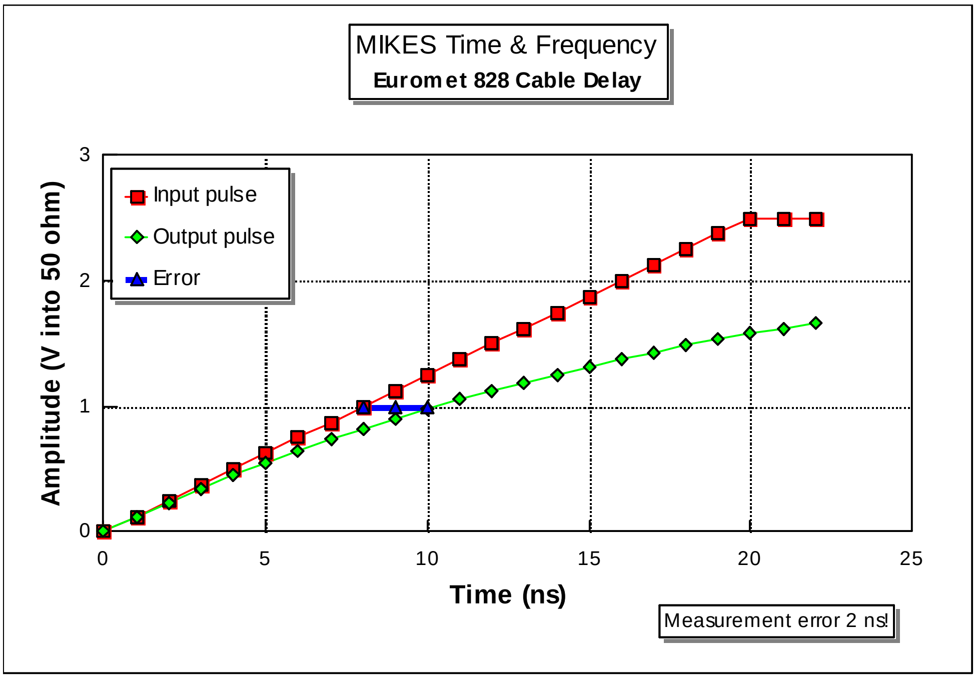


Fig 2 . The principle of measurement

Fig. 2 depicts what happens in a cable due to delay dispersion. Input pulse is idealized to correspond 20 ns rise time. Output pulse is shifted left to conveniently start from the same origin. The beginning of the output pulse corresponds the contribution of high frequency (f >1 MHz) components and the remainder that of low frequency components. Naturally some low pass filtering effect (rounding-off) exists, too, but it is marginal compared to the effect of propagation dispersion.

The horizontal bar indicates the measurement error assuming that the beginning of the pulse is the "holy" point. What else could be used as the right point?

Naturally we can't set the trigger level down to zero volts to catch the right point. However, by selecting a relatively low trigger level lowers the inherent error and eases the extrapolation of the pulse beginning. We have done this extrapolation job by studying the pulse shape with a fast digital oscilloscope (Tektronix TDS 2024, BW 200 MHz). This error dominates in case of "medium" and "long" cables.

A S-shaped pulse occurs as an output pulse in long and bad quality cables, especially if the input pulse is sharp. In this case low pass effect is significant compared to the propagation dispersion effect. As a result of this high frequency attenuation, a low "pedestal" appears at the leading edge of the pulse. In this case the extrapolation back to the beginning of the pulse is practically impossible.

It is not necessary, however, because "pedestal" represents Fourier components outside the -3 dB boundary of the propagation media. In other words, those frequency components are not in the intended pass band. This is a good reason to omit them. The simplest way to omit the pedestal is to filter the input pulse to the cable, i.e. to use rounded pulse instead of a sharp one.

Fourier spectrum of a "tick" pulse

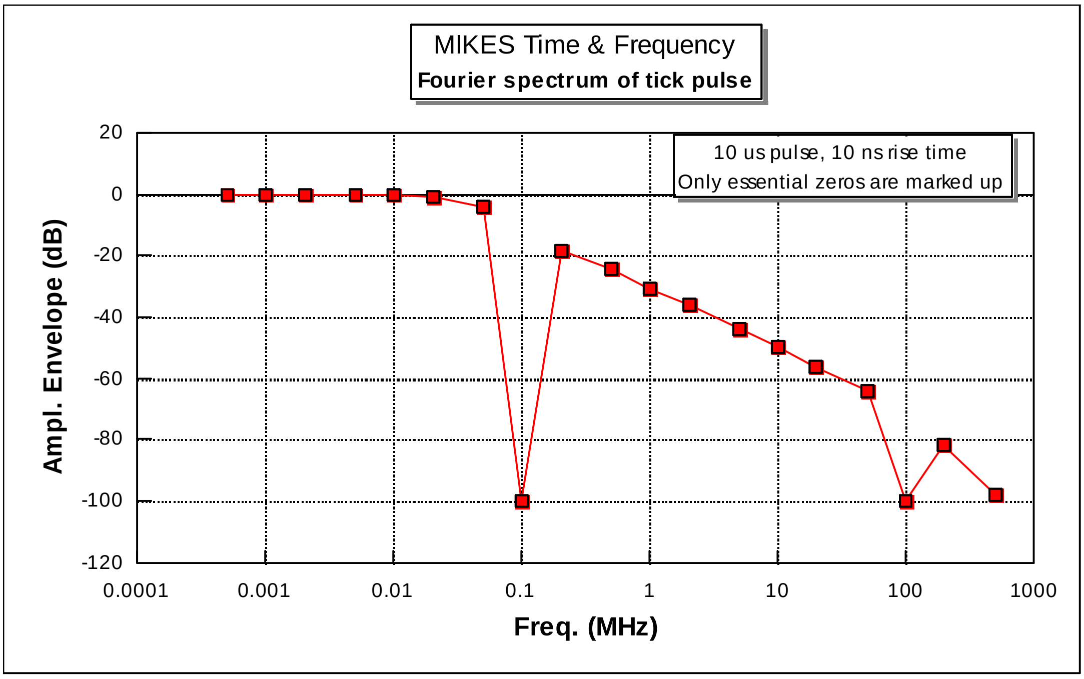


Fig 3 Fourier Spectrum of conventional tick pulse

Fig. 3 depicts the envelope of the Fourier spectrum of a conventional tick pulse. Two essential zeros are marked up. The first one (100 kHz) corresponds pulse width τ ($f = 1/\tau$) and second one (100 MHz) corresponds rise time t_r ($f = 1/ t_r$). The actual spectra up to 50 MHz can be calculated from well known sin(x)/x equation.

Frequency components up to 100 kHz ($f = 1/\tau$) define the basic “body” of the pulse. Components between 100 kHz and 100 MHz define the edges (rise & fall times). Because the spectrum follows 1/f –law, all components are important. The sum of those 1/f components approaches infinity when f increases without any limit. Amplitudes of frequency components after 100 MHz follows $1/f^2$ -law and they have only slight effect on pulse edges.

Results

In the following tables uncertainty evaluation and measurement results are given.
BNC I-connector was as a reference, when DUT was disconnected from the automatic measurement system. "T.Level A" means random components due to noise, jitter etch. "T.Level B" means evaluation of the difference between pulse beginning and 1 V (trigger) level using an oscilloscope. One has to note that this result (Estimate) depends very significantly on the rise time of a test pulse. Sharp pulse increases this estimate. Test pulse has to “match” the bandwidth of the DUT.
Due to laboratory conditions temperature and humidity are stable. Therefore, we have not evaluated corresponding effects. By contrast, atmospheric pressure varies in laboratories. Pressure sensitivity coefficient like - 0.9 ps/mbar (long cable) is based to our earlier experience. In pulse case it seems to be dwarfed by other effects.

Long	cable				
Quantity	Estimate ps	Standard Uncertainty	Sensitivity Coefficient	Contribution ps	Remarks
I-connector	80	20	1	20	
TIC 53132	0	22	1	22	N = 100
T.Level A	0	68	1	68	
T.Level B	1100	200	1	200	
Pressure	1000 mbar	10 mbar	-0.9 ps/mbar	-9	
Result	174.46 ns		Uncertainty	214 ps	

Medium	cable				
Quantity	Estimate ps	Standard Uncertainty	Sensitivity Coefficient	Contribution ps	Remarks
I-connector	80	20	1	20	
TIC 53132	0	22	1	22	N = 100
T.Level A	0.00	50	1	50	
T.Level B	300	100	1	100	
Pressure	1000 mbar	10 mbar	-0.3 ps/mbar	-3	
Result	48.49 ns		Uncertainty	116 ps	

Short	cable				
Quantity	Estimate ps	Standard Uncertainty	Sensitivity Coefficient	Contribution ps	Remarks
I-connector	80	20	1	20	
TIC 53132	0	22	1	22	N = 100
T.Level A	0.00	47	1	50	
T.Level B	180	50	1	50	
Pressure	1000 mbar	10 mbar	-0.1 ps/mbar	-1	
Result	20.37 ns		Uncertainty	77 ps	

Appendix A.NMi/VSL

Comparison of time interval (cable delay) measurement
EUROMET supplementary comparison TF.TI-K1

Results of NMi-VSL

E.J. Kroon and J. de Vreede

Nederlands Meetinstituut
Van Swinden Laboratorium
Department of Electricity

Delft, 27 June 2006

Table of contents **Page**

1 Introduction 153
2 Method of measurement 153
  2.1 Time difference measurement 153
  2.2 Measurement using Pulse shaped signal 153
3 Measurement conditions 155
4 Results 155
5 Detailed uncertainty budget 156
  5.1 Uncertainty Budget for Short cable 156
  5.2 Details 157
  5.3 Medium and long cable 159
  5.4 Uncertainty budget following technical protocol 161
6 Other measurements 162
  6.1 CW measurement 162
  6.2 TDR Measurement 162
  6.3 Using a Vector Network Analyser (VNA) 163

INTRODUCTION

This is the report of NMi-VSL of the Euromet cable delay measurements. There are three cables enclosed in a box ‘Travelling Standard’. The primarly measurement is done by a pulse shaped signal and an interval counter. Secondary measurements are done using a Continus Sine Wave form (CW), Time Domain Reflection (TDR) and using a Vector Network Analyzer (VNA).

METHOD OF MEASUREMENT

TIME DIFFERENCE MEASUREMENT

At NMi-VSL, we use the Time difference measurement procedure (S_EL_TF_001) to measure the delay of the cables. It is based on a time interval measurement using an interval counter. To connect the travelling standard using cables, we have to correct for the extra delay. For the delay measurements we use a pulse shaped signal in a 50Ω system. Additional measurements are made using a CW signal, measuring the phase delay on a frequency of 70 MHz. Also a Time Domain Reflection (TDR) measurement is done.

MEASUREMENT USING PULSE SHAPED SIGNAL

The measurement is done by making a ‘null’ measurement following by inserting the travelling standard and measure the time delay. The connection is for the ‘null’ measurement is shown in figure 1.

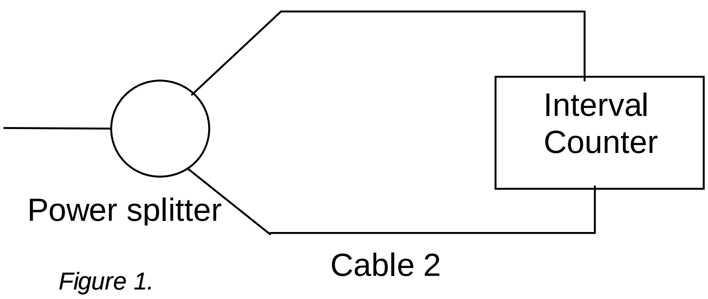


Figure 1.

The delay measurement is done inserting the travelling standard and measure the time delay. The connection is for the ‘delay’ measurement is shown in figure 2.

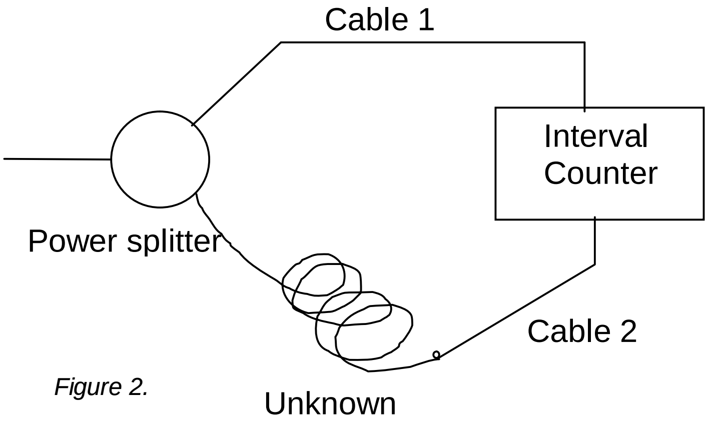


Figure 2.

The calculation for the delay is:

$$T_x = T_{delay} - (T_{null} + T_{extra})$$

Where: T_x = unknown delay

T_{delay} = value off all delays

T_{null} = delay of connection cables

T_{extra} = delay of extra adapters not measured at T_{null}

MEASUREMENT CONDITIONS

A summary of the measurement conditions is given in Table 1.

Table 1 Measurement conditions with the uncertainties (*k* = 2)

	Average	Minimum	Maximum	Uncertainty
Temperature	23.2 °C	22.9 °C	23.4 °C	0.3 °C
Humidity	33.2 %	23.2 %	43.3 %	5.0 %

RESULTS

Time delay using pulse signal (see technical report 2.3.1).

Table 2 Measurement results with the uncertainties (*k* = 2)

Cable	Delay (ns)	Uncertainty (ns)
Short	20.474	0.089
Medium	48.583	0.089
Long	175.298	0.089

Time delay using CW signal at 70 MHz (see technical report 2.3.2)

Table 3 Measurement results with the uncertainties (*k* = 2)

Cable	Delay (ns)	Uncertainty (ns)
Short	19.771	0.090
Medium	48.076	0.090
Long	174.581	0.090

DETAILED UNCERTAINTY BUDGET

The uncertainty of the pulse shape measurement is explained, for other measurement methods see paragraph [0.]

UNCERTAINTY BUDGET FOR SHORT CABLE

The mode of the counter is ‘time interval A-B’ The start pulse was used on channel A and the stop pulse was used on channel B. The measurement is done 10 times. The values were averaged and used in this uncertainty budget. The counter used was a Stanford Research Systems model SR620. The following values were used for the uncertainty calculation.

Rise time start signal	1.09 ns
Delta voltage rise time start	1.184 V
Noise at start signal	0.022 Vrms
Rise time stop signal	1.14 ns
Delta voltage rise time stop	1.196 V
Noise at stop signal	0.022 Vrms
Sample size	10
Measured result (T_{delay}-T_{null})	20.050 ns
Standard deviation	3.73 ps

Standard values for SR620 at VSL ($k = 1$):

Internal noise	350 µVrms	Specification
Trigger level error A <	10 mV	Calibrated
Trigger level error B <	10 mV	Calibrated
Time base Error	$1\cdot10^{-11}$ Hz/Hz	VSL reference short term.
Non linearity	50 ps	Specification
A-B delay uncertainty	50 ps	Calibrated
Resolution	25 ps	Specification

The ‘null’ measurement was to set the counter value to zero (T_{null}). For the next measurement the value T_{delay} is obtained. We have to correct for an extra adapter that was used to connect the travelling standard. The delay change of the adapter was calculated using the measured geometrical length of the adapter using a propagation velocity

of $2 \cdot 10^8$ m/s. The adapter has a delay change of 27.05 ps and an uncertainty of 0.05 ps ($k = 2$)

Result of Short cable:

$$T_x = T_{delay} - (T_{null} + T_{extra}) = 20.501\,\text{ns} - (0\,\text{ns} + 0.02705\,\text{ns}) = 20.474\,\text{ns}$$

DETAILS

a) Uncertainty in start trigger point due to noise:

$$\text{StartTriggerNoise} = \frac{\sqrt{(\text{internal noise})^2 + (\text{external signal noise})^2}}{\text{slewrate at start trigger point (in } {}^{\text{V}}\!/_{\text{s}})} \bullet \frac{1}{\sqrt{n}}$$

$$u_1 = \frac{\sqrt{(350\,\text{uVrms})^2 + (22\,\text{mVrms})^2}}{8.73 \cdot 10^8\ {}^{\text{V}}\!/_{\text{s}}} \bullet \frac{1}{\sqrt{10}} = 8.197\,ps$$

Remark:

The slew rate is calculated using rise time and amplitude measurement. The value is used for calculation of the trigger noise uncertainty.

$$\text{Slewrate} = \frac{90\%\ \text{voltage marker} - 10\%\ \text{voltage marker}}{\text{time marker at } 90\% - \text{time marker at } 10\%} = \frac{\Delta V}{\Delta t}$$

b) Uncertainty in stop trigger point due to noise:

$$\text{StopTriggerNoise} = \frac{\sqrt{(\text{internal noise})^2 + (\text{external signal noise})^2}}{\text{slewrate at stop trigger point (in } {}^{\text{V}}\!/_{\text{s}})} \bullet \frac{1}{\sqrt{n}}$$

$$u_2 = \frac{\sqrt{(350\,\text{uVrms})^2 + (22\,\text{mVrms})^2}}{8.37 \cdot 10^8\ {}^{\text{V}}\!/_{\text{s}}} \bullet \frac{1}{\sqrt{10}} = 8.549\,ps$$

c) Uncertainty in trigger due to start trigger level setting error:

$$\text{Start Trigger Level} = \frac{\text{trigger level error (in V)}}{\text{slew rate at start trigger piont (in } {}^{\text{V}}\!/_{\text{s}})}$$

$$u_3 = \frac{10\ \text{mV}}{8.73 \cdot 10^8\ {}^{\text{V}}\!/_{\text{s}}} = 6.613\ \text{ps}$$

d) Uncertainty in trigger due to start trigger level setting error:

$$\text{Stop Trigger Level} = \frac{\text{trigger level error (in V)}}{\text{slew rate at stop trigger point (in } {}^{\text{V}}\!/_{\text{s}})}$$

$$u_4 = \frac{10\ \text{mV}}{8.37 \cdot 10^8\ {}^{\text{V}}\!/_{\text{s}}} = 6.897\ \text{ps}$$

e) Uncertainty in resolution:

$$\text{resolution} = \sqrt{\frac{(\text{resolution})^2}{n}}$$

$$u_5 = \sqrt{\frac{(25\ \text{ps})^2}{10}} = 7.906\ \text{ps}$$

f) Uncertainty in time base:

$$\text{time base uncertainty} = \text{time base uncertainty UTC(VSL)} \cdot \text{measured result}$$

$$u_6 = 1 \cdot 10^{-13}\, Hz / Hz \cdot 20.05 ns \approx 0\ \text{ps}$$

Because of the small delay value the time base error is almost zero.

g) Uncertainty in linearity

$$u_7 = \frac{\text{non - linearity}}{\sqrt{3}}$$

$$u_7 = \frac{50\ \text{ps}}{\sqrt{3}} = 28.87\ \text{ps}$$

h) Uncertainty A-B delay

$$u_8 = \frac{\text{A - B delay}}{\sqrt{3}}$$

$$u_8 = \frac{50\ \text{ps}}{\sqrt{3}} = 28.87\ \text{ps}$$

Combined uncertainty:

$$dY = \sqrt{u_1{}^2 + u_2{}^2 + u_3{}^2 + u_4{}^2 + u_5{}^2 + u_6{}^2 + u_7{}^2 + u_8{}^2}$$

$$dY = \sqrt{8.197^2 + 8.549^2 + 6.613^2 + 6.897^2 + 7.906^2 + 0^2 + 28.87^2 + 28.87^2} = 44\ \text{ps}$$

Total uncertainty including standard deviation and uncertainty adapter:

$$dY_t = \sqrt{dY^2 + u_{\text{standard deviation}}{}^2 + u_{\text{adapter}}{}^2}$$

$$dY_t = \sqrt{44^2 + 3.73^2 + 0.025^2} = 44.15\ \text{ps}$$

Expanded uncertainty for *k* = 2

$$44.15\ \text{ps} \cdot 2 = 88.31\ \text{ps}$$

Result is 20.474 ns ± 0.089 ns by *k* = 2

MEDIUM AND LONG CABLE

The uncertainty of the medium and long cable is calculated as the short cable. Only the value of T_{delay} and the standard deviation is different. The different values are the table.

Medium cable:

Measured result (T_{delay}-T_{null})	48.610 ns
Standard deviation	3.23 ps

Long cable:

Measured result (T_{delay}-T_{null})	175.298 ns
Standard deviation	4.56 ps

Result of Medium cable:

$$T_x = T_{delay} - (T_{null} + T_{extra}) = 48.610\,\text{ns} - (0\,\text{ns} + 0.02705\,\text{ns}) = 48.583\,\text{ns}$$

Total uncertainty including standard deviation and uncertainty adapter for medium cable:

$$dY_t = \sqrt{dY^2 + u_{\text{standard deviation}}{}^2 + u_{\text{adapter}}{}^2}$$

$$dY_t = \sqrt{44^2 + 3.23^2 + 0.025^2} = 44.05\,\text{ps}$$

Expanded uncertainty for *k* = 2

$$44.05\,\text{ps} \cdot 2 = 88.10\,\text{ps}$$

Result is 48.583 ns ± 0.089 ns by *k* = 2

Result of Long cable:

$$T_x = T_{delay} - (T_{null} + T_{extra}) = 175.325\,\text{ns} - (0\,\text{ns} + 0.02705\,\text{ns}) = 175.298\,\text{ns}$$

Total uncertainty including standard deviation and uncertainty adapter for medium cable:

$$dY_t = \sqrt{dY^2 + u_{\text{standard deviation}}{}^2 + u_{\text{adapter}}{}^2}$$

$$dY_t = \sqrt{44^2 + 4.56^2 + 0.025^2} = 44.23\,\text{ps}$$

Expanded uncertainty for *k* = 2

$$44.23\,\text{ps} \cdot 2 = 88.46\,\text{ps}$$

Result is 175.298 ns ± 0.089 ns by *k* = 2

UNCERTAINTY BUDGET FOLLOWING TECHNICAL PROTOCOL

Model equation:

$$T_x = T_2(1 + TB(t)) + dR + dT_j + dT_L - T_1 + dT_1$$

Parameters:

TB(τ) – relative frequency deviation due to short term stability of time base frequency.

δR - time interval deviation due to resolution of TIC.

δT_j - time interval deviation due to trigger jitter.

δT_L - time interval deviation due to trigger level error

δT_1 - time interval deviation due to error in measuring residual time delay of the system.

Conversion of combined uncertainties:

$$TB(t) = u_6$$

$$dR = u_5$$

$$dT_j = \sqrt{{u_1}^2 + {u_2}^2}$$

$$dT_L = \sqrt{{u_3}^2 + {u_4}^2}$$

$$dT_1 = \sqrt{{u_7}^2 + {u_8}^2}$$

values are in ns

Quantity X_i	Estimate x_i	Standard uncerainty $U(x_i)$	distrubution	Sensitivity coefficient c_i	Uncertainty contribution $U_i(y)$
$T_2 - T_1$	20.474	0.00373	Normal	1	0.00373
TB(τ)	0	<0.001	Normal	1	<0.001
δR	0	0.007906	Normal	1	0.007906
δT_j	0	0.00118	Normal	1	0.00118
δT_L	0	0.00955	Normal	1	0.00955
δT_1	0	0.04082	Normal	1	0.04082
T_x	20.474 ns				0.044 ns
				k = 2	0.088 ns

OTHER MEASUREMENTS

CW MEASUREMENT

The delay measurement using a CW signal was taken by a Mitrex modem used for TWTFT. The frequency was 70 MHz using a Pseudo Random Noise modulation of 2.5 MHz band wide. The delay is measured by an interval counter. The effect of lower frequency (70 MHz) instead of 1 GHz should be smaller than 1%. The results are in paragraph 0. The uncertainty budget look like the one for pulse shape calibration.

TDR MEASUREMENT

The TDR measurement was preformed using a pulse generator a power splitter and a high-speed oscilloscope. One side of the cable was left open to create a reflection. The delay value was calculated form the oscilloscope using cursors measurement.

Table 4 Measurement results with the uncertainties ($k = 2$)

Cable	Delay (ns)	Uncertainty (ns)
Short	20.1	1.0
Medium	48.1	1.0
Long	173.5	1.0

USING A VECTOR NETWORK ANALYSER (VNA)

Method

A RF VNA, Hewlett-Packard model 8753E with external test set 85046A, is used both in frequency and in time domain mode. The frequency range is from “DC” to 3 GHz using a harmonic series of 801 frequencies: step size= 3.74 MHz. In the frequency domain the electrical delay is obtained using the internal function of the VNA (introducing a phase shift per MHz): the delay is shifted in such a way to get an almost frequency independent phase for the transmission up to 1 GHz. For the time domain a transformation from frequency to time is carried out, after which a suitable time span is chosen before determining the top of the transmission peak.

Measurements

The BEV box contains female BNC-connectors as ports. The VNA was calibrated for Type-N connectors. This means that an additional delay is present due to adapters from N-BNC (twice). In order to know the influence of the adapters, the two possible combinations of adapters are measured (BNC male to N-female and BNC female to N-male, and the other way around): one expect a similar delay as they are part of an accessory kit of the VNA. From this set of 4 adapters the two adapters with BNC male are used to connect the DUT to the VNA.

In Table 1 the results of the measurements in the two domains (frequency and time) are given

Table 1: Electrical delay

Cable	Phase shift – Electrical delay (ns)	TDR – Electrical delay (ns)
Short	20.337	20.32
Medium	48.254	48.23
Long	173.86	173.89

Uncertainty

The uncertainty in the electrical delay for the frequency domain is determined mainly by the variation (noise) in the phase values as function of frequency. In principle the uncertainty in phase for VNA's is only a few degrees.

For the time domain the uncertainty is mainly due to which frequency range is selected for the transformation from frequency to time. The reproducibility is of the order

of 0.01 ns.

Differences between the two VNA-methods

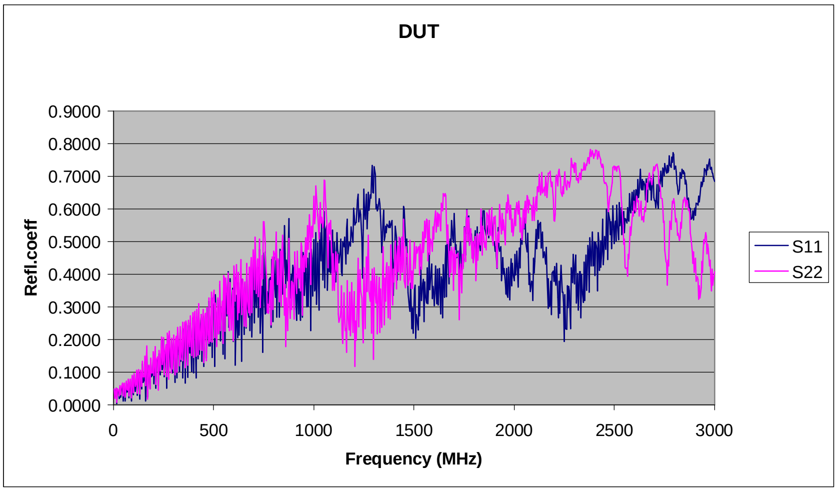
The bandwidth of the TWTF-signal is relative small. This means that a CW measurement on the electrical delay is better in line with the normal measurement set-up than a pulse measurement: the higher frequency components are dominant and could distort the signal in such a way that the result is no longer representative for a specific frequency.

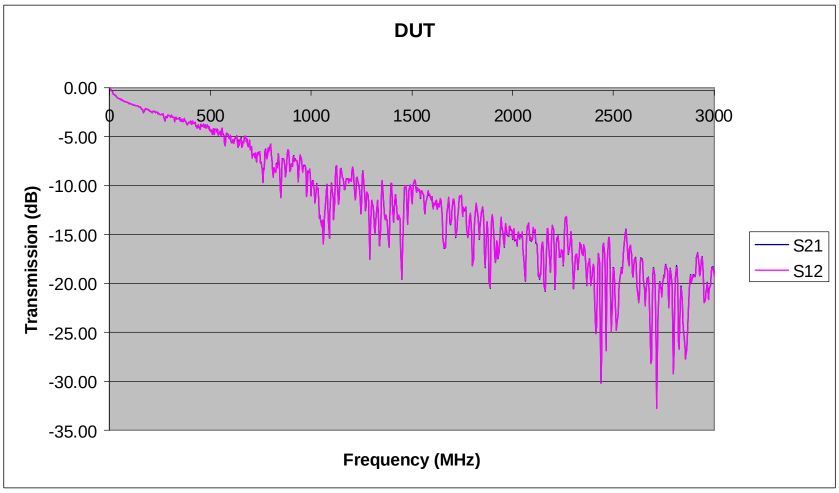
Note:

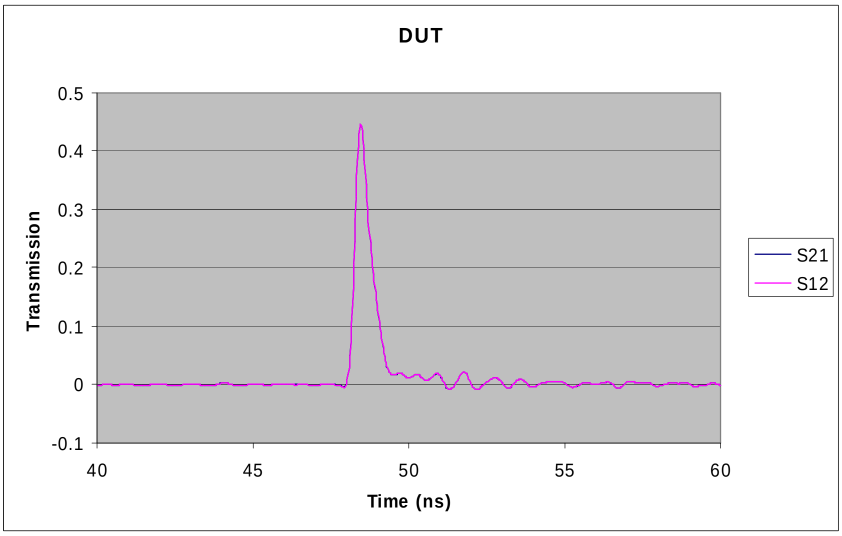
A potential source of uncertainty is the poor quality of the cables in the BEV-box: high reflection (about 0.5 at 1 GHz or VSWR=3) and a transmission which is not a smooth function of frequency. The result of measurements on the medium cable is given in Figure 3 as illustration.

Figuur 3.

Frequency domain: **DUT=** **BEV01-medium**





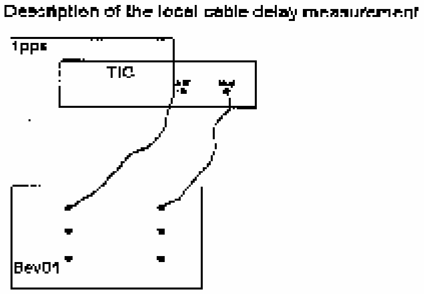


Appendix A.IPQ

Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organiosation group.

Description of the measurement method(s) and relevant instruments:



Time interval counter with 10 MHz external reference from HP 5071A

1PPS from HP 5071A via Austron Pulse Distribution 1294

Participating laboratory:IPQ

Date2006.04.11:

Signature

Fabiano Marques

2-4

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be given to be used for the final report.

1. Measuring system

Type of TIC used:	HP5370B
Is the TIC independent of other national measurement laboratory (NML) ?	YES
If not independent, please give the name of NMI.	
Date of last measurement in the NML	

2. Measuring method

TIC Method	100
Number of repeated measurements:	6

3. Measurement condition

Ambient temperature in the room in °C	22,2
Ambient humidity in the room in %	51

Participating laboratory: IPQ

Date: 2006.04.11

Signature

3-4

Annex 5: Measurement results for traveling standard no: BEV01

Measurand: time interval $T_X(l)$ for measuring cable lengths:
All figures are in µs.

cable length	$T_X(l)$	combined standard uncertainty $u(T_X)$	eff. degree of freedom ν_{eff}
3 m	*0.020168*	*0.000097*	*661*
10 m	*0.048295*	*0.000084*	*674*
35 m	*0.174682*	*0.000085*	*685*

4/6

CABLE#1				
T2	**σT2**	T1	σ **T1**	T-T2-T1
2.3218E-08	6.91E-11	3E-09	6.6E-11	2.0218E-08
2.3216E-08	6.56E-11			2.0216E-08
2.3215E-08	7.16E-11			2.0215E-08
2.3234E-08	7.43E-11			2.0234E-08
2.3209E-08	6.91E-11			2.0209E-08
2.3209E-08	6.36E-11			2.0209E-08
CABLE#2				
T2	σT2	T1	σ T1	**T-T2-T1**
5.1286E-08	4.30E-11	3E-09	6.6E-11	4.8286E-08
5.1296E-08	4.64E-11			4.8296E-08
5.1295E-08	5.23E-11			4.8295E-08
5.129E-08	5.31E-11			4.829E-08
5.1294E-08	4.67E-11			4.8294E-08
5.1294E-08	5.30E-11			4.8294E-08
CABLE#3				
T2	σT2	**T1**	σ T1	**T-T2-T1**
1.77696E-07	4.84E-11	3E-09	6.6E-11	1.7470E-07
1.77681E-07	4.97E-11			1.7468E-07
1.77688E-07	5.08E-11			1.7469E-07
1.77681E-07	4.86E-11			1.7468E-07
1.77673E-07	5.21E-11			1.7467E-07
1.77673E-07	5.15E-11			1.7467E-07

	xi	u(xi)		ci	v
T			A	1	599
δR	2.02E-11	2.31E-12	B	1	∞
δTi	7.21682E-12	7.22E-12	B	1	∞
δTj	2.02073E-12	2.02E-12	B	1	∞

5/6

	u(T)	uc(T)	
CABLE#1	9.54302E-11	9.78337E-11	
CABLE#2	8.2018E-11	8.48024E-11	
CABLE#3	8.29865E-11	8.57395E-11	

6|6

Appendix A.ROA

Annex 3: Measurement report A

In this part A of the report a free description should be given including drawings and references, whereas in part B a tabular form has to be filled out. These informations will be used to be mentioned in the final report to be prepared by the organization group.

Description of the measurement method(s) and relevant instruments.

The used method is based on six independent measurements of (100 samples) time intervals between Start and Stop pulses, by using a Universal Interval Counter SR620, of Stanford Research Systems. Also, a 4 GHz bandwidth divider of power, three RG58 cables with male BNC connectors in their ends, and two adapters (female) BNC – BNC (one of them mechanized to be convertible to F BNC – M BNC without variation in the time of internal propagation) have been used as auxiliary elements.

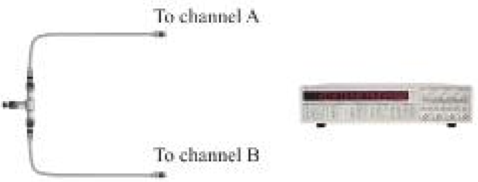
The pulse used during the calibration possesses the following features:

- 0 - 5 Volts.
- Slew rate: > 1e+9 Volts./s
- Impedance: 50 Ω.
- Signal noise: -80 dBm. Typical.

Previously, minimum and maximum trigger level for each configuration and channel were measured to determine the levels of trigger (50%) to be set along the calibration process.

They are made up to 7 sets of measures to determine the different components of delay, and in particular to estimate the bigger and most dynamic: the internal difference of delay between channels. This way the error of 0.5 ns proposed by the manufacturer is delimited and considered as a contribution to the uncertainty A type.

The setups used for the calibration are the following ones (the first one repeats again exactly before and after the calibration that includes the DUT):

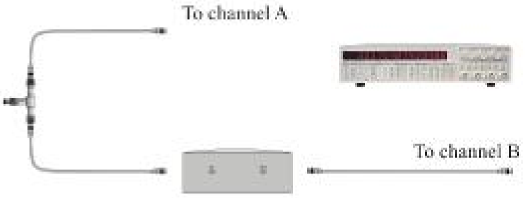


Measure 1, 5 and 7) ΔT_{AB}

Measure 2) ΔT_{ABxC}

Measure 3) ΔT_{ABxyC}

Measure 4) ΔT_{AByC}



Measure 6) ΔT_x

The measure function is the following one:

$$X = \Delta T_X + \Delta T_{AB} - \Delta T_{ABxC} + \Delta T_{ABxyC} - \Delta T_{AByC} - (1-m)\Delta T_{AB(bef)} - m\Delta T_{AB(aft)}$$

With $m = \dfrac{Time_X - Time_{(bef)}}{Time_{(aft)} - Time_{(bef)}}$.

Participating laboratory: Real Observatorio de la Armada (ROA – Spain)

Date: 24th march, 2006.

Signature:

Annex 4: Measurement report B

In this part B of the report a tabular description of the measurement system and method(s) has to be used for the final report.

1. Measuring system

Type of TIC used:	High single – shot timing resolution, low jitter, and reciprocal counting architecture.
Is the TIC independent of other national measurement laboratory (NML)?	Yes
If **not** independent, please give the name of NML.	
Date of last measurement in the NML	

2. Measuring method

Number of repeated measurements	6

3. Measurement condition

Ambient temperature in the room in ºC	23 ± 1
Ambient humidity in the room in %	50 ± 10

Participating laboratory: Real Observatorio de la Armada (ROA – Spain)

Date: 24th march, 2006.

Signature:

Annex 5: Measurement results for traveling standard nº: BEV01

Measurand: time interval $T_X(i)$ for measuring cable lengths:
All figures are in µs.

Cable length	$T_x(i)$	Combined standard uncertainty $u(T_X)$	Eff. degree of freedom ν_{eff}
3 m	20,519E-03	0,012E-03	22704
10 m	48,793E-03	0,013E-03	22681
35 m	175,965E-03	0,013E-03	23749

Participating laboratory: Real Observatorio de la Armada (ROA – Spain)

Date: 24th march, 2006.

Signature: