CIPM MRA
Comparison reports

EURAMET.TF-S1

Time interval

SUPPLEMENTARY COMPARISON

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Central Office of Measures

EURAMET

EURAMET.TF-S1
Supplementary Comparison

Comparison of time interval measurements

(EURAMET Project #1485)

Report of comparison – Final report

(Project Draft A – version 4a
approved by Participants on 26th March, 2025
Projekt Draft B – approved by TCTF on 9th May, 2025, approved by CCTF WG-MRA on 29th September, 2025)

GUM, March 3rd, 2026

Content

1 Introduction on the subject and exact definition of the measurand(s) of the comparison 3
2 Description of the scheme/topology of the comparison 4
3 Participants 4
4 Description of the transfer (travelling) standards and the handling of the equipment 5
4.1 General information 5
4.2 Description of the transfer standards 6
4.2.1 Photos 6
4.2.2 Data 7
4.2.3 Designation 8
4.2.4 Handling of the equipment 9
5 Description of the used calibration method and calibration points 9
6 Measurement conditions and equipment of each participant 12
7 The stability determination of the transfer standard(s) and required corrections (if applicable) 16
8 The participants' results, including uncertainties 18
9 Calculation of a reference value of the comparison 22
10 The degree of equivalence (DoE) of each participant with respect to the reference value 25
11 Uncertainty budget of each participant with indication of the resulting combined uncertainty 30
12 Appropriate analysis to verify if uncertainty claims correspond to those of published CMCs 30
13 First conclusions 31
14 References 36
15 Appendixes (copies of participants' measurement reports): 38

This report was mainly prepared with collaboration of the pilot laboratory (GUM – A. Czubla, Poland) and the support group consisting of: SIQ (K. Starc, Slovenia), LNE/OP (J. Achkar, France), VSL (E. Dierikx, Netherlands), NPL (P. Whibberley, United Kingdom), FTMC (R. Miskinis, Lithuania).

1 Introduction on the subject and exact definition of the measurand(s) of the comparison

a) Introduction on the subject of the comparison

The KC in TF domain (CCTF-K001.UTC) gives participating laboratories traceability to SI second by determination UTC-UTC(k) corrections, which allows to determine frequency offsets of the local timescales and clocks as well as is generally sufficient to perform time and frequency measurements correctly. However, CCTF-K001.UTC does not directly confirm the measurement proficiency in TF domain, in principle. Whereas time interval measurements are crucial for the correct calibration of time transfer systems, determination delays of signals and timing control.

This Supplementary Comparison (SC) is aimed to support CMC claims in time interval measurements. It was preceded by the experience with a cable delay measurement within #828 EURAMET Project [1], that showed that a cable delay is not well-defined measured quantity and its value is significantly dependent on the shape of signals used for cable delay measurements. For the needs of this SC, two types of TI standards were prepared within #1288 EURAMET Project [2]: (a) TI Generator (TIGen) based on PLL loops and programmable logic and counters, which can generate 127 different time intervals within the range from c. 20 ns to c. 12 μs (4 of them are chosen for this SC) and (b) 3 Delay standards (InLambda standards) based on stabilised fiber delays of c. 20 ns, c. 100 ns and c. 300 ns respectively. TI are generated by TIGen with instability and reproducibility not exceeded 3 ps of assigned expanded uncertainty and by InLambda standards with instability and reproducibility not exceeded 10 ps of assigned expanded uncertainty - verified within #1288 EURAMET Project [2].

In this comparison, GUM (Central Office of Measures, Poland) was selected as a pilot laboratory, which is responsible for preparing the technical protocol, coordinating the schedule, collecting and analysing the comparison data, and preparing the report. The support group, consisting of SIQ (Klemen Starc – instead of Borut Pinter, Slovenia), LNE/OP (Joseph Achkar, France), VSL (Erik Dierikx, Netherlands), NPL (Peter Whibberley, United Kingdom), FTMC (Rimantas Miskinis, Lithuania), support the pilot laboratory in organization of the comparison, preparation the technical protocol, data analysis and preparation the report.

The SC follows the rules described in EURAMET Guide on Comparisons – EURAMET Guide No. 4, Version 1.0 (05/2016), replaced by Version 2.0 (04/2021) [3] as well as in CIPM MRA-D-05: Measurement comparisons in the CIPM MRA [4]

b) Exact definition of the measurand(s) of the comparison

As measurands of the comparison, there were selected 7 different time intervals between the pulse signals at the START and STOP outputs of each transfer standard defined between appearing rising slopes of the pulses at the outer ends of the dielectric of the SMA connectors (for TIGen) / BNC connectors (for InLambda standards) at the START and STOP outputs at the same trigger level. The START and STOP pulse outputs were precisely matched, so the amplitude and the shape of output signals were closely the same. However, in order to avoid ambiguity:

The recommended and reference trigger level was fixed to 0,5 V (at 50 Ω).

The complete reference conditions are specified in the Table 1.

Table 1. The reference conditions

	TIGen (base unit)	InLambda standards
Warm-up time	to perform measurements after adaptation to local environmental conditions and	to perform measurements after adaptation to local environmental conditions and after the warm-up

	after the warm-up time – at least 15 min	time – until "Stabilized" diode stops blinking
External input signals	Standard freq.. 10 MHz ± 1 Hz (<1E-7 fractional frequency), (0,5 ÷ 2) V_{p-p} / 50 Ω (the increased noise of external frequency can cause the increased noise of the generated time intervals)	Pulse signals: low level – 0 V, high level – (1,75 ÷ 2,25) V / 50 Ω frequency: ≤ 200 Hz, rise time: < 10 ns (it can be applied 1 pps signals) duty cycle: ≤ 50% pulse width: to avoid the pulse widths close (<± 10 ns) to the measured time intervals (observed resonance)
Ambient conditions	Temperature: (22 ± 4) °C,	Humidity: (50 ± 30) %
Other information		Alarm diode is off Required a double configuration (as in Fig. 2c)
START and STOP Trigger level (fixed reference value)	0,5 V / 50 Ω	0,5 V / 50 Ω

2 Description of the scheme/topology of the comparison

The comparison was realized in a form of three consecutive circulation loops, each of them starting from and ending in the pilot laboratory. In each circulation loop, all transfer standards travelled together being circulated around the participants. The third circulation loop was arranged with ATA carnet.

The first loop included 10 participants, together with the pilot laboratory. The second loop included 7 participants and the third one included 7 participants.

3 Participants

Table 2. The list of participants

No	*Institute*	*Acronym*	*Country*	*Date of measurements*
1	Central Office of Measures	GUM	Poland	16-17.12.2019
2	Center for Physical Sciences and Technology	FTMC	Lithuania	27.12.2019-03.01.2020
3	VTT Technical Research Centre of Finland Ltd.	VTT MIKES	Finland	17.01.2020
4	RISE Research Institutes of Sweden	RISE	Sweden	29.01.2020
5	Physikalisch-Technische Bundesanstalt	PTB	Germany	18-20.02.2020
6	VSL	VSL	Netherlands	28.02-10.03.2020
7	FPS Economy, S.M.E.s, Self-employed and Energy Budget en Beheerscontrole	SMD	Belgium	08-12.06.2020
8	Instituto Portugues da Qualidade	IPQ	Portugal	29.06-02.07.2020

No	*Institute*	*Acronym*	*Country*	*Date of measurements*
9	Real Instituto y Observatorio de la Armada	ROA	Spain	08-09.07.2020
10	SIQ Ljubljana	SIQ	Slovenia	21-22.07.2020
End of the first loop, pilot verification measurements and beginning of the second loop				
11	Slovak Institute of Metrology	SMU	Slovakia	20-24.08.2020
12	BRML-INM	INM	Romania	09-10.09.2020
13	Bulgarian Institute for Metrology	BIM	Bulgaria	25.09.2020
14	Hellenic Institute of Metrology	EIM	Greece	06-14.10.2020
15	Bundesamt fur Eich-und Vermessungwesen	BEV	Austria	23.10.2020
16	Institut luxembourgeois de la normalisation, de l'accrėditation, de la sécuritė et qualitė des produits et sevices	ILNAS	Luxembourg	02-05.11.2020*
17	National Physical Laboratory	NPL	United Kingdom	04-07.12.2020*
End of the second loop, pilot verification measurements and beginning of the third loop				
18	TUBITAK UME	UME	Turkey	05-12.01.2021
19	Ministry of Economy – Bureau of Metrology	BoM	North Macedonia	25.02-03.03.2021
20	Directorate of Measures and Precious Metals	DMDM	Serbia	20-23.03.2021
21	Montenegrin Bureau of Metrology	MBM	Montenegro	15.04.2021
22	Institute of Metrology of Bosnia and Herzegovina	IMBIH	Bosnia and Herzegovina	20.05.2021
23	Saudi Standards, Metrology and Quality Org National Measurement and Calibration Center	SASO	Saudi Arabia	27.06.2021
24	Justervesenet	JV	Norway	10.10.2021
End of the third (last) loop and pilot verification measurements				

* - Missed one measured Time Interval (InL 20 ns had stopped working – disconnection of the DC supply connector inside, before the next loop repaired successfully, no influence for results)

4 Description of the transfer (travelling) standards and the handling of the equipment

4.1 General information

For this comparison, there were selected two types of traveling standards: TIGen – 1 item, and InLambda standards – 3 items.

A. **TIGen** is an electronic based time interval generator developed by AGH University of Science and Technology and GUM (Poland). TIGen is property of GUM. TIGen required external 10 MHz input frequency and generates 127 different time intervals between 1 pps outputs. The set of generated time intervals is determined by the applied PLL lines and programmable logic and counters. All signal inputs/outputs are ended with SMA-female connectors. TIGen is equipped with DC power supplier which has to be connected to the input terminal in the rear panel. Three auxiliary SMA-male-BNC-female adapters are attached in order to facilitate the measurements if the usage of BNC-connectors is possible only.

B. **InLambda** delay standards were developed by InLambda company (Instrumentation Technologies) in cooperation with SIQ (Slovenia) and are based on temperature stabilised fiber delays of approximately 20 ns, 100 ns and 300 ns respectively. InLambda standards are purchased and owned by SIQ. InLambda standards require external input pulses and should be used in pairs (in double configuration) – details are described in further sections precisely. Small influence of external temperature on the measured time intervals between output signals is recognized. All signal inputs/outputs are ended with BNC-female connectors. Power supplying – 230VAC, IEC C14 socket. Power cords are not attached.

No measurement cables were attached to the standards.

4.2 Description of the transfer standards

4.2.1 <u>Photos</u>

A. **TIGen**:

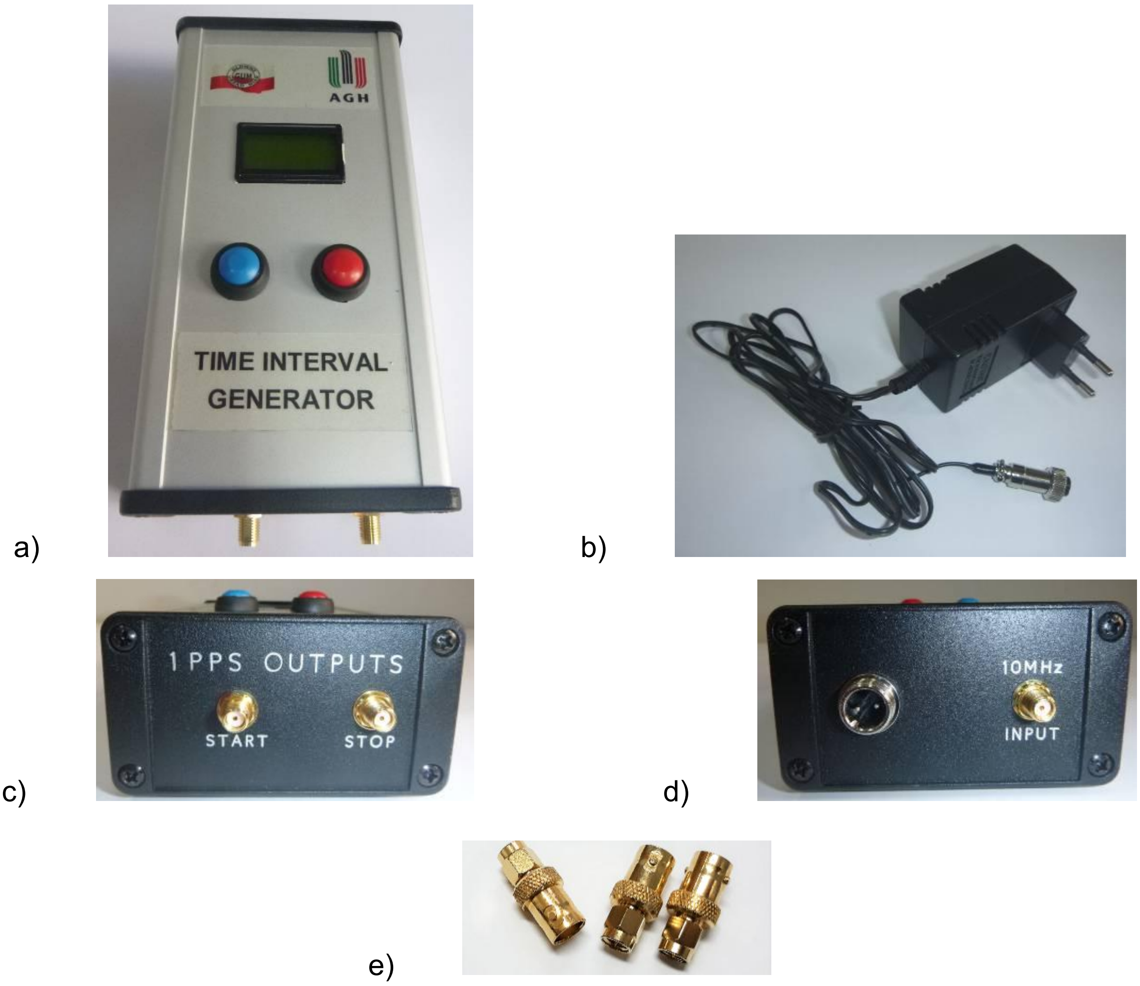


Fig 1. TIGen: a) the base unit (blue and red buttons – used for the selection of numbers of

output time intervals), b) DC power supplier, c) front panel of the base unit, d) rear panel of the base unit, e) three auxiliary SMA-male-BNC-female adapters

B. **InLambda** standards – 3 items.

a)

b)

c)

Fig 2. InLambda standards: a) front panel (1 – nominal value of delay: 20 ns, 100 ns or 300 ns, 2 – status diodes: System On, Stabilized, Alarm, 3 – input for external pulses, 4 – output of START pulses, 5 – output of STOP pulses), b) rear panel, c) required double configuration for measurements (external input pulses are passed onto the input of the auxiliary device and start output signals from the auxiliary device are passed onto the input of the device under tests (DUT))

4.2.2 Data

Table 3. Mechanical dimensions and specifications

	TIGen (base unit)	**InLambda standards**
depth x width x high	c. 18 cm x 8,5 cm x 5,5 cm	c. 26 cm x 17 cm x 6 cm (each item)
Weight	< 1000 g	<1500 g (each item)
Connectors:	SMA female connectors, 50 Ω	BNC female connectors, 50 Ω
External input signals	Standard frequency: 10 MHz ± 1 Hz (<1E-7 fractional	Pulse signals: Low level – 0 V, High level – 2 V

	TIGen (base unit)	**InLambda standards**
	frequency), (0,5 ÷ 2) V_{p-p}	
Outputs	2 x 1 pps, 2,25 V / 50 Ω	2 x pulse signals, 2 V / 50 Ω
Rise time of output pulses (20%-80%)	<0,5 ns	<0,5 ns
Number of time intervals	127 (dn0, ..., dn126)	single nominal value for every item
Range of time intervals	from about 20 ns to 12 μs	c. 20 ns for "Inλ 20" c. 100 ns for "Inλ 100" c. 300 ns for "Inλ 300"
AC Power	85-264 VAC/ (50 ÷ 60) Hz	85-264 VAC/ (50 ÷ 60) Hz
Warm-up time	15 min	< 15 min – until "Stabilized" diode stops blinking
Influence of temperature	not observed at least within: (22 ± 5) °C	when Alarm diode is off c. (0,6 ± 0,2) ps/ K for "Inλ 20" c. (1,4 ± 0,2) ps/ K for "Inλ 100" c. (2,5 ± 0,3) ps/ K for "Inλ 300" not observed difference between a single and a double configuration
Influence of the rise time of input pulses	not applicable	in a single configuration: c. 9 ps/ ns in a double configuration: not observed if rise time <10 ns c. 0,5 ps/ ns if rise time ≥10 ns
Stability, repeatability and reproducibility of the phase difference between output signals	not exceed ±3 ps (in reference conditions)	not exceed ±10 ps (in reference conditions)
Other information	Blue and red buttons: up and down buttons for selection time intervals	status diodes: System On, Stabilized (blinking until stabilization is reached),**Alarm (blinking during warm-up and overheat problems)**

4.2.3 <u>Designation</u>

A. **TIGen**:

Identification name: Time Interval Generator, Ser. No. n/a

B. **InLambda** standards:

Identification name: Time Interval Standard TIE-10

- Inλ 20 (nominal value of delay: 20 ns) Ser. No. n/a
- Inλ 100 (nominal value of delay: 100 ns) Ser. No. n/a
- Inλ 300 (nominal value of delay: 300 ns) Ser. No. n/a

4.2.4 Handling of the equipment

Before measurement the SMA and BNC connectors had to be inspected if they are clean and are not damaged. Next, it should be done the following operation:

A. (in the case of) **TIGen**:

- connect DC power supplier to DC terminal in the rear panel,
- insert the plug into 230 VAC power supply (TIGen will switch automatically and display the current number of generated time interval),
- connect external standard 10 MHz frequency signal into the 10 MHz input in the rear panel,
- using blue and red button select required number of time interval (**dn0, dn3, dn7 or dn126)**,
- check the presence of 1 pps output signals (c. 2,25 V / 50 Ω),
- wait at least 15 minutes (warm-up time).

B. (in the case of) **InLambda standards:**

- prepare 3 power cords with IEC C14 connector and connect to IEC C14 sockets in the rear panels,
- insert the plugs into 230 VAC power supply and manually switch on the InLambda standards (the manual switches are at rear panels),
- with a short cable connect the START output of one InLambda standard (auxiliary device) with the pulse input of the another InLambda standard (device under tests) creating a double configuration (as in Fig. 2c),
- prepare the source of the pulse signals, check the presence of the required parameters given in the reference conditions for InLambda standards and connect external pulse signal into the pulse input of the auxiliary InLambda standard,
- check the presence of pulse output signals (c. 2 V / 50 Ω),
- wait a few minutes until the diodes Stabilized/ Alarm stop blinking (warm-up time).

A proper measurements should be performed after adaptation of the standards to the local environmental conditions and fulfilling the required reference condition.

5 Description of the used calibration method and calibration points

a) Used calibration methods

The participants were free to choose their own method of measurement. However, it was recommended to perform measurements in such way to reduce differential channel delays of the used measurement system (Time Interval Counter, Oscilloscope, etc.) and differential delays of the used connecting cables between DUT and the used measurement system.

The measurement setups used by the participants are shown in Fig. 3 and the Table 4.

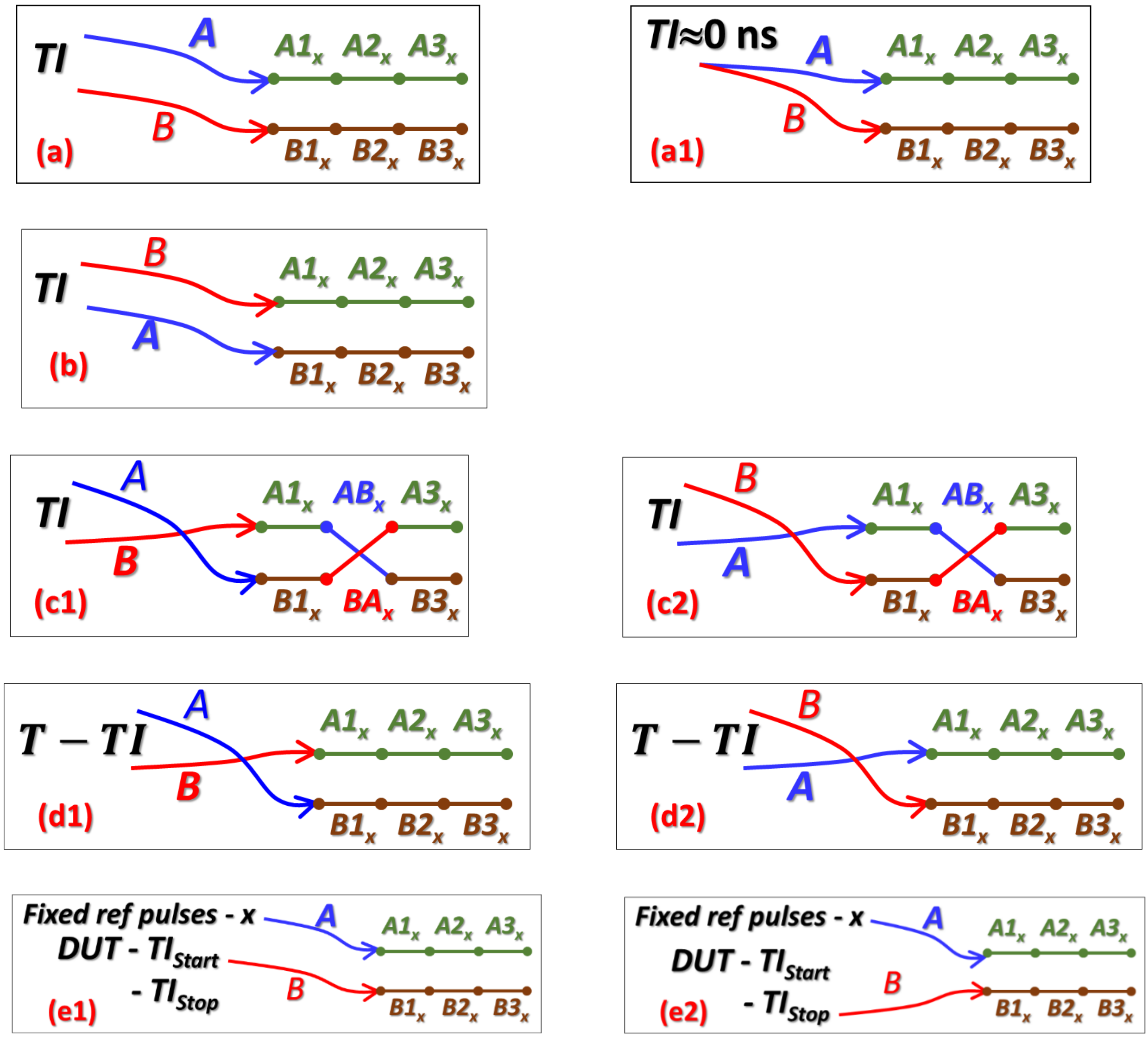


Fig 3. Illustration of the measurement setups: (a), (a1), (b), (c1), (c2), (d1), (d2), (e1) and (e2) used during calibration ($\boldsymbol{TI}$ – the measured time interval, $\boldsymbol{T}$ – period of repetition of the measured time interval, $\boldsymbol{A}, \boldsymbol{B}$ – delays of the cables applied to connect the source of Start/Stop signals with A/B channels of TIC (Time Interval Counter), $\boldsymbol{A1_x + A2_x + A3_x}$ / $\boldsymbol{B1_x + B2_x + B3_x}$ - internal delays inside A/B channels of TIC, $\boldsymbol{BA_x}$ /$\boldsymbol{AB_x}$ - crossing delays between (B and A)/ (A and B) channels during reverse direction of measurements inside TIC (from B channel to A channel))

Table 4. Measurement setups referred to schemes (a), (b), (c1), (c2), (d1), (d2), (e1) and (e2) in Fig.3 and the used base equipment (HSO means High Speed Oscilloscope)

No	*Acronym*	*Code of Lab*	*Applied method*	*Used equipment*
1	GUM	A	(a) preceded by (a) and (d2)	T4100U
2	FTMC	B	(a) preceded by (a) and (b)	SR620
3	VTT MIKES	C	(e1) and (e2)	53230A

No	*Acronym*	*Code of Lab*	*Applied method*	*Used equipment*
4	RISE	D	(a) preceded by measurement of systematic differential delays ((a1) measurement of the split pulse signal by T-connector or splitter)	PM6681
5	PTB	E	(e1) and (e2)	SR620
6	VSL	F	(a) preceded by (a) and (d1) as well as by (a) and (b) (averaged results based on 2 TICs – originally the second TIC was to be used only for control)	SR620 (x2)
7	SMD	G	(a) accompanied by measurement of systematic differential delays (not specified in details)	53230A
8	IPQ	H	(a)	SR620
9	ROA	I	(a) and (c1) averaged results based on 2 TICs	SR620 x2
10	SIQ	J	(a) and (c2) or (c1)	53230A
11	SMU	K	(a)	53132A
12	INM	L	(a)	PM6681R
13	BIM	M	(a), (c1), (b) and (c2)	CNT91
14	EIM	N	(a)	PM6681R
15	BEV	O	(a) and (b)	SR620
16	ILNAS	P	(a) and (d2)	53230A
17	NPL	Q	(a) and (b) averaged results based on 3 TICs	SR620 x3
18	UME	R	(a) and (d2)	HSO
19	BoM	S	(a) and (c2)	CNT91
20	DMDM	T	(a) and (d2)	CNT91
21	MBM	U	(a) and (c2)	53230A
22	IMBIH	V	(a)	SR620
23	SASO	W	(a)	53230A
24	JV	X	(a), (c1), (b) and (c2)	53230A

Comments to the applied measurement methods:

[1]A single (a) measurement setup – not accompanied by other measurement setups, was typically used with a pair of cables A and B of nearly the same length (with very close delays).

[2]Applying (a1) measurements of the same pulse signal split by T-connector or splitter, it allows to measure and reduce systematic differential delays of a pair of cables A and B and channels jointly. Anyway it works as well as the assumption of T-connector/splitter symmetry is maintained.

[3]Applying consecutive (a) and (b) measurement setups allowed to reduce cables asymmetry delay.

[4]Applying (a) and (d1) measurement setups allowed to reduce differential channel delay of TIC's inputs.

[5]Applying (a) and (d2) measurement setups allowed to reduce asymmetry of the cables delays and differential channel delay of TIC's inputs jointly.

[6]Applying (a) and (c1) allowed to reduce some part of differential channel delay of TIC's inputs, leaving a possible small residual delay asymmetry in TIC's inputs resulting from a possible mismatching between the normal and reverse directions of time interval measurements.

[7]Applying (a) and (c2) allowed to reduce the cables delay asymmetry and some part of differential channel delay of TIC's inputs jointly, leaving a possible small residual delay asymmetry in TIC's inputs resulting from a possible mismatching between the normal and reverse directions of time interval measurements.

[8]Consecutive (e1) and (e2) measurement setups (pivot method [5]) allowed to make the measurement not influenced by differential channels and cables delays, however this method can be valid only if the phase between ref pulses and DUTs signals is fixed during measurements and may introduced additional jitter between ref pulses and the measured DUTs signals.

[9]Most of measurements with SR620s were preceded by AUTOCAL procedure to minimise differential channel delays and optimise influence of non-linearities.

b) Calibration points

In this comparison, the following time intervals were measured:

- **dn0, dn3, dn7, dn126** (c. 20 ns, 250 ns, 1,5 μs and 12 μs) **generated by TIGen** and
- three single time intervals generated by **Inλ 20** (c. 20 ns), **Inλ 100** (c. 100 ns) and **Inλ 300** (c. 300 ns) respectively **in a double configuration** as shown in Fig. 2c.

6 Measurement conditions and equipment of each participant

The details on measurement conditions observed during measurements and applied equipment is included in the measurement reports attached as Appendixes from A to X to this report. The required reference conditions were specified in the Table 1 (Section 1.) Below, there are presented a summary in a form of graphs, comments and tables.

The ambient conditions reported by the participants are arranged in Fig. 4 and 5. In the case of ambient temperature, most of measurements were performed in the range of (23 ± 1) °C, except of two participants who carried out their measurement in the ambient temperature around 25 °C. The mean value of the reported ambient temperature amounted to 22.97 °C.

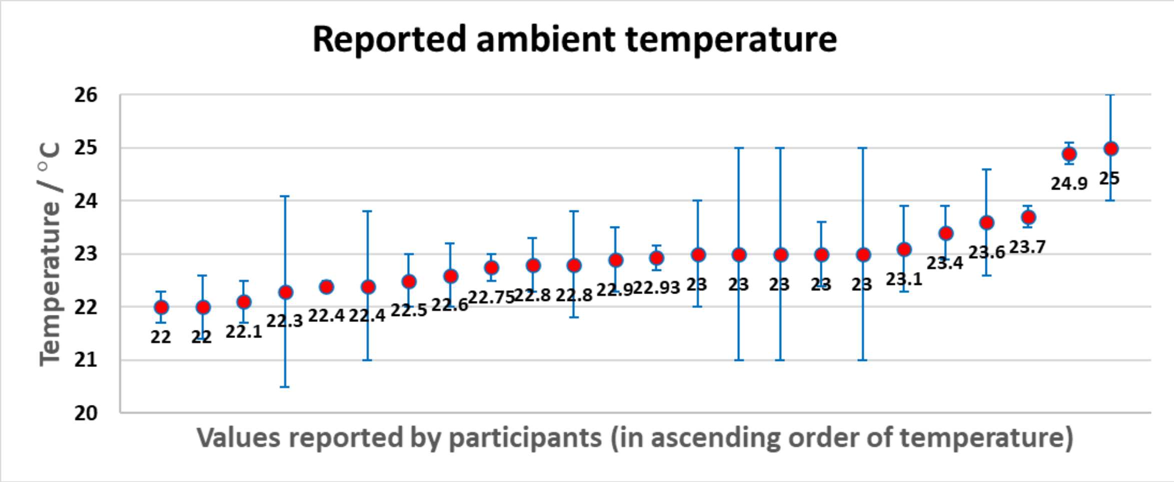


Fig. 4. Ambient temperature observed during measurements reported by participants (required reference conditions: (22 ± 4) °C)

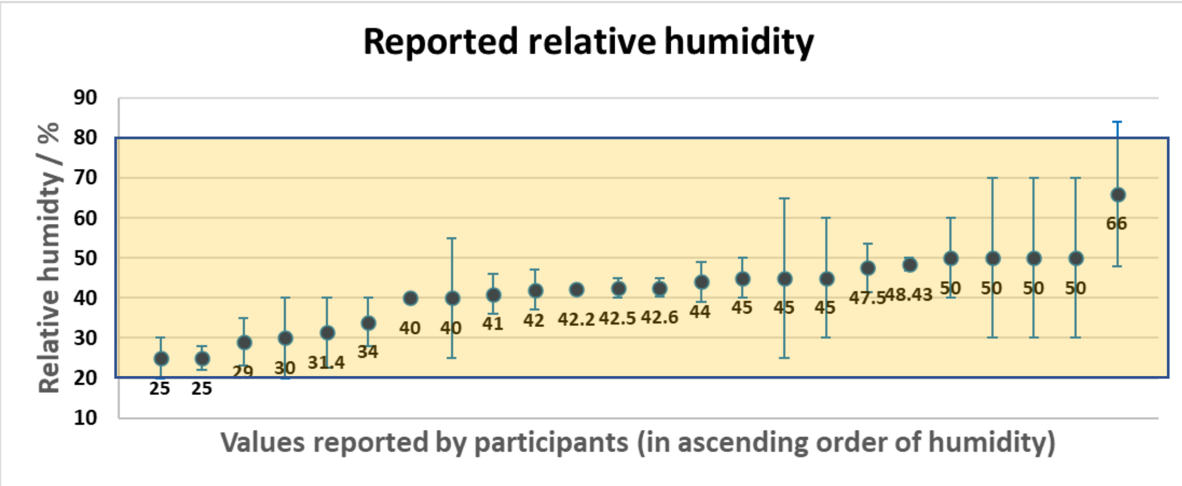


Fig. 5. Ambient relative humidity observed during measurements reported by participants (required reference conditions: (50 ± 30) %)

The reported by participants relative humidity met the assumed reference condition, with a small exception of one participant where the single reported value was given as (66 ± 18) % and possible range of changes of relative humidity exceeded the upper limit (80%) by 4%. However, during characterization of the transfer standards, there was not observed any influence of relative humidity for the results of measurement. So, the limits of the relative reference conditions has been arbitrary accepted to avoid any potential influence of wet condensation or accumulation of the electrostatic charge at surface of standards and connectors only. The obtained measurement results reported by this participant do not manifest any negative influence of a bit higher relative humidity observed during measurements.

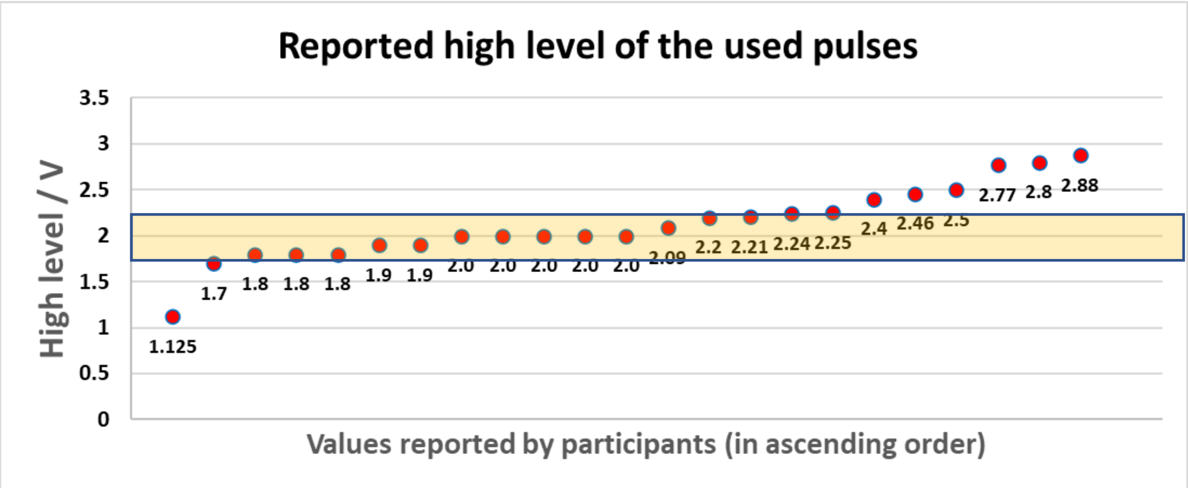
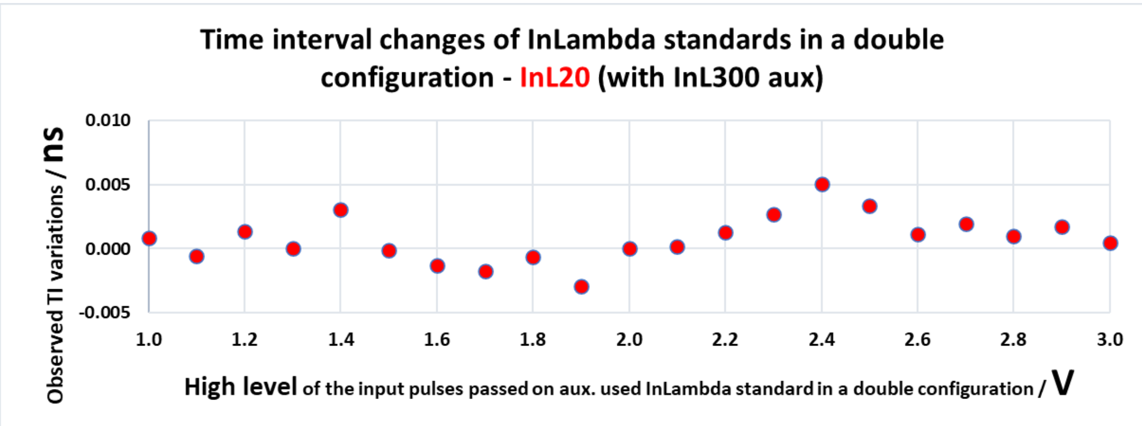


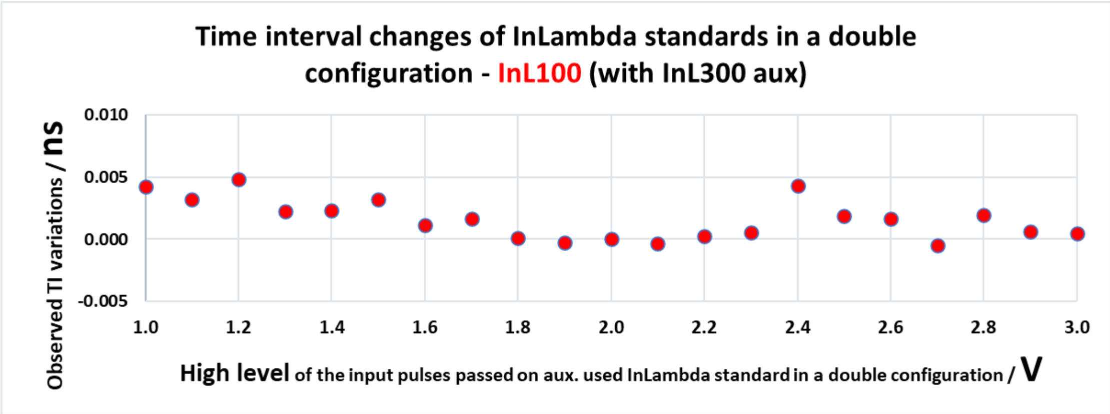
Fig. 6. Reported by participants the high level of the used pulses for pending auxiliary InLambda standards in a double configuration (required reference conditions: (1,75 ÷ 2,25) V / 50 Ω).

The reported by participants the high level of the used pulses for pending auxiliary InLambda standards in a double configuration was out of the assumed reference condition in the case of 8 participants per 24 total. However, the reference conditions for input pulses were specified originally based on a single configuration of InLambda standard, but all measurements were performed in a double configuration.

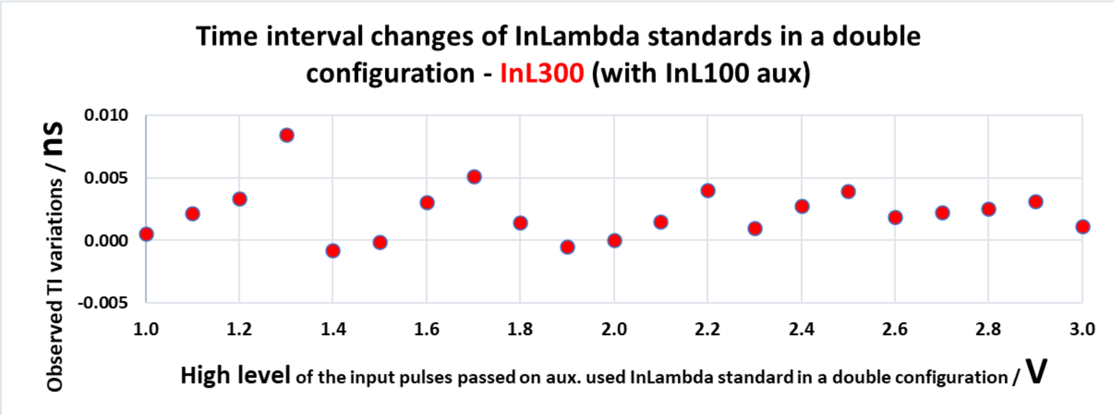
The influence of the high level pulse signals for InLambda standards in a double configuration were verified by the pilot laboratory after finishing the last comparison loop and showed in Fig. 7. The obtained results for the high level of the used pulses within the range of (1 ÷ 3) V / 50 Ω confirmed, that a double configuration of InLambda standards allows successfully to extend the reference conditions of the acceptable values of the high level of the input pulses at least up to the range of (1 ÷ 3) V / 50 Ω. There was not observed any systematic offset in the range below 1,75 V and above 2,25 V nor increased measurement noise (between 5 ps and 9 ps in all cases – a typical for the used TIC) with regard to the specified stability, repeatability and reproducibility of InLambda standards within of ± 10 ps.

a)





b)



c)

Fig.7. Results of verification measurements of the influence of the high level of the used pulses within the range of (1 ÷ 3) V / 50 Ω for InLambda standards in a double configuration (performed in March 2022). In every case, the observed TI variations were calculated with reference to TI values determined for 2 V of the high level of the input pulses.

The reported applied equipment is gathered in the Table 4 and 5. Despite the usage of the same type of equipment, different uncertainty budget's assumptions referred to different conditions was typically adopted or a different measurement configuration was applied (see: Table 4.) resulting in different treatment of uncertainty budget's components.

Table 5. The equipment applied by participants with chosen assigned standard uncertainty components related to a residual nonlinearities and other dominant not reduced systematic effects

Used brand of TICs	Number of participants applied a given TIC	Code of Lab	Declared by participants in the uncertainty budgets of measurement results	
			standard uncertainty component related to a residual nonlinearities	other dominant not reduced systematic effect (standard uncertainty components)
SR620	8	B	500 ps (with internal offsets)	20 ps (trigger level timing)
		E	50 ps	20 ps (trigger level timing)
		F	15.6 ps	50 ps (internal offsets)
		H	75 ps	289 ps (other unknown errors)
		I	50 ps	
		O	118 ps	√2 x 10 ps (trigger level timing)

		Q	250 ps (including internal offsets)	
		V	75 ps	50 ps (input filter)
53230A	7	C	50 ps (for each channel, tot. x √2)	
		G	40** ps	8.2 ps (residual internal offset)
		J		250 ps (x √2 / 2)
		P	46 ps	50 ps
		U	100 ps (accuracy)	(total - 120 ps all components)
		W	144 ps	18 ps (trigger level timing)
		X	100 ps	43 ps (input filter)
CNT91	3	M		100 ps (residual components)
		S		289 ps (channel asymmetry)
		T	58 ps	16 ps (trigger level timing)
PM6681	3	D		173 ps (all residual compon.)
		L	60 ps	300** ps (inter channel asymmetry)
		N		300 ps (all systematic effects)
53132A	1	K		0,3 ns (resolution)
T4100U	1	A	12 ps	
HSO	1	R		≤ 1 ps

** Changed after circulation Report – Draft A (see: Appendix G and Appendix L)

The lack of uniformity in dealing with the same equipment and, likely, different level of knowledge about their metrological characteristics and the arbitrary choice of estimations of uncertainty budget's components are clearly visible in the collected data. Therefore, a quick and simply comparison of the assigned values is not justified here, but it may be valuable for a deeper individual analysis of the relevant, with the applied equipment, uncertainty budgets.

7 The stability determination of the transfer standard(s) and required corrections (if applicable)

Stability check of the transfer standards were performed by measuring the standards in the beginning and the end of comparisons and between loops by the pilot laboratory (total - 4 times), i.e: in Dec 2019, Aug 2020, Dec 2020 and Nov 2021. All checking measurements were performed with expanded uncertainty U = 0.030 ns. The obtained results are shown in the Table 6.

Table 6. Results of stability checking performed by the pilot laboratory

	dn0, ns	dn3, ns	dn7, ns	dn126, ns	Inλ20, ns	Inλ100, ns	Inλ300, ns
Dec 2019	22.655	250.012	1508.965	12039.490	24.196	104.516	307.321
Aug 2020	22.661	250.009	1508.969	12039.510	24.199	104.517	307.320
Dec 2020	22.659	250.023	1508.975	12039.490	24.203	104.511	307.325
Nov 2021	22.658	250.006	1508.951	12039.496	24.192	104.514	307.321

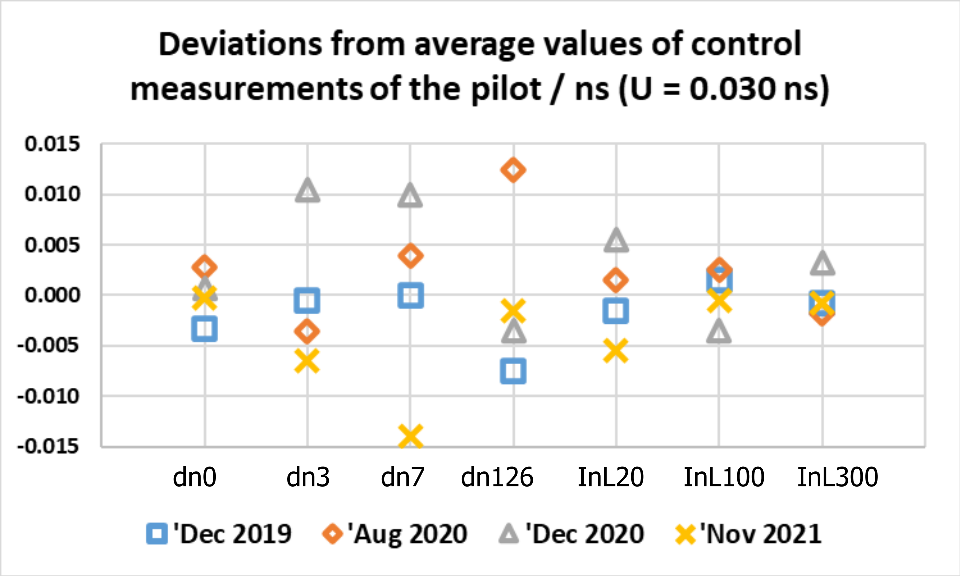


Fig. 8. Results of the stability checking transfer standards performed by the pilot laboratory.

The observed maximum peak-to-peak difference between checking measurements amounted to: 6 ps, 17 ps, 24 ps and 20 ps for TiGen and 11 ps, 6 ps and 5 ps for InLambda respectively. All changes are included within the non-linearities of TIC (T4100U) [6, 7] and the applied procedure of delay compensation by the pilot laboratory. There was not observed any signs of the loss of the stability of the transfer standards.

Due to the need of quantitative assessment of temperature influence on the measurement results of InLambda standards, the common reference ambient temperature was considered as 22.75 °C (the ambient temperature reported by the Lab with the smallest uncertainties of time interval measurements), so chosen without loss of generality to minimize the possible negative influence of recalculation for the results with the highest weights at determination of the reference values. At the same time, this temperature is very close to the mean value of the reported ambient temperatures by all participants equal to 22.97 °C. The obtained results of analysis are gathered in the Table 7.

Table 7. Based on the reported ambient temperatures, the list of theoretical corrections for the measured time intervals for InLambda standards - Inλ20, Inλ100 and Inλ300 with regard to a differences between the ambient temperature met during measurement and the reference temperature (here adopted as 22.75 °C)

		Ambient temperature / °C		Correction for Inλ20 / ns		Correction for Inλ100 / ns		Correction for Inλ300 / ns		Reported U for TI measur.
LAB	**Code**	**T**	**±ΔT**	**Estimate**	**U**	**Estimate**	**U**	**Estimate**	**U**	**U / ns**
GUM	A	22.1	0.4	0.000	0.001	0.001	0.001	0.002	0.001	0.030
FTMC	B	25	1	-0.001	0.001	-0.003	0.001	-0.006	0.003	1.0
VTT MIKES	C	22.4	0.1	0.000	0.001	0.000	0.001	0.001	0.001	0.14
RISE	D	23	1	0.000	0.001	0.000	0.001	-0.001	0.003	0.4
PTB	E	23.6	1	-0.001	0.001	-0.001	0.001	-0.002	0.003	0.16
VSL	F	22.8	0.5	0.000	0.001	0.000	0.001	0.000	0.001	0.13
SMD	G	22	0.3	0.000	0.001	0.001	0.001	0.002	0.001	0.084**
IPQ	H	24.9	0.2	-0.001	0.001	-0.003	0.001	-0.005	0.001	0.66
ROA	I	22	0.6	0.000	0.001	0.001	0.001	0.002	0.002	0.072

SIQ	J	23	2	0.000	0.001	0.000	0.003	-0.001	0.005	0.42
SMU	K	23	2	0.000	0.001	0.000	0.003	-0.001	0.005	0.68
INM	L	22.5	0.5	0.000	0.001	0.000	0.001	0.001	0.001	0.61**
BIM	M	22.93	0.24	0.000	0.001	0.000	0.001	0.000	0.001	0.2
EIM	N	23.4	0.5	0.000	0.001	-0.001	0.001	-0.002	0.001	0.70
BEV	O	22.8	1	0.000	0.001	0.000	0.001	0.000	0.003	0.24
ILNAS*	P	23	0.6	-----	-----	0.000	0.001	-0.001	0.002	0.16
NPL*	Q	22.4	1.4	-----	-----	0.000	0.002	0.001	0.004	0.5
UME	R	22.75	0.25	0.000	0.001	0.000	0.001	0.000	0.001	0.003
BoM	S	22.3	1.8	0.000	0.001	0.001	0.003	0.001	0.005	0.61
DMDM	T	22.9	0.6	0.000	0.001	0.000	0.001	0.000	0.002	0.12
MBM	U	23.1	0.8	0.000	0.001	0.000	0.001	-0.001	0.002	0.34
IMBIH	V	23.7	0.2	-0.001	0.001	-0.001	0.001	-0.002	0.001	0.2
SASO	W	23	2	0.000	0.001	0.000	0.003	-0.001	0.005	0.29
JV	X	22.6	0.6	0.000	0.001	0.000	0.001	0.000	0.002	0.22

* Missed InLambda 20 standard measurements due to disconnection DC supply connector inside the device (lack of P20 and Q20 results),
** Changed after circulation Report – Draft A (see: Appendix G and Appendix L).

Taking into account the observed very small theoretical corrections for the measured time intervals of Inλ20, Inλ100 and Inλ300 with regard to the assigned uncertainties (except of UME results) to the particular measurements, and which are also below resolution of the most reported results (except of GUM, SMD, ROA and UME results), the influence of temperature can be neglected at calculation of reference values of Inλ20, Inλ100 and Inλ300 time intervals and related degrees of equivalence. Choosing any values of the reference ambient temperature from the range of the reported ambient temperature values (between 22 °C and 25 °C) would shift this group of 4 labs results in practice only, whereas the ambient temperature reported by these 4 labs are from 22 °C to 22.75 °C, which correspond to differences between temperature corrections smaller or equal to (1.9 ± 1.5) ps and may be omitted with regard to the specified stability, repeatability and reproducibility of InLambda standards within of ± 10 ps. There is no significant influence of the reported temperature on the interpretation of the results of the comparison.

In conclusion, considering the results of stability analysis, results of verification of influence of measurement conditions and pre-assigned to transfer standards additional uncertainty components, there is no need to apply any corrections for calculation reference values and degrees of equivalence.

8 The participants' results, including uncertainties

The reported by participants results are presented in the Tables 8a and 8b and Fig. 9. (estimates and expanded uncertainties for a coverage probability of approximately 95 %). To facilitate handling of measurement results an additional column with simply code for each participant has been added (from A to X). These codes jointly with numbers included in the adopted designations of the measured time intervals (numbers: 0, 3, 7 and 126 for dn0, dn3, dn7 and dn126 respectively as well as numbers: 20, 100 and 300 for Inλ20, Inλ100 and Inλ300 respectively) allow to refer to each result separately, eg. as A0, A3, A7, A126, A20, A100 and A300 for all results obtained by the first laboratory.

In the case of two participants, after circulation of the Report – Draft A, Laboratories had modified uncertainty budgets slightly. In one case (G# Lab), the uncertainty component related to the non-linearity error was changed from 5.8 ps into 40 ps of standard uncertainty (see. Appendix G), which increased the expanded uncertainties of G# results from 0.032 ns or 0.033 ns into 0.084 ns. The found by G# Lab issue concerned correction of evaluation uncertainty only and was the result of re-analysis of the measurement data obtained in the range from 1 ns to 100 ns using a stepper in March, 2020, before the actual measurements. In the second case (L# Lab), the missed uncertainty component related to inter-channel asymmetry, estimated based on manufacturer data at the level of 300 ps of standard uncertainty, was added to uncertainty budgets (see: Appendix L), which increased the expanded uncertainties of L# results from 0.13 ns into 0.61 ns. This issue was found by L# Lab during re-analysis of the applied measurement method.

In both above cases, no estimates of the measurement results were changed. It has no negative impact on the interpretation of the results of other participants. The agreement of all participants was expressed by e-mail acceptance or lack of objection within up to 30 days after the request were sent by the pilot.

Table 8a. The reported results by the participants obtained for TIGen - dn0, dn3, dn7 and dn126 (all values are expressed in ns)

		dn0		dn3		dn7		dn126	
CODE	**LAB**	**Estimate**	**U**	**Estimate**	**U**	**Estimate**	**U**	**Estimate**	**U**
A	GUM	22.655	0.030	250.012	0.030	1508.965	0.030	12039.490	0.030
B	FTMC	22.6	1.0	250.0	1.0	1509.0	1.0	12039.5	1.0
C	VTT MIKES	22.66	0.24	250.01	0.24	1508.95	0.24	12039.50	0.24
D	RISE	22.7	0.4	250.1	0.4	1509.1	0.4	12039.4	0.4
E	PTB	22.66	0.16	250.00	0.16	1508.97	0.16	12039.48	0.16
F	VSL	22.72	0.12	250.08	0.15	1509.05	0.13	12039.54	0.13
G	SMD	22.648	0.084**	249.998	0.084**	1508.948	0.084**	12039.477	0.084**
H	IPQ	22.999	0.66	250.39	0.66	1509.361	0.66	12039.839	0.66
I	ROA	22.684	0.072	249.997	0.072	1508.966	0.072	12039.484	0.072
J	SIQ	22.64	0.42	250	0.42	1508.95	0.42	12039.470	0.42
K	SMU	22.52	0.68	249.92	0.68	1508.86	0.68	12039.320	0.7
L	INM	22.55	0.61**	249.94	0.13	1508.93	0.61**	12039.370	0.61**
M	BIM	22.66	0.2	249.99	0.2	1508.97	0.2	12039.500	0.2
N	EIM	22.59	0.70	249.998	0.70	1508.993	0.70	12039.426	0.70
O	BEV	22.6	0.24	249.95	0.24	1508.96	0.24	12039.440	0.24
P	ILNAS	22.64	0.16	250	0.16	1508.95	0.16	12039.480	0.16
Q	NPL	22.75	0.5	250.1	0.5	1509.03	0.5	12039.570	0.5
R	UME	22.6526	0.0040	250.0002	0.0040	1508.952	0.004	12039.485	0.004
S	BoM	22.63	0.61	249.976	0.61	1508.925	0.61	12039.452	0.61
T	DMDM	22.66	0.12	249.97	0.12	1508.99	0.12	12039.49	0.12
U	MBM	22.65	0.34	249.99	0.34	1508.93	0.34	12039.48	0.34
V	IMBIH	22.674	0.2	250.052	0.2	1508.987	0.2	12039.603	0.2
W	SASO	22.81	0.29	250.18	0.29	1509.11	0.29	12039.61	0.29
X	JV	22.7	0.22	250.08	0.22	1509.01	0.22	12039.5	0.22

** Changed after circulation the Report – Draft A. The previous values of U amounted to: 0,032 ns, 0,032 ns, 0,033 ns and 0,033 ns for G# Lab and 0.13 ns for L# Lab respectively.

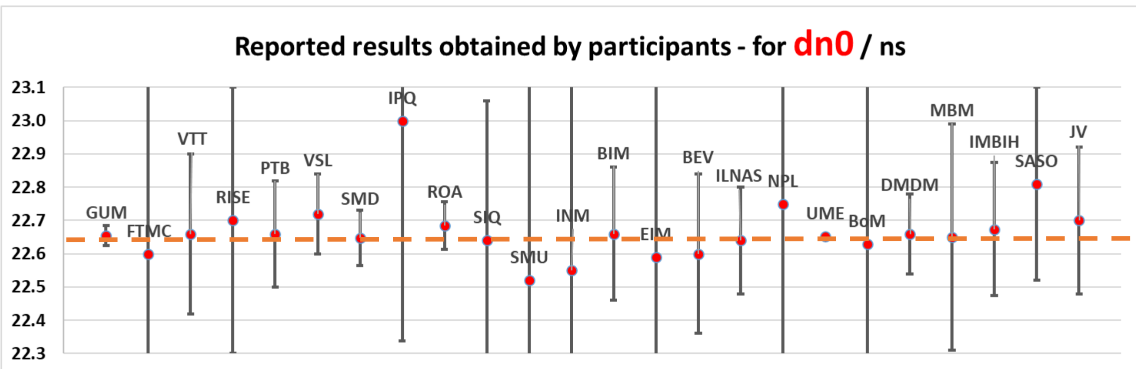
Table 8b. The reported results by the participants obtained for InLambda standards - Inλ20, Inλ100 and Inλ300 (all values are expressed in ns)

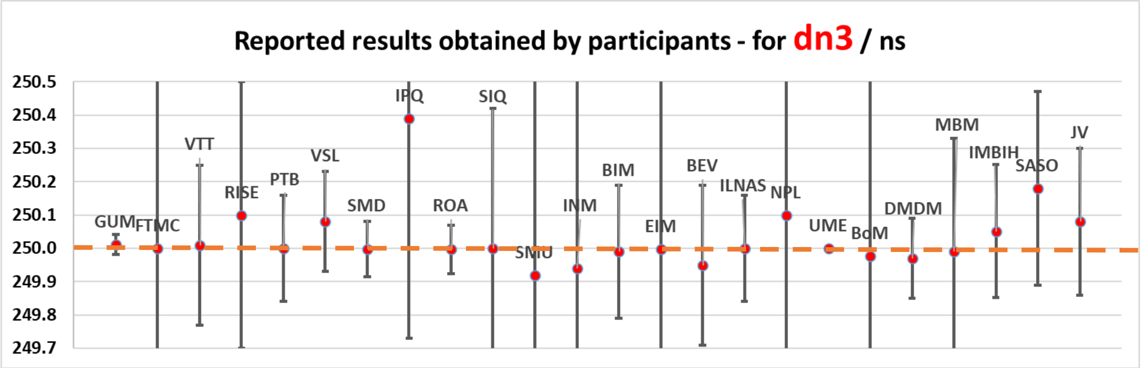
		Inλ20		Inλ100		Inλ300	
CODE	**LAB**	**Estimate**	**U**	**Estimate**	**U**	**Estimate**	**U**
A	GUM	24.196	0.030	104.516	0.030	307.321	0.030
B	FTMC	24.2	1.0	104.5	1.0	307.3	1.0
C	VTT MIKES	24.17	0.14	104.48	0.14	307.29	0.14
D	RISE	24.2	0.4	104.5	0.4	307.4	0.4
E	PTB	24.19	0.16	104.51	0.16	307.29	0.16
F	VSL	24.19	0.11	104.53	0.12	307.31	0.13
G	SMD	24.184	0.084**	104.492	0.084**	307.290	0.084**
H	IPQ	24.531	0.66	104.876	0.66	307.691	0.66
I	ROA	24.203	0.072	104.532	0.072	307.315	0.072
J	SIQ	24.18	0.42	104.48	0.42	307.28	0.42
K	SMU	24.23	0.65	104.47	0.67	307.26	0.68
L	INM	24.06	0.61**	104.44	0.61**	307.28	0.61**
M	BIM	24.23	0.2	104.54	0.2	307.34	0.2
N	EIM	24.142	0.70	104.482	0.70	307.329	0.70
O	BEV	24.14	0.24	104.44	0.24	307.22	0.24
P	ILNAS*	----------	--------	104.48	0.16	307.28	0.16
Q	NPL*	---------	--------	104.58	0.50	307.35	0.5
R	UME	24.1870	0.0030	104.5025	0.0030	307.3302	0.0030
S	BoM	24.147	0.61	104.435	0.61	307.229	0.61
T	DMDM	24.21	0.12	104.48	0.12	307.27	0.12
U	MBM	24.17	0.34	104.46	0.34	307.27	0.34
V	IMBIH	24.217	0.2	104.526	0.2	307.358	0.2
W	SASO	24.16	0.29	104.46	0.29	307.27	0.29
X	JV	24.21	0.22	104.51	0.22	307.31	0.22

* Missed InLambda 20 standard measurements due to disconnection DC supply connector inside the device (lack of P20 and Q20 results).

** Changed after circulation the Report – Draft A. The previous values of U amounted to 0,032 ns, 0,032 ns and 0,033 ns for G# Lab and 0.13 ns for L# Lab respectively.

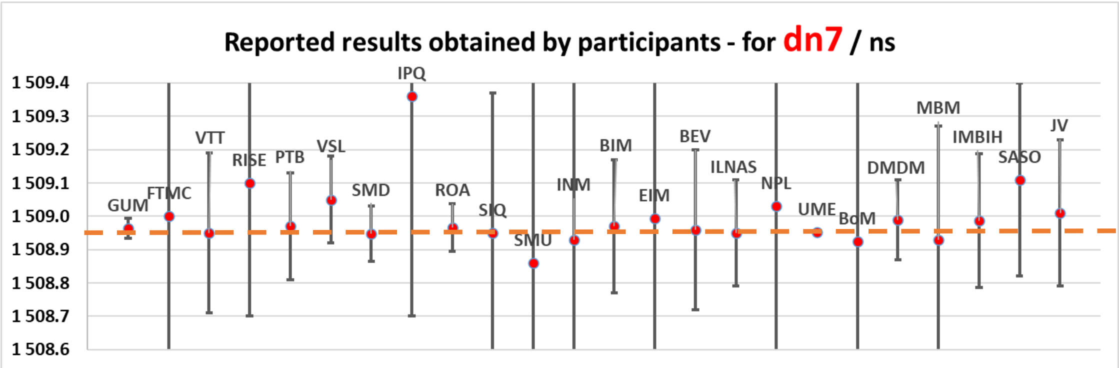
a)





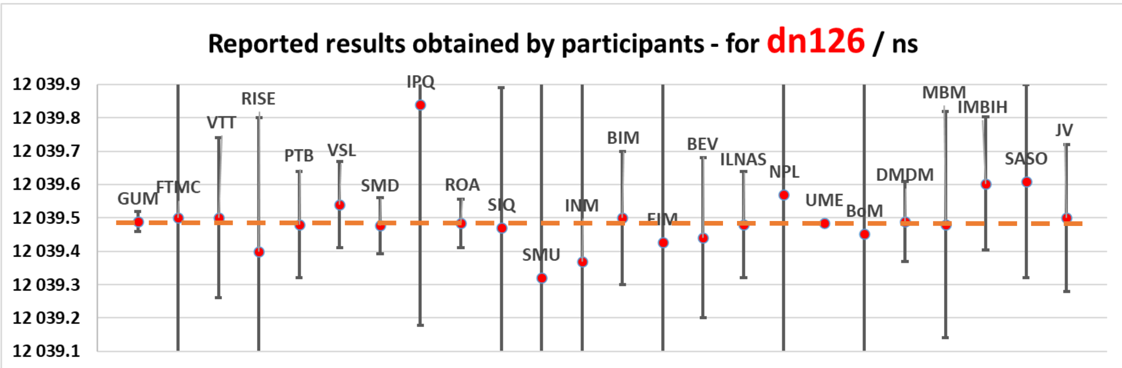
Reported results obtained by participants - for dn3 / ns
250.5
250.4
250.3
250.2
250.1
250.0
249.9
249.8
249.7
GUM
FTMC
VTT
RISE
PTB
VSL
SMD
IPQ
ROA
SIQ
SMU
INM
BIM
EIM
BEV
ILNAS
NPL
UME
BoM
DMDM
MBM
IMBIH
SASO
JV

b)



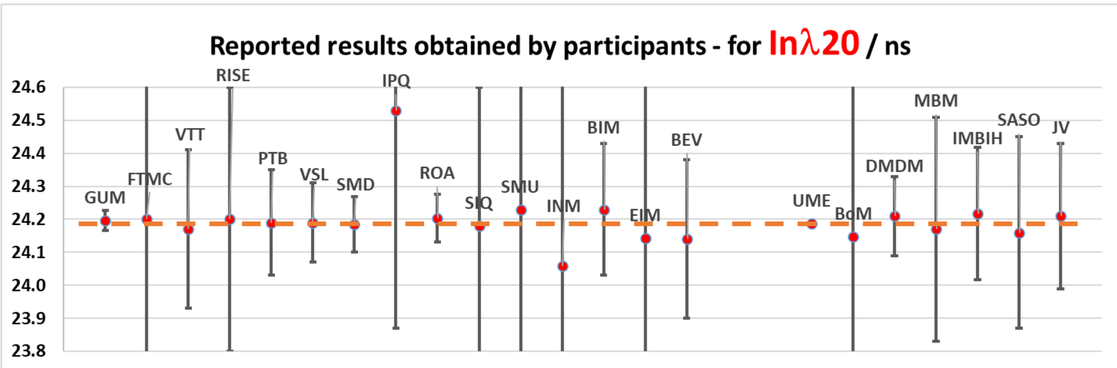
Reported results obtained by participants - for dn7 / ns
1 509.4
1 509.3
1 509.2
1 509.1
1 509.0
1 508.9
1 508.8
1 508.7
1 508.6
GUM
FTMC
VTT
RISE
PTB
VSL
SMD
IPQ
ROA
SIQ
SMU
INM
BIM
EIM
BEV
ILNAS
NPL
UME
BoM
DMDM
MBM
IMBIH
SASO
JV

c)



Reported results obtained by participants - for dn126 / ns
12 039.9
12 039.8
12 039.7
12 039.6
12 039.5
12 039.4
12 039.3
12 039.2
12 039.1
GUM
FTMC
VTT
RISE
PTB
VSL
SMD
IPQ
ROA
SIQ
SMU
INM
BIM
EIM
BEV
ILNAS
NPL
UME
BoM
DMDM
MBM
IMBIH
SASO
JV

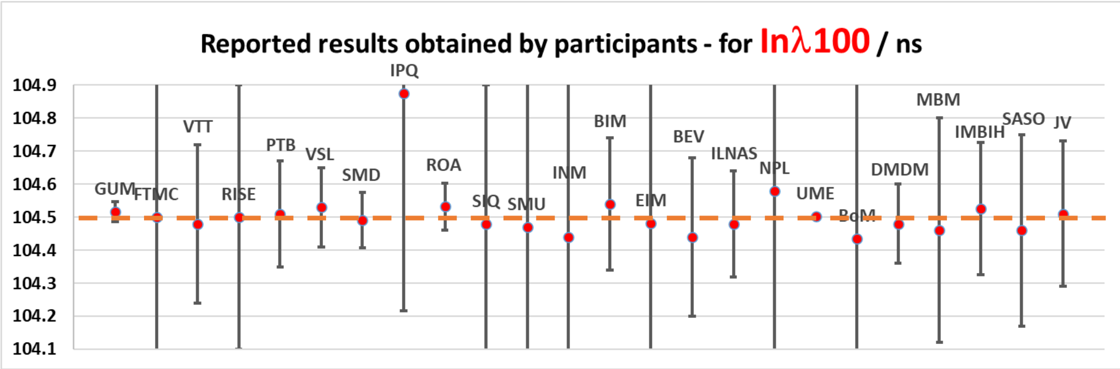
d)



Reported results obtained by participants - for Inλ20 / ns
24.6
24.5
24.4
24.3
24.2
24.1
24.0
23.9
23.8
GUM
FTMC
VTT
RISE
PTB
VSL
SMD
IPQ
ROA
SIQ
SMU
INM
BIM
EIM
BEV
UME
BoM
DMDM
MBM
IMBIH
SASO
JV

e)

f)



g)

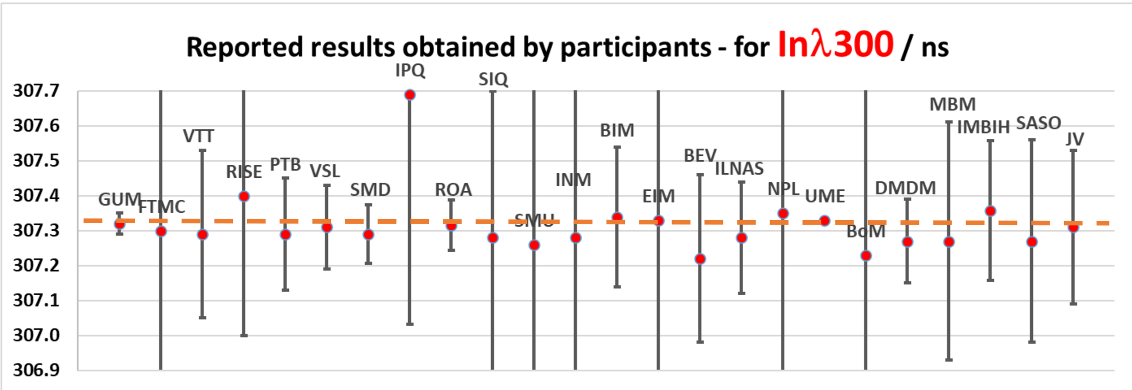


Fig. 9.a-g Reported results obtained by the participants for each measured time interval, including expanded uncertainties. For better clarity of the presented results, the vertical axes ranges were limited to 0.8 ns. Dashed lines indicate the approximated level of the reference values.

9 Calculation of a reference value of the comparison

The reference value x_{Ref} for each measured time interval was calculated as weighted average of the measurement results obtained by the participants, according to the formula:

$$x_{Ref} = \frac{\sum_{i=1}^{N} \delta_i \frac{1}{u_i^2} x_i}{\sum_{i=1}^{N} \delta_i \frac{1}{u_i^2}}, \qquad (1)$$

where the *i*-index refers to the result obtained by the *i*-th participant (x_i - estimate of the results, u_i - standard uncertainty) from total number of *N*-participants for a given time interval, and δ_i is an additional parameter equal to 1 for the "most reliable" results or equal to 0 for other results, i.e. $\delta_i = \begin{cases} 1 \\ 0 \end{cases}$. Originally, it was assumed that the most reliable results are the results for which it is unambiguously stated that the residual non-linearities of the measurement system and other non-compensated effects are included into uncertainties (eg. for SR620 – if expanded uncertainty is ≥0,15 ns [8]) and which are consistent with other results (omitting outliers). That was aimed to remove the results with relatively small uncertainties and possible bias greater than an assigned uncertainty, which could influence negatively the weighted average value.

Finally, the decision on the "reliability" has been made collectively, involving the support group and all participants as well as taking into account initially calculated degrees of equivalence, expressed with the usage of the equivalence coefficients E_i (eq. 3) and their further interpretation: positive or negative, in order to avoid arbitrary change of their interpretation.

The standard uncertainty of the reference values u_{Ref} was calculated according to the propagation law of uncertainties, including the standard uncertainties of weighted average u_{wei} and the standard uncertainty u_{rep} assigned to the stability, reproducibility and repeatability of transfer standards equal to 3 ps/2 for TIGen and 10 ps/2 for InLambda standards respectively:

$$u_{Ref}^2 = u_{wei}^2 + u_{rep}^2, \quad (2)$$

where:

$$u_{wei} = \frac{1}{\sqrt{\sum_{i=1}^{N} \delta_i \frac{1}{u_i^2}}}. \quad (2a).$$

During analysis of the reliability and computing the reference values, the results of which are collected in the Table 9, the following cases were considered:

Case #1 – all results recognized as equally reliable,

Case #2 – the results with expanded uncertainties less than 10 ps marked as not reliable (R# group of results (with U = 4 ps or 3 ps) removed from computing the reference values – 1 Lab),

Case #3 – the results with expanded uncertainties less than 50 ps marked as not reliable (R# and A# groups of results (with U = 3 ps or 4 ps and 30 ps) removed from computing the reference values – 2 Labs),

Case #4 – the results with expanded uncertainties less than 100 ps marked as not reliable (R#, A#, I# and G# groups of results (with U = 3 ps or 4 ps, 30 ps, 72 ps and 84 ps) removed from computing the reference values – 4 Labs).

Table 9a. The considered cases of computing the reference values with expanded uncertainties and its influence on the positive or negative interpretation of the comparison results – obtained for TIGen - dn0, dn3, dn7 and dn126 (reference values are expressed in ns)

Case	Parameter	Ref dn0	Ref dn3	Ref dn7	Ref dn126
#1	**Ref_value**	**22.653 ± 0.005**	**250.001 ± 0.005**	**1508.953 ± 0.005**	**12039.485 ± 0.005**
	Max E_i	0.560	0.619	**0.749**	0.589
	Min E_i	-0.220	-0.254	-0.160	-0.236
	Pos/Neg	24 / 0	24 / 0	24 / 0	24 / 0
#2	**Ref_value**	**22.662 ± 0.024**	**250.011 ± 0.024**	**1508.970 ± 0.024**	**12039.492 ± 0.024**
	Max E_i	0.513	0.585	0.628	0.561
	Min E_i	-0.377	-0.443	**-0.726**	-0.269
	Pos/Neg	24 / 0	24 / 0	24 / 0	24 / 0
#3	**Ref_value**	**22.672 ± 0.038**	**250.009 ± 0.038**	**1508.977 ± 0.038**	**12039.494 ± 0.038**
	Max E_i	0.496	0.595	0.586	0.556
	Min E_i	-0.513	-0.344	-0.652	-0.249
	Pos/Neg	24 / 0	24 / 0	24 / 0	24 / 0
#4	**Ref_value**	**22.675 ± 0.052**	**250.020 ± 0.054**	**1508.995 ± 0.053**	**12039.506 ± 0.053**
	Max E_i	0.492	0.562	0.557	0.507
	Min E_i	-0.432	-0.469	**-0.800**	-0.391
	Pos/Neg	24 / 0	24 / 0	24 / 0	24 / 0

Table 9b. The considered cases of computing the reference values with expanded uncertainties and its influence on the positive or negative interpretation of the comparison results - obtained for InLambda standards - Inλ20, Inλ100 and Inλ300 (reference values are expressed in ns)

Case	Parameter	Inλ20	Inλ100	Inλ300
#1	**Ref_value**	**24.187 ± 0.010**	**104.503 ± 0.010**	**307.330 ± 0.010**
	Max E_i	0.521	0.566	0.547
	Min E_i	-0.208	-0.261	-0.498
	Pos/Neg	22 / 0	24 / 0	24 / 0
#2	**Ref_value**	**24.195 ± 0.026**	**104.512 ± 0.025**	**307.313 ± 0.025**
	Max E_i	0.509	0.551	0.680
	Min E_i	-0.325	-0.384	-0.388
	Pos/Neg	22 / 0	24 / 0	24 / 0
#3	**Ref_value**	**24.194 ± 0.039**	**104.507 ± 0.038**	**307.300 ± 0.038**
	Max E_i	0.511	0.560	**0.775**
	Min E_i	-0.229	-0.281	-0.339
	Pos/Neg	22 / 0	24 / 0	24 / 0
#4	**Ref_value**	**24.194 ± 0.053**	**104.500 ± 0.051**	**307.297 ± 0.051**
	Max E_i	0.513	0.572	0.646
	Min E_i	-0.229	-0.254	-0.328
	Pos/Neg	22 / 0	24 / 0	24 / 0

In practice, a large number of participants (24), very good mutual consistency of the most results within assigned uncertainties and, in general, lack of the results with relatively small uncertainties and possible bigger bias jointly make the weighted average more resistant to potential “less” reliable results.

The possible reliability of the R# group of results, with the smallest uncertainties (U = 4 ps and 3 ps) performed with HSO, had been confirmed before within the pilot comparison #1288 Euramet project [2] and is not questionable. A gross error in R# group of estimates (performing a typo during recording or reporting measurement results) has been excluded, too.

Removing, from the reference value calculation, the results with the smallest uncertainties (the most influencing the weighted average value – R#, A#, I# and G# groups of results) does not change the reference value significantly (see: Cases #2-4), but it causes relatively significant increase in the uncertainty value assigned to the reference values and does not change the final (positive) interpretation of the equivalence coefficient values. The observed variations of the values of equivalence coefficients between Cases #1-4 reflect a natural discrepancy of measurement results, assigned uncertainties and applied level of reduction of systematic components (delays) in measurement configurations.

However, before taking the final decision and in order to minimise the risk of wrong interpretation of R# group of results (with the highest weights), the additional auxiliary measurements of traveling standards have been performed with a high speed oscilloscope of DSO90254A. It was carried out by the pilot laboratory with support of National Institute of Telecommunications in Warsaw-Miedzeszyn (Poland), in April 2024. The results presented in the Table 10 were obtained, which are consistent within a few picoseconds with R# results very well.

Table 10. Results of auxiliary measurements of traveling standards performed with a high speed oscilloscope of DSO90254A (ambient temperature (22.1 ± 0.4) °C) obtained in April 2024, during preparation the report Draft A. The results and given with expanded uncertainties (at $p \approx 95$ %) (values expressed in ns) - not included into further calculation of the reference values.

dn0	dn3	dn7	dn126
22.648 ± 0.005	249.995 ± 0.005	1508.948 ± 0.005	12039.481 ± 0.005
Inλ20	Inλ100	Inλ300	
24.186 ± 0.005	104.498 ± 0.005	307.328 ± 0.005	

Finally, to avoid arbitrary choice of the reliability assessment, the Case #1 (with all results marked as equally reliable) was chosen for calculation of the reference values and equivalence coefficient values for interpretation of the comparison results. For better clarity, the final reference values of the measured time intervals are collected in the Table 11.

Table 11. The final reference values with expanded uncertainties (at coverage probability of approx.. 95 %) obtained for TIGen - dn0, dn3, dn7 and dn126, and InLambda standards - Inλ20, Inλ100 and Inλ300 (values expressed in ns)

Ref dn0	**Ref dn3**	**Ref dn7**	**Ref dn126**
22.653 ± 0.005	**250.001 ± 0.005**	**1508.953 ± 0.005**	**12039.485 ± 0.005**
Ref Inλ20	**Ref Inλ100**	**Ref Inλ300**	
24.187 ± 0.010	**104.503 ± 0.010**	**307.330 ± 0.010**	

10 The degree of equivalence (DoE) of each participant with respect to the reference value

The Degree of equivalence (DoE) of each participants and each results has been expressed mathematically by the equivalence coefficient E_i calculated according to the formula:

$$E_i = \frac{x_i - x_{Ref}}{U(x_i - x_{Ref})} \quad (3)$$

where:

$$u^2(x_i - x_{Ref}) = u_i^2 + (1 - 2\delta_i)u_{wei}^2 + u_{rep}^2 \quad (3a)$$

and

$$U(x_i - x_{Ref}) = 2u(x_i - x_{Ref}), \quad (3b)$$

with the minus sign at uncertainty calculation because of a possible correlation between weighted average and participant's results [9].

For $|E_i| \leq 1$ – the comparison results are positive, and for $|E_i| > 1$ – the comparison results are negative.

In the Table 12a-d and Fig. 10a-g, there are presented deviations from the reference values with expanded uncertainties of this deviations and resulting equivalence coefficients.

Table 12a. Degree of equivalence of each participants for the measured time intervals (deviations from reference values with expanded uncertainties – expressed in ns, and the resulting equivalence coefficients) – obtained for TIGen - dn0 and dn3.

		dn0			**dn3**		
CODE	**LAB**	$x_i - x_{Ref}$	U_i	E_i	$x_i - x_{Ref}$	U_i	E_i
A	GUM	0.002	0.030	0.072	0.012	0.030	0.385
B	FTMC	-0.053	1.0	-0.053	0.000	1.0	0.000
C	VTT MIKES	0.007	0.24	0.030	0.010	0.24	0.040
D	RISE	0.047	0.40	0.118	0.100	0.40	0.249
E	PTB	0.007	0.16	0.045	0.000	0.16	-0.003
F	VSL	0.067	0.12	0.560	0.080	0.15	0.530
G	SMD	-0.005	0.084	-0.058	-0.002	0.084	-0.030
H	IPQ	0.346	0.66	0.524	0.390	0.66	0.590
I	ROA	0.031	0.072	0.433	-0.003	0.072	-0.049
J	SIQ	-0.013	0.42	-0.031	0.000	0.42	-0.001
K	SMU	-0.133	0.68	-0.195	-0.080	0.68	-0.118
L	INM	-0.103	0.61	-0.169	-0.060	0.61	-0.099

		dn0			dn3		
CODE	**LAB**	$x_i - x_{Ref}$	U_i	E_i	$x_i - x_{Ref}$	U_i	E_i
M	BIM	0.007	0.20	0.036	-0.010	0.20	-0.052
N	EIM	-0.063	0.70	-0.090	-0.002	0.70	-0.004
O	BEV	-0.053	0.24	-0.220	-0.050	0.24	-0.210
P	ILNAS	-0.013	0.16	-0.080	0.000	0.16	-0.003
Q	NPL	0.097	0.50	0.194	0.100	0.50	0.199
R	UME	0.000	0.003	-0.083	0.000	0.003	-0.097
S	BoM	-0.023	0.61	-0.037	-0.024	0.61	-0.040
T	DMDM	0.007	0.12	0.060	-0.030	0.12	-0.254
U	MBM	-0.003	0.34	-0.008	-0.010	0.34	-0.031
V	IMBIH	0.021	0.20	0.106	0.052	0.20	0.258
W	SASO	0.157	0.29	0.542	0.180	0.29	0.619
X	JV	0.047	0.22	0.214	0.080	0.22	0.361

Table 12b. Degree of equivalence of each participants for the measured time intervals (deviations from reference values with expanded uncertainties – expressed in ns, and the resulting equivalence coefficients) – obtained for TIGen - dn7 and dn126.

		dn7			dn126		
CODE	**LAB**	$x_i - x_{Ref}$	U_i	E_i	$x_i - x_{Ref}$	U_i	E_i
A	GUM	0.012	0.030	0.412	0.005	0.030	0.161
B	FTMC	0.047	1.0	0.047	0.015	1.0	0.015
C	VTT MIKES	-0.003	0.24	-0.011	0.015	0.24	0.062
D	RISE	0.147	0.40	0.368	-0.085	0.40	-0.213
E	PTB	0.017	0.16	0.108	-0.005	0.16	-0.032
F	VSL	0.097	0.13	0.749	0.055	0.13	0.422
G	SMD	-0.005	0.084	-0.056	-0.008	0.084	-0.097
H	IPQ	0.408	0.66	0.619	0.354	0.66	0.536
I	ROA	0.013	0.072	0.185	-0.001	0.072	-0.016
J	SIQ	-0.003	0.42	-0.006	-0.015	0.42	-0.036
K	SMU	-0.093	0.68	-0.136	-0.165	0.70	-0.236
L	INM	-0.023	0.61	-0.037	-0.115	0.61	-0.189
M	BIM	0.017	0.20	0.087	0.015	0.20	0.074
N	EIM	0.040	0.70	0.058	-0.059	0.70	-0.085
O	BEV	0.007	0.24	0.030	-0.045	0.24	-0.188
P	ILNAS	-0.003	0.16	-0.017	-0.005	0.16	-0.032
Q	NPL	0.077	0.50	0.155	0.085	0.50	0.170
R	UME	0.000	0.003	-0.160	0.000	0.003	-0.059
S	BoM	-0.028	0.61	-0.045	-0.033	0.61	-0.054
T	DMDM	0.037	0.12	0.311	0.005	0.12	0.040
U	MBM	-0.023	0.34	-0.067	-0.005	0.34	-0.015
V	IMBIH	0.034	0.20	0.172	0.118	0.20	0.589
W	SASO	0.157	0.29	0.542	0.125	0.29	0.430
X	JV	0.057	0.22	0.261	0.015	0.22	0.067

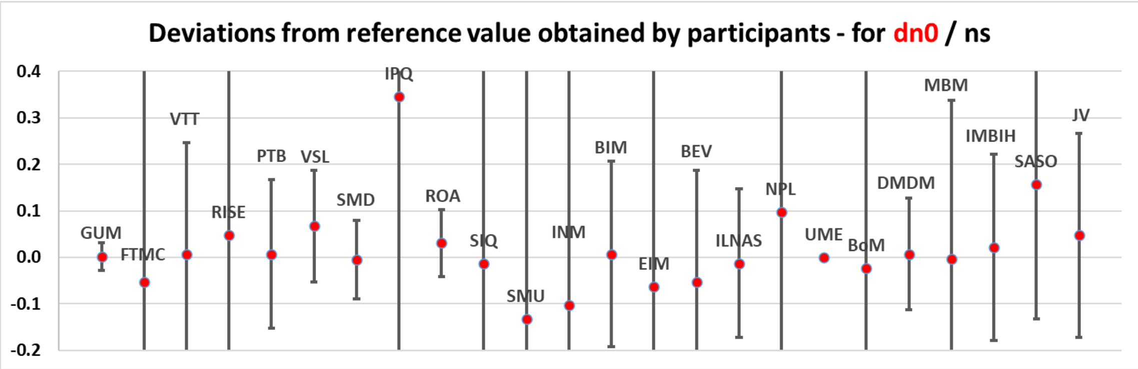
Table 12c. Degree of equivalence of each participants for the measured time intervals (deviations from reference values with expanded uncertainties – expressed in ns, and the resulting equivalence coefficients) – obtained for InLambda standards - Inλ20 and Inλ100.

		Inλ20			Inλ100		
CODE	**LAB**	$x_i - x_{Ref}$	U_i	E_i	$x_i - x_{Ref}$	U_i	E_i
A	GUM	0.009	0.031	0.282	0.013	0.031	0.424
B	FTMC	0.013	1.0	0.013	-0.003	1.0	-0.003
C	VTT MIKES	-0.017	0.14	-0.122	-0.023	0.14	-0.161
D	RISE	0.013	0.40	0.032	-0.003	0.40	-0.007
E	PTB	0.003	0.16	0.018	0.007	0.16	0.046
F	VSL	0.003	0.11	0.026	0.027	0.12	0.227
G	SMD	-0.003	0.085	-0.037	-0.011	0.085	-0.126
H	IPQ	0.344	0.66	0.521	0.373	0.66	0.566
I	ROA	0.016	0.073	0.218	0.029	0.073	0.404
J	SIQ	-0.007	0.42	-0.017	-0.023	0.42	-0.054
K	SMU	0.043	0.65	0.066	-0.033	0.67	-0.049
L	INM	-0.127	0.61	-0.208	-0.063	0.61	-0.103
M	BIM	0.043	0.20	0.214	0.037	0.20	0.186
N	EIM	-0.045	0.70	-0.064	-0.021	0.70	-0.030
O	BEV	-0.047	0.24	-0.196	-0.063	0.24	-0.261
P	ILNAS	-	-	-	-0.023	0.16	-0.141
Q	NPL	-	-	-	0.077	0.50	0.155
R	UME	0.000	0.010	-0.013	0.000	0.010	-0.016
S	BoM	-0.040	0.61	-0.066	-0.068	0.61	-0.111
T	DMDM	0.023	0.12	0.190	-0.023	0.12	-0.188
U	MBM	-0.017	0.34	-0.050	-0.043	0.34	-0.125
V	IMBIH	0.030	0.20	0.149	0.023	0.20	0.117
W	SASO	-0.027	0.29	-0.094	-0.043	0.29	-0.147
X	JV	0.023	0.22	0.104	0.007	0.22	0.033

Table 12d. Degree of equivalence of each participants for the measured time intervals (deviations from reference values with expanded uncertainties – expressed in ns, and the resulting equivalence coefficients) – obtained for InLambda standards - Inλ300.

		Inλ300		
CODE	**LAB**	$x_i - x_{Ref}$	U_i	E_i
A	GUM	-0.009	0.031	-0.283
B	FTMC	-0.030	1.0	-0.030
C	VTT MIKES	-0.040	0.14	-0.284
D	RISE	0.070	0.40	0.175
E	PTB	-0.040	0.16	-0.249
F	VSL	-0.020	0.13	-0.153
G	SMD	-0.040	0.085	-0.472
H	IPQ	0.361	0.66	0.547
I	ROA	-0.015	0.073	-0.205
J	SIQ	-0.050	0.42	-0.119
K	SMU	-0.070	0.68	-0.103

		Inλ300		
CODE	LAB	$x_i - x_{Ref}$	U_i	E_i
L	INM	-0.050	0.61	-0.082
M	BIM	0.010	0.20	0.050
N	EIM	-0.001	0.70	-0.001
O	BEV	-0.110	0.24	-0.458
P	ILNAS	-0.050	0.16	-0.311
Q	NPL	0.020	0.50	0.040
R	UME	0.000	0.010	0.028
S	BoM	-0.101	0.61	-0.165
T	DMDM	-0.060	0.12	-0.498
U	MBM	-0.060	0.34	-0.176
V	IMBIH	0.028	0.20	0.140
W	SASO	-0.060	0.29	-0.206
X	JV	-0.020	0.22	-0.090



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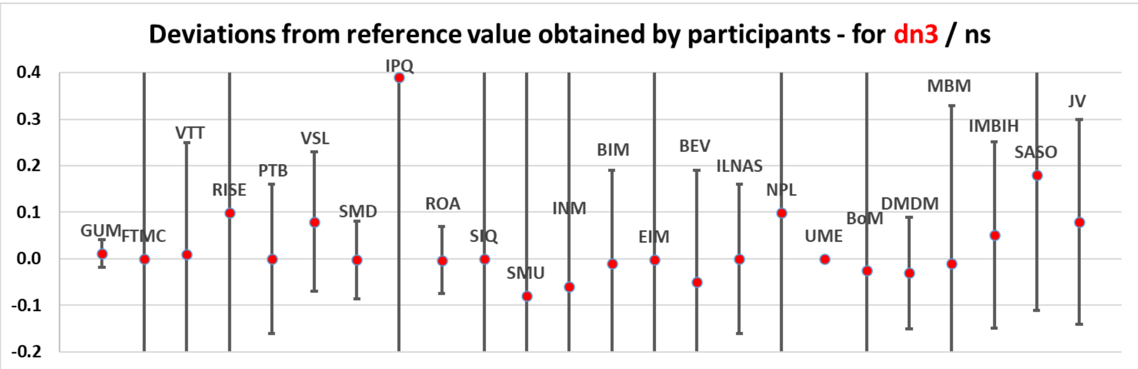

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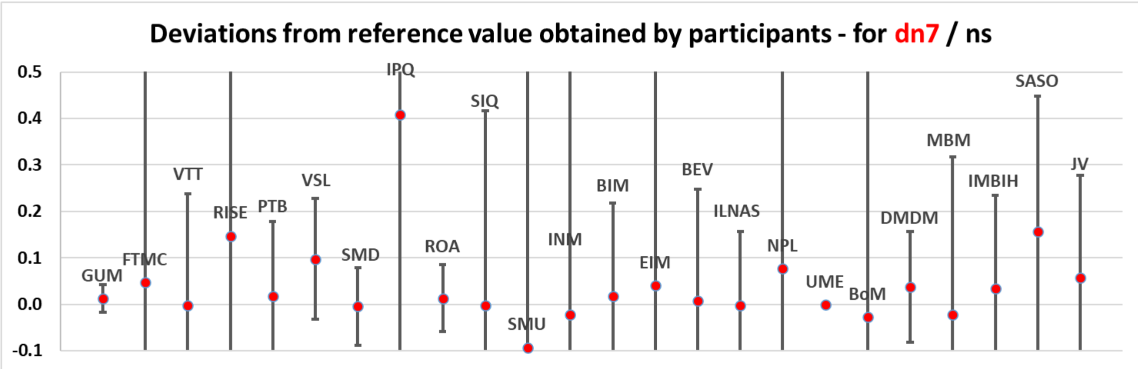

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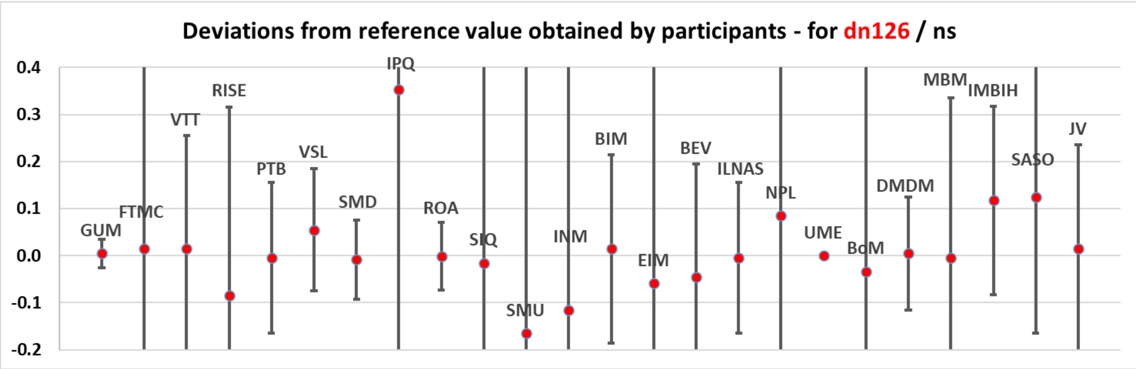

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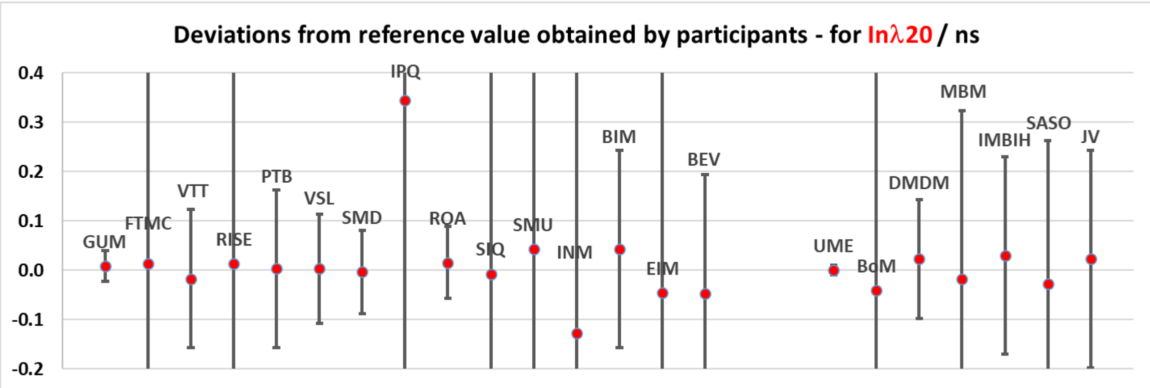
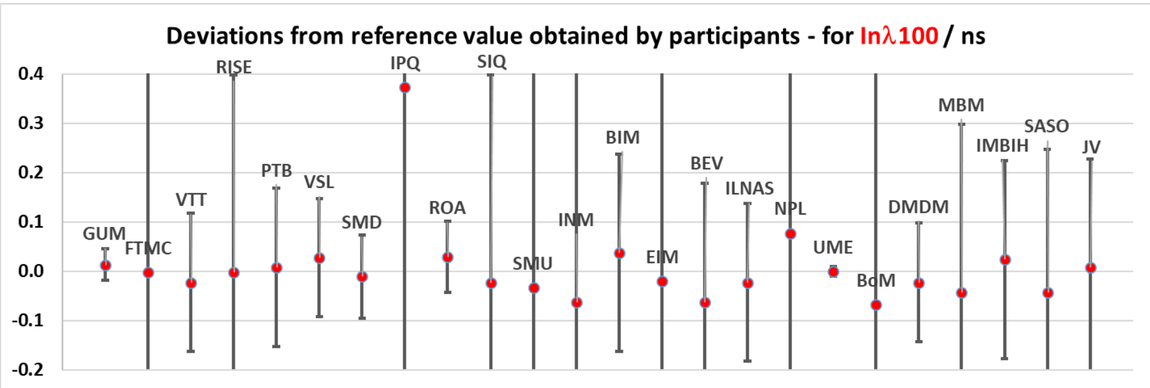
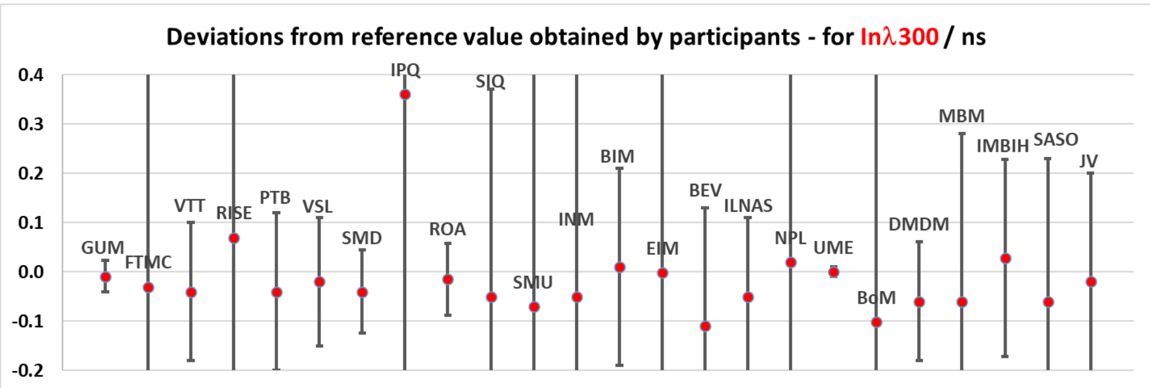


e)



f)



g)

Fig. 10.a-g Deviations from the reference values with expanded uncertainties of those deviations obtained by the participants for each measured time interval. On each vertical axes, 0.0 ns corresponds to the level of the reference value. The vertical axes ranges were limited to 0.6 ns – the same for each graph.

11 Uncertainty budget of each participant with indication of the resulting combined uncertainty

Uncertainty budgets of each participant with indication of the resulting combined uncertainty are included in the measurement reports, collected in the Appendixes from A to X.

The uncertainties were evaluated at a level of one standard uncertainty and expanded uncertainty for a coverage probability of approximately 95 % and were estimated according to the JCGM 100:2008 (GUM 1995 with minor corrections) [10].

In the uncertainty budget should be taken into account all uncertainty components which are of importance in measurements. A list of the evaluated uncertainty components used by each participant was presented in the form of a table according to the EA-4/02 M:2013 (replaced by EA-4/02 M:2022) [11].

12 Appropriate analysis to verify if uncertainty claims correspond to those of published CMCs

Only three labs explicitly reported the need to refer the comparison results to the claimed (VSL), new proposed (GUM) or planned candidate (MBM) CMC values.

VSL
The uncertainties reported by VSL in this comparison are less than or equal to 0.15 ns (at $p \approx 95$ %), which are well below its CMC claim (1 ns). The reported VSL results agree with the comparison reference values within assigned uncertainties, thus the VSL results support the current CMC claim for time interval calibrations and justify reducing the current CMC values to lower values.

GUM
The uncertainties reported by GUM in this comparison, together with the collected measurements during stability determination of the standards as a pilot laboratory, are equal to 0.030 ns (at $p \approx 95$ %), which are well below its CMC claim (0.20 ns). They are sufficient to agree with the comparison reference values within assigned uncertainties. However, the observed maximum deviation of the stability determination results from the comparison reference values reaches 0.025 ns, which corresponds to the absolute value of the equivalence coefficient slightly more than 0.80. So, the proposed expanded uncertainties of 0,030 ns for the update or new proposed CMC services of GUM for time interval measurements between two pulse signals with closely the same shape of the rising slopes of the measured pulse signals and with rise time <1 ns, is supported by the comparison results, but it may be exposed to some risk of underestimation, at the same time.

MBM
The uncertainties reported by MBM in this comparison are equal to 0.34 ns (at $p \approx 95$ %) and the MBM results agree with the comparison reference values very well (the observed maximum deviation from the reference values amounts to 0.060 ns), thus the MBM results support the planned candidate CMC for time interval measurements with an expanded uncertainty both of 0.5 ns and 0.34 ns or of even lower value.

Other conclusions referred supporting by the comparison results the existing, updating or planned CMC claims for time interval measurements are included inside or at the end of the next section.

13 First conclusions

Main conclusion based on DoE

For every result, collected in the Tables 12a-d, the equivalence coefficient is between the limits -1 and 1, thus the results of supplementary comparison of time interval measurements are positive for each participant.

Differential input channel delay and cable delay asymmetry

H#, K#, L#, N#, V# and W# groups of results were obtained by measurements in a single measurement setup (marked (a) in Fig. 3) only, not accompanied or preceded by measurements in other configurations. Despite using the cables of almost the same length closely, it arises a risk of additional error (bias) caused by not reduced differential channel delay of the applied TIC. This risk occurred in the case of:

- H# results (differed from the reference value by 0.368 ns on average),
- L# results (differed from the reference value by -0.077 ns on average, with variation of the shift up to 104 ps peak-to-peak),
- V# results (differed from the reference value by 0.044 ns on average, with variation of the shift up to 97 ps peak -to-peak),
- W# results (differed from the reference value by 0.055 ns for TIGen and by -0.033 ns for InLambda standards on average).

Indeed, in each of the above cases, the assigned uncertainties allow accepting the observed deviations from the reference values due to inclusion the sufficiently large uncertainty components which can cover a possible non-zero residual differential channel delay and cable delay asymmetry. Initial omission (see: Appendix L) of such important uncertainty component in L# results, had increased significantly the risk of negative assessment of L126 and L20 results. Moreover, it draws attention the adopted correction for a cable delay difference for L# results especially that it was taken as 0 ns with a very small standard uncertainty of 0.006 ns.

It is worth noting that the estimates of V# results vary within similar limits as in the case of L# results and both labs use pairs of cables of equal length from one manufacturer (not necessarily the same), however a non-zero correction of 0.075 ns for a cable delay difference with assigned a four times larger standard uncertainty (of 0.023 ns) was applied by V Lab. Assuming that the length accuracy and repeatability of cutting cable by manufacturer may be about of 1 % (a cable is typically unwound from the spool and is not perfectly straight), it corresponds to possible ±75 ps of a cable delay difference for 1.5 m cable lengths approximately. There are also possible small imperfections in mounting cables connectors and slightly different (mismatch of) pass-band characteristics of connectors, causing additional frequency dependent asymmetry of propagation delay.

Anyway, both cables should be marked and distinguishable so as not to confuse in configuration the order of cable connections of Start and Stop signals with TIC's inputs with regard to the applied cable delay asymmetry correction sign. This may be one of the possible explanations of the observed in W# results a significant difference (of 0.070 ns on average and of 0.239 ns peak-to-peak) between deviations from the reference values for TIGen standard and for InLambda standards. Another reason of this observation can be separation in time of measurements of TIGen standard from InLambda standards, sufficient to change the internal measurement conditions inside TIC (eg. differential channel delay).

A nearly fixed systematic deviation (of 0.368 ns) of H# results from the reference values may be easy explained as a sum of non-reduced internal differential channel delay, including the internal non-linearities of TIC, and/or asymmetry of cable delays, although it is covered successfully by the uncertainty component generally related to 'influence of wrong measurements' and estimated as 0.289 ns ($p \approx 68$ %). It may be symptomatic, that this lab, along with L# and N# labs, had reported to the pilot problems with repeatability of measurements during repetitions of measurements and every one of them applied a simply measurement setup without reduction differential channel delay. Finaly, H# results were obtained as average values of data collected on 3 different days, with more than 75 measurements per day.

Most of the abovementioned problems could be avoided by applying a bit more complex measurements with inter-change cable connections (see: Fig. 3 and Tab. 4), where a cable delays asymmetry did not affect the final measurements results. Even so, some of labs (eg. O#) applied cables with clearly visible different lengths intentionally to facilitate measurements and avoid additional source of mistakes, arising slightly the risk of causing additional frequency dependent asymmetry of propagation delay only. Also, performing TIC's autocalibration procedures before the measurements, if it was available, allowed successfully to optimize the internal differential channel delay and internal non-linearities influence (eg. B# or Q# labs).

Internal non-linearities

The observed variations of deviations from the reference values obtained by participants in division into the used brand of TICs, presented in the Table 13, should be free of a fixed systematic shifts theoretically and may be interpreted as some representation of residual non-compensated internal non-linearities. Due to the limited set of the measured time interval values in the comparison, the real range of the possible non-linearities can be wider. Each specific TIC may feature individual characteristics of non-linearities as well as some specific condition of measurements (averaging time, type of correlation of the time base with the measured time interval) may decrease the non-linearities to some extent, but some general conclusions can be drawn.

Interpretation of the data collected in the Table 13 may be additionally influenced by the applied method of reduction differential cable and channel delay, so called offset measurements, number and duration of measurement series, number of repetition, schedules of measurements. If proper time interval measurements were preceded by auxiliary differential cable/channel delay measurements separated for TIGen group results and separated for InLambda group results, then the last column in the Table 13 represents jointly non-linearities as well as differences in auxiliary measurements between both group of results. So, these values figured in the last column should be interpreted very carefully. There is also a possible some random noise contribution to all values given there.

Table 13. Observed variations of deviations from the reference values with regard to the used brand of TICs. (x2, x3 – refers to the results which were obtained by averaging estimates from 2 or 3 devices of the same brand respectively)

Used brand of TICs	Code of Lab	Obtained by participants variation (peak-to-peak) of deviations from the reference values		
		for TIGen	for InLambda	total (for both standards jointly)
SR620	B	100 ps	43 ps	100 ps
	E	22 ps	47 ps	57 ps
	F	42 ps (x2)	47 ps (x2)	117 ps (x2)
	H	62 ps	29 ps	64 ps
	I	35 ps (x2)	44 ps (x2)	46 ps (x2)
	O	60 ps	63 ps	117 ps
	Q	22 ps (x3)	57 ps (x3)	79 ps (x3)
	V	97 ps	7 ps	97 ps

Used brand of TICs	Code of Lab	Obtained by participants variation (peak-to-peak) of deviations from the reference values		
		for TIGen	for InLambda	total (for both standards jointly)
53230A	C	18 ps	23 ps	55 ps
	G	6 ps	37 ps	37 ps
	J	15 ps	43 ps	49 ps
	P	12 ps	27 ps	49 ps
	U	20 ps	43 ps	57 ps
	W	55 ps	33 ps	239 ps
	X	65 ps	43 ps	99 ps
CNT91	M	28 ps	33 ps	55 ps
	S	10 ps	61 ps	78 ps
	T	68 ps	83 ps	97 ps
PM6681/	D	232 ps	73 ps	232 ps
PM6681R	L	92 ps	77 ps	104 ps
	N	103 ps	44 ps	103 ps
53132A	K	85 ps	113 ps	208 ps
T4100U	A	10 ps	22 ps	22 ps
HSO	R	0.3 ps	0.4 ps	0.8 ps

In the case of **SR620**, the observed range (peak-to-peak) of variations of deviations from the reference values does not exceed 100 ps typically (117 ps in total), whereby employing two (x2) or three (x3) devices may improve this characteristics, although caution is recommended, because two or three items may not be representative for this statistically enough or, paradoxically, might result in the observed wider variations due to better coverage of the non-linearities range. This may explain the observed wider variations in case of Q# (3x) than in the cases of E#, H# or I#. These results are consistent with manufacture's documentation [8] concerning non-linearities and with long series of continuous time interval measurements performed with the SR620 and compared to phase measurements performed with higher accuracy with the usage of standard frequency comparator [6, 11]. Observed total variations in cases of F# and O# differ from obtained separately variations for TIGen and InLambda standards significantly and may represent individual differences in auxiliary measurements between both group of results additionally.

In the case of **53230A**, the observed range of variations of deviations from the reference values does not exceed about 70 ps or less typically (99 ps in total), which agrees with manufacturer specification very well [12], except of the discussed before case of W# results with a significant difference (239 ps peak-to-peak) between deviations for TIGen standard and for InLambda standards which are likely of a different un-known origin. This estimation agrees with the results of non-linearity verification performed and reported by ILNAS (P# results) for the same type of TIC, where the possible non-linearities up to 80 ps peak-to-peak were shown during changing the measured time interval. The case of G# results is also very interesting, because of a very small variations and deviations from the reference values and a high repeatability observed for the most results, what it suggested the possibility of averaging 53230A's non-linearities over time to some extent, allowing for some specific measurement conditions applied by G# Lab, i.e. 5 sessions (one per day) of 100 measurements repeated for each time interval – over 5 days totally. It is worth noting, that measurement conditions of G# Lab for TIGen and for InLambda standards are slightly different in frequency repetition of the measured time intervals: 1 Hz – for TIGen, and 10 Hz – for InLambda standards, which may result in different representations and different averaging non-linearities (for TIGen: observed 6 ps peak-to-peak variation of deviation from the reference values, and for InLambda standards: observed 37 ps peak-to-peak variation).

Quite opposite, the longer beaks between series of measurements may cause the weaker reduction of the 53230A's non-linearities, as it may be deduced from the case of X# results with auxiliary determined residuals, corresponding to inconsistencies of differential channels and cables delays between different pairs of measurements. Observed by X# Lab residuals for InLambda standards do not exceed 1 ps, as all series of measurements in the four required cable configurations for each time interval separately were performed within 3 min in total approximately (10 s lasting series of measurements with 10 Hz frequency and with breaks of 40-50 s between series), whereas the residuals obtained for TIGen are changing up to more than 20 ps, as all series of measurements in the four required cable configurations lasted 10 times longer in total (within 30 min approximately – 50 s lasting series of measurements with 1 Hz frequency repetition and with breaks of 6 min at least between series). Although both X# and G# groups of results were obtained with the same brand of TICs and repetition frequencies (1 Hz and 10 Hz appropriately) of the measured time intervals, but measurements were performed by both Labs in another configurations of connection cables and another schedule of collection measurement series.

In the uncertainty budget related to G# group results (see: Appendix G), the initially adopted assumption of noise character of the non-linearity component drawn attention, especially which it was supposed to be smoothing out with $1/\sqrt{n}$ factor, where $n = 100$ was a number of measurements in one series. Despite specific conditions applied during measurement procedure, validity of a such assumption seems to be broken to some extent, as this is compared to the observed variations of deviations from the reference values for measurements performed with the same brand of TIC as in the case of G#. Although the other G# results match the reference values very well, some residual random quasi-systematic character of non-linearities, not subject to averaging, might have occurred more clearly for one single result of G300.

In the case of **CNT91**, the observed range of variations of deviations from the reference values does not exceed about 80 ps or less typically (97 ps in total). It can be also assigned to residual internal non-linearities inside of the TIC, although this value is lower than a random quantization error (1σ) of 100 ps given in manufacturer's documentation [13], however which should be subject to averaging statistically (i.e. 10 times smaller for series of 100 measurements) as a random component.

In the case of **PM6681**, there are observed variations of deviations from the reference values in the range of a bit more than 100 ps, except of D126 result (reported as the last one in the summary of the results of D# lab, sic!), whose deviation differs from the deviations of the other D# results up to 232 ps. In the uncertainty budgets of D# results, a correction for the measured systematic delay (due to internal counter asymmetry, connecting cables, and trigger level setting errors, calculated as the arithmetic mean of individual measurements) takes on identical values, which suggests that this correction was measured once for the whole set of time interval measurements. Although, this deviation meets the general manufacturer's specifications [14] very well, where a typical systematic error due to inter-channel asymmetry is given as <300 ps, anyway a very slow changing character of systematic error was rather expected as well as to be more dominant than its non-linear part.

In the cases of **53132A** and **T4100U**, the observed variations of deviations from the reference values are up to 208 ps and 22 ps respectively, which are consistent with the results of verification their non-linearities reported in [15] (up to 450 ps peak-to-peak variations for 53132A) and [6] (up to 15 ps peak-to-peak variation for T4100U) allowing for the possible noise contribution in the case of A# results (applied 10 measurements in one series only with standard deviation up to 6 ps).

For HSO (generalizing, for event timers) with time interval measurement based on continuous time stamping with high frequency clock, the non-linearities dependent of the measured time interval should not appear. Anyway, some systematic effects are possible to some extent (mismatching of: inputs, cable connectors, trigger levels).

Summary conclusions

Considering the above remarks and findings as well as analysing the applied measurement methods together with the reported uncertainty budgets of participants, it can be concluded that:

a. For precise time interval measurements, the methods independent of cable delay asymmetry and with reduction of differential channel delay of TIC are recommended. Non-reduced quasi-systematic part of internal differential channel delay and residual internal non-linearities should be included into uncertainty budgets.

b. Internal differential channel delay and internal non-linearities inside TICs are both quasi-systematic and quasi-random nature, because they vary with the value of the measured time interval and over time. For different devices of the same brand of TICs or for different brands of TICs, the range of variations and rate (dynamics) of change over time of the non-linearities may be different, thus applying better estimation of systematic effects than stated in manufacturer's documentation is possible but should be justified.

c. Extension of measurements in time may reduce by averaging the fast changing in time non-linearity components but simultaneously separation of the series of measurements in time may expose the slow changing in time non-linearity components to increase significantly. There should be a compromise between the duration of measurements and the observed variation in time of the quasi-systematic components.

d. The additional auxiliary measurements of the systematic components (offset measurements, cable and channel asymmetry measurements, e.t.c.), if applicable, should be performed both before and after proper series of measurements to verify the validity of the correction for systematic effects over time.

e. Usage of the average value of the results obtained with more than one TIC for measurements of the same time interval and with applying the propagation law of uncertainty, allow to reduce the influence of internal differential non-linearities inversely proportional to the square root of the number of the used TICs, successfully, provided that the correct and representative estimate of the range of non-linearities changes is adopted in the uncertainty budget (see: g. conclusion, too).

f. Executing **AUTOCAL procedure** in **SR620** allowed to optimize internal differential channel delay and internal non-linearities successfully. The same effect is obtained employing pivot method, if it is justified (as both measured signals are repeated periodically and the phase difference of each measured signals is fixed with reference to the auxiliary pivot signal – an increased jitter of measurements may be expected (compare: e.g. E# and F# uncertainty budgets)) or other method reducing cable asymmetry and differential channel delay correctly.

g. The observed variations of deviations from the reference values in this comparison are not necessary fully representative for possible full ranges of changes of the internal non-linearities inside the used brand of TICs, but they can be a good reference/starting point for uncertainty evaluation of systematic effects in time interval measurements and for further investigations.

h. Consistently, some of the results reported in this comparison have got assigned significantly conservative (with overestimated influence of some effects) values of the uncertainties, which can be lowered **up to 0.20 ns** ($p \approx 95$ %) at least or better. This may be applied to **the B# and Q# results** (performed with SR620s with reducing cable asymmetry and after AUTOCAL procedures), **J# and U# results** (performed with 53230As, with reduced cable asymmetry and differential channel delay correctly) and **S# results** (performed with CNT91, with reduced cable asymmetry and differential channel delay correctly).

i. Consistently, despite the positive results of the comparison, it is recommended some labs to inspect or investigate its own uncertainty budgets carefully to justify better specific measurement conditions and assumptions, when assigning smaller than typically obtained uncertainties with the same type of TIC on regular basis, with and without even observing a larger bias of the results.

j. Allowing for lowering uncertainty to single picoseconds level for the real time High Speed Oscilloscopes, it is recommended to investigate and verify possible systematic effects influencing a possible non-compensated bias of the measured time intervals, too.

The obtained comparable results were possible due to a very good matching parameters of the measured pulse signals generating by the transfer standards and therefore well-defined measurands, making the measured time intervals nearly insensitive to pass-bands of the TIC's inputs in practice (minimising frequency dependent asymmetry of propagation delay) and nearly insensitive to different characteristics of the used auxiliary local signals. However, this situation is realistic in some specific cases only, as both signals are taken from the same system or device with well-matched outputs. Whereas time interval measurements between the pulse signals with different rising slopes, different amplitudes and different frequency characteristics are performed more frequently (signals taken from different systems/devices or traveling along different paths with different attenuations and frequency pass-bands) – in a such case a proper and unambiguous definition of measurand and accounting individually influence of TIC and connecting cables is more complex.

The obtained comparison results support the existing, being updated or planned for update CMC claims for time interval measurements of each participants under condition that the above conclusions are taken into account carefully. There is possible the improvement of many existing CMC claims, however the lower limit of the assigned uncertainties than a typical one for the observed residual internal non-linearities and differential channel delays must be verified and justified individually according to the applied or improved measurement method and the characteristics of the applied measurement instrument.

The proposed form of publishing the results of comparison after approval by all the participants is publishing in the Technical supplement of Metrologia or other scientific publications as well as presentation these results in a conference.

14 References

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15 Appendixes (copies of participants' measurement reports):

1. Appendix A (GUM report)
2. Appendix B (FTMC report)
3. Appendix C (VTT report)
4. Appendix D (RISE report)
5. Appendix E (PTB report)
6. Appendix F (VSL report)
7. Appendix G (SMD report)
8. Appendix H (IPQ report)
9. Appendix I (ROA report)
10. Appendix J (SIQ report)
11. Appendix K (SMU report)
12. Appendix L (NIM report)
13. Appendix M (BIM report)
14. Appendix N (EIM report)
15. Appendix O (BEV report)
16. Appendix P (ILNAS report)
17. Appendix Q (NPL report)
18. Appendix R (UME report)
19. Appendix S (BoM report)
20. Appendix T (DMDM report)
21. Appendix U (MBM report)
22. Appendix V (IMBIH report)
23. Appendix W (SASO report)
24. Appendix X (JV report)

Appendix A

GUM report

Supplementary comparison EURAMET.TF-S1
Time interval measurements
(within EURAMET project of #1485)

Measurement report
of Central Office of Measures (GUM)

(measurements performed on 16-17 December 2019)

Time and Frequency Laboratory
Central Office of Measures (GUM)
Elektoralna 2 Str.
00-139 Warsaw, Poland

e-mail: albin.czubla@gum.gov.pl

Warsaw, 14 January 2020

1. Participating Laboratory:

   Central Office of Measures (GUM), Time and Frequency Laboratory

   Acronym of institute: GUM Country: Poland

2. Description of calibration method:

It was applied direct measurement of time interval between pulse signals with the usage of Time Interval Counter (TIC) in configuration shown in Fig. 1 a). The proper measurements were proceeded by auxiliary precise calibration of differential channels of TIC and connecting cables delays performed in configurations shown in Fig. 1 a) and Fig. 1 b). During all measurements, the external standard input signals for Devices Under Tests (DUT) were used: 10 MHz or 1 pps of UTC(PL), so the pulse signals at the pairs of outputs of DUTs were generated with the fixed period T_0 close equal to nominal value of 1 s (it was confirmed/ verified by additional auxiliary direct measurements of frequency output signals of DUTs performed with time/frequency counter with longer gate time).

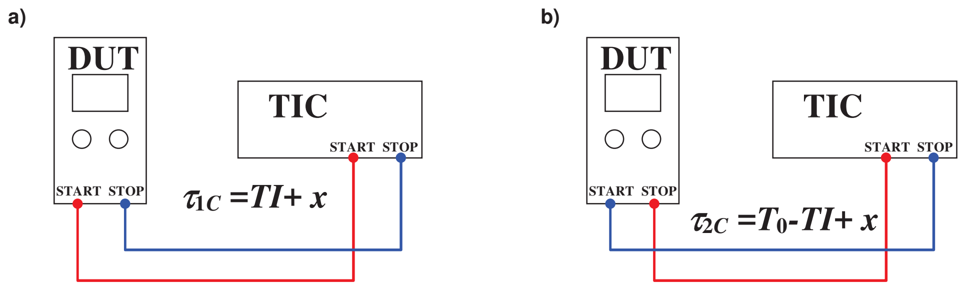

Fig. 1. Scheme of auxiliary precise calibration of differential channels of TIC and connecting cables delays (denoted here as x): a) normal configuration, b) configuration with the reverse order of cables between the START and STOP outputs of the periodic source of the measured signals (the order of the cables at the inputs of TIC has been not changed during measurements).

Each measurement was performed as a series of 10 consecutive measurement and was repeated to verify the observed stability of the results – recorded average values and standard deviation.

The above calibration method is described in the calibration procedures of GUM: IW1-TF (calibration of frequency generators) and IW5-TF (calibration of time/frequency counters).

3. Description of calibration set-up and equipment

The applied calibration set-up is shown in Fig. 2.

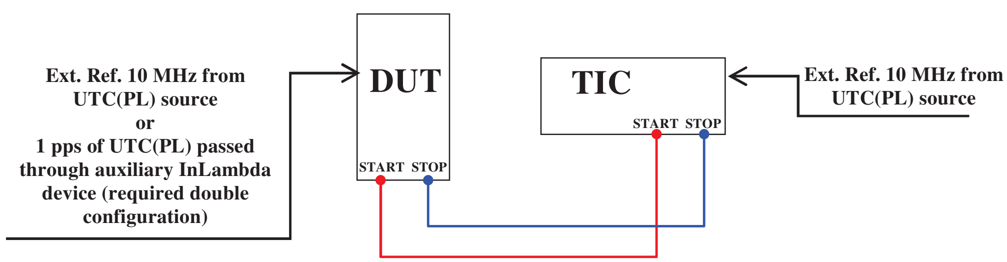

Fig. 2. Scheme of calibration set-up.

There were used short connecting cables #s030 and #s031 (c. 2,5 m of lengths and c. 12 ns of delays) ended with sma male connectors. For measurements of InLambda standards, there were used extra BNC(male)-sma(female) adapters.

Time interval measurements were performed with TIC of T4100U, sn 00D13356D17144F9, of PikTime Systems, with external reference 10 MHz taken from UTC(PL) frequency distribution amplifier.

Verification of the value of the fixed value of the period T_0 of the output pulses of DUTs were performed with time/frequency counter of CNT-81, sn SM847754, of Pendulum, with external reference 10 MHz taken from UTC(PL) frequency distribution amplifier.

4. Traceability chart:

The applied traceability chart is shown in Fig. 3.

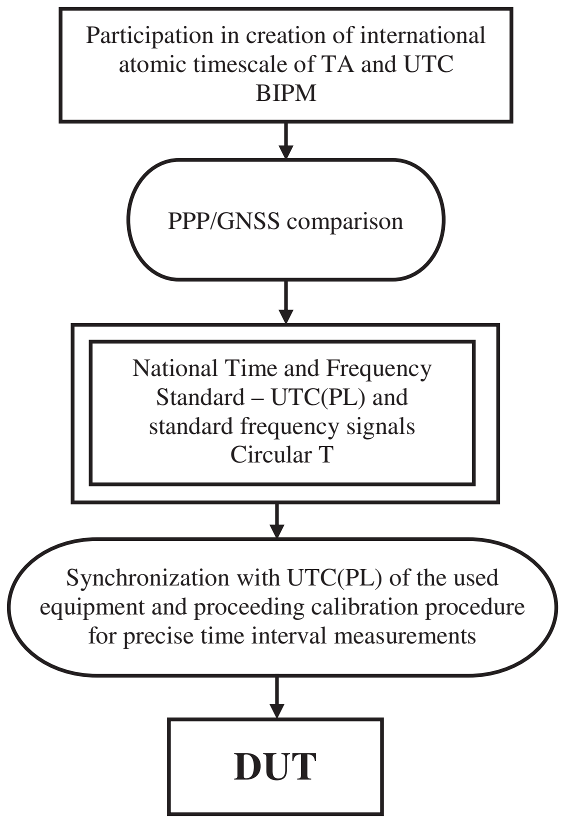

Fig. 3. Scheme of traceability chain.

5. Used relationship for obtaining estimates of results and uncertainty budget:

Model equation that follows from the measurement setup:

$$TI = \tau_1 + \frac{T_0 - (\tau_{1c} + \tau_{2c})}{2} + \delta_1$$

Description of the quantities in the model equation:

Quantity X_i	Description
TI	The measured time interval between pulses generated by DUT

τ_1	Observed indication of Time Interval Counter (TIC) during measurement of *TI* in "normal" configuration" (used the same connecting cables as during auxiliary precise calibration of differential channels and cables delays)
T_0	Fixed period of the output signals of DUT observed at both outputs during auxiliary precise calibration of differential channels and connecting cables delays
τ_{1c}	Observed indication of TIC during auxiliary precise calibration of differential channels and connecting cables delays – measurement in "normal" configuration (the same order of the cables at the outputs of DUT as during measurement of *TI*)
τ_{2c}	Observed indication of TIC during auxiliary precise calibration of differential channels and connecting cables delays – measurement in configuration with reverse order of the cables at the outputs of the source of periodical signals (the reverse order of the cables at the outputs of DUT as during measurement of *TI*)
δ_1	Correction for internal nonlinearities and other non-compensated systematic effects in TIC

6. Obtained results of measurements:

Obtained results for TIGen:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Associated standard uncertainty (in ns)	Unit of measure
"dn0"	22,655	±	0,030	0,015	ns
"dn3"	250,012	±	0,030	0,015	ns
"dn7"	1508,965	±	0,030	0,015	ns
"dn126"	12039,490	±	0,030	0,015	ns

Obtained results for InLambda standards:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Associated standard uncertainty (in ns)	Unit of measure
Inλ 20	24,196	±	0,030	0,015	ns
Inλ 100	104,516	±	0,030	0,015	ns
Inλ 300	307,321	±	0,030	0,015	ns

The resulted expanded measurement uncertainties (evaluated at p ≈ 95 %) have been increased to the value of 0,030 ns – a new proposed CMC value of PL (GUM) service for time interval measurements between two pulse signals with closely the same shape of the rising slopes of the measured pulse signals and with rise time <1 ns. The assumed coverage factor is $k = 2$.

The residual non-linearities of the measurement system were included into the uncertainty budget in the component of δ_1, with assumed estimate of 0 ns and standard uncertainty of 0,020 ns/√3 ≈ 0,012 ns of the applied TIC (T4100U of PikTime). Other systematics effects were compensated by performing procedure of the auxiliary precise calibration of differential channels of TIC and connecting cables delays.

All measurements were performed at trigger level fixed to 500 mV at 50 Ω.

Detailed uncertainty budget tables are given below:

- Uncertainty budget used for TIGen: dn0

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
τ_1	22.684 ns	0.00231 ns	t-student	A	1	0.00231 ns	9
T_0	1 s	<0.005 ns	normal	B	0.5	<0.00250 ns	∞
τ_{1c}	22.685 ns	0.00272 ns	t-student	A	-0.5	-0.00136 ns	9
τ_{2c}	1 s – 22.627 ns	0.00506 ns	t-student	A	-0.5	-0.00253 ns	9
δ_1	0 ns	0.01155 ns	rectangular	B	1	0.01155 ns	∞
TI	**22.655 ns**						

Combined standard uncertainty	u_c	0.01238 ns
Effective degrees of freedom	ν_{eff}	2900
Expanded uncertainty ($p \approx 95\%$)	U	0.02475 ns

- Uncertainty budget used for TIGen: dn3

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
τ_1	250.041 ns	0.00190 ns	t-student	A	1	0.00190 ns	9
T_0	1 s	<0.005 ns	normal	B	0.5	<0.00250 ns	∞
τ_{1c}	22.685 ns	0.00272 ns	t-student	A	-0.5	-0.00136 ns	9
τ_{2c}	1 s – 22.627 ns	0.00506 ns	t-student	A	-0.5	-0.00253 ns	9
δ_1	0 ns	0.01155 ns	rectangular	B	1	0.01155 ns	∞
TI	**250.012 ns**						

Combined standard uncertainty	u_c	0.01231 ns
Effective degrees of freedom	ν_{eff}	3599
Expanded uncertainty ($p \approx 95\%$)	U	0.02461 ns

- Uncertainty budget used for TIGen: dn7

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
τ_1	1508.994 ns	0.00395 ns	t-student	A	1	0.00395 ns	9
T_0	1 s	<0.005 ns	normal	B	0.5	<0.00250 ns	∞
τ_{1c}	22.685 ns	0.00272 ns	t-student	A	-0.5	-0.00136 ns	9
τ_{2c}	1 s – 22.627 ns	0.00506 ns	t-student	A	-0.5	-0.00253 ns	9
δ_1	0 ns	0.01155 ns	rectangular	B	1	0.01155 ns	∞
TI	**1508.965 ns**						

Combined standard uncertainty	u_c	0.01279 ns
Effective degrees of freedom	ν_{eff}	833
Expanded uncertainty ($p \approx 95\%$)	U	0.02557 ns

- Uncertainty budget used for TIGen: dn126

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
τ_1	12039.519 ns	0.00538 ns	t-student	A	1	0.00538 ns	9
T_0	1 s	<0.005 ns	normal	B	0.5	<0.00250 ns	∞
τ_{1c}	22.685 ns	0.00272 ns	t-student	A	-0.5	-0.00136 ns	9
τ_{2c}	1 s – 22.627 ns	0.00506 ns	t-student	A	-0.5	-0.00253 ns	9
δ_1	0 ns	0.01155 ns	rectangular	B	1	0.01155 ns	∞
TI	**12039.490 ns**						

Combined standard uncertainty	u_c	0.01329 ns
Effective degrees of freedom	ν_{eff}	319
Expanded uncertainty ($p \approx 95\%$)	U	0.02659 ns

- Uncertainty budget used for InLambda standards: Inλ 20

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
τ_1	24.218 ns	0.00168 ns	t-student	A	1	0.00168 ns	9
T_0	1 s	<0.005 ns	normal	B	0.5	<0.00250 ns	∞
τ_{1c}	24.217 ns	0.00174 ns	t-student	A	-0.5	-0.00087 ns	9
τ_{2c}	1 s – 24.172 ns	0.00601 ns	t-student	A	-0.5	-0.00300 ns	9
δ_1	0 ns	0.01155 ns	rectangular	B	1	0.01155 ns	∞

TI	**24.196 ns**						

Combined standard uncertainty	u_c	0.01234 ns
Effective degrees of freedom	ν_{eff}	2317
Expanded uncertainty ($p \approx 95\%$)	U	0.02467 ns

- Uncertainty budget used for InLambda standards: Inλ 100

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
τ_1	104.538 ns	0.00247 ns	t-student	A	1	0.00247 ns	9
T_0	1 s	<0.005 ns	normal	B	0.5	<0.00250 ns	∞
τ_{1c}	24.217 ns	0.00174 ns	t-student	A	-0.5	-0.00087 ns	9
τ_{2c}	1 s – 24.172 ns	0.00601 ns	t-student	A	-0.5	-0.00300 ns	9
δ_1	0 ns	0.01155 ns	rectangular	B	1	0.01155 ns	∞
TI	**104.516 ns**						

Combined standard uncertainty	u_c	0.01247 ns
Effective degrees of freedom	ν_{eff}	1826
Expanded uncertainty ($p \approx 95\%$)	U	0.02494 ns

- Uncertainty budget used for InLambda standards: Inλ 300

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
τ_1	307.343 ns	0.00139 ns	t-student	A	1	0.00139 ns	9
T_0	1 s	<0.005 ns	normal	B	0.5	<0.00250 ns	∞
τ_{1c}	24.217 ns	0.00174 ns	t-student	A	-0.5	-0.00087 ns	9
τ_{2c}	1 s – 24.172 ns	0.00601 ns	t-student	A	-0.5	-0.00300 ns	9
δ_1	0 ns	0.01155 ns	rectangular	B	1	0.01155 ns	∞
TI	**307.321 ns**						

Combined standard uncertainty	u_c	0.01230 ns
Effective degrees of freedom	ν_{eff}	2402
Expanded uncertainty ($p \approx 95\%$)	U	0.02460 ns

7. Identification and description of the source 10 MHz reference frequency for TIGen standard and of the used pulse signals for InLambda standards

External standard 10 MHz reference frequency applied for TIGen standard was given directly from the UTC(PL) source, i.e. 10 MHz from Hydrogen Maser of 1003M steered by Femtostepper and distributed by Frequency Distribution Amplifier.

The used pulse signals for InLambda standards were given directly from the UTC(PL) source, i.e. 1 pps signals generated by Femtostepper (based on 10 MHz input frequency taken from Hydrogen Maser of 1003M) and distributed by Pulse Distribution Amplifier. For connection with auxiliary used InLambda standard and between InLambda standards, short cables were used to avoid worsening the parameters of the input 1 pps signals.

The characteristics of the used signals for steering TIGen standard and for InLambda standards are given in the tables below.

External standard 10 MHz reference frequency applied for TIGen standard	
Source (Cs clock, HM, …)	HM 1003M + Femtostepper+ FDA – 10 MHz
Amplitude (at 50 Ω)	2 V_{p-p}

External input pulses applied to an auxiliary InLambda standard	
Source (Cs clock, HM, frequency generator, ..)	HM 1003M + Femtostepper + PDA – 1 pps
1 pps (yes / no)	yes
Frequency	1 Hz
Low level	0 V
High level (at 50 Ω)	2 V
Rise time (20% to 80 %)	<1 ns
Duty cycle	0,002 %
Pulse width	20 µs
Application of a double configuration	
DUT – Device Under Test	Auxiliary used device
Inλ 20	Inλ 100
Inλ 100	Inλ 20
Inλ 300	Inλ 100

8. Ambient conditions met during measurements

The source of the measured Time Interval	Ambient temperature during measurements (for every InLambda standard separately – including expanded uncertainty, 95%)			Unit of measure
TIGen	22,1	±	0,4	°C
Inλ 20	22,1	±	0,3	°C

The source of the measured Time Interval	Ambient temperature during measurements (for every InLambda standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 100	22,0	±	0,3	°C
Inλ 300	22,2	±	0,3	°C

Ambient humidity during measurements			**Unit of measure**
34	±	6	%

9. Average date of measurements

 16-17 December 2019

Albin Czubla
(Name)

A. Czubla
14 January 2020
(Date and signature)

Appendix B

FTMC report

Annex 7. Minimum contents for the measurement report

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: FTMC Country: Lithuania

Time period of the measurements: 2019.12.27 - 2020.01.03

Remarks:

Identification of the participating laboratory: LT.

- Description of the calibration method: time interval measurements using different cable connections to eliminate the difference in cable delays from the measurement results. At first, the Start output of the DUT was connected via the cable A to the channel A of a SR620 time interval counter (TIC), while the Stop output of the DUT was connected via the cable B to the channel B of the TIC. Then, the cables were interchanged and the measurement was repeated. Finally, the cables were interchanged once again to return to the initial connection, and the measurement was repeated once again. The mean value of the results of the measurements 1 and 3 was averaged with the result of the measurement 2. In this way, influence of the difference between the cable delays was eliminated. On the other hand, the cables A and B were of similar length – (24.5±0.2) cm and (25.5±0.2) cm, respectively. They were of the same type, manufactured from the same materials.

The differential delay between channels A and B was estimated by means of measuring the time difference between PPS coming from the same source using different cable connections. The value was found to be at the picosecond level (which is consistent with the device specification) and accounted for when estimating uncertainty of measurement.

- Description of the calibration set-up and equipment. Measurement setup is shown in Fig.1. The measurements have been made with a SR620 time interval counter disciplined to a HP5071A caesium atomic clock, which realizes the UTC(LT) time scale and has also served as a source of the reference 10 MHz signal for the TIGen measurements.

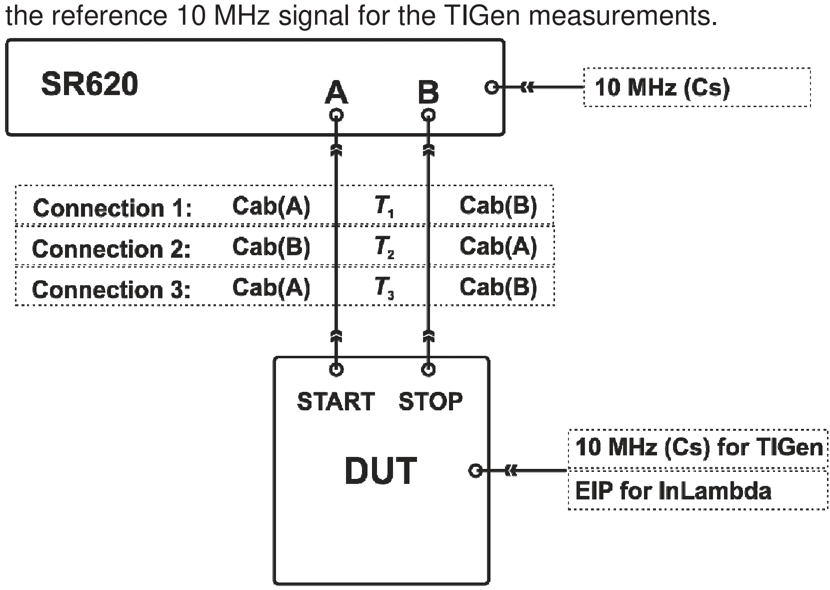

Fig. 1. Setup of the connections used for time interval measurements during the supplementary comparison EURAMET.TF-S1. EIP – external input pulses from a 1 PPS output of the Cs clock

- Traceability: the UTC(LT) time scale realized by the caesium atomic clock used as a source of the reference 10 MHz signal is traceable to the UTC by means of continuous comparison between the time signals generated by the atomic clock and those coming from the GPS, which is done by using a TTS-5 time transfer system. Traceability is documented in *Circular T* available at ftp://ftp2.bipm.org/pub/tai/publication/utclab/utc-lt.

- Relationship/equation used for obtaining estimates of results and uncertainty budget:

$$TI = \frac{1}{2}\left(\frac{T_1 + T_3}{2} + T_2\right),$$

where TI is the result reported, T_1 is the time interval measured using the connection 1 depicted in Fig. 1 (see above), T_2 is the time interval measured using the connection 2, i. e., the same as the connection 1, except that the cables A and B are interchanged, and T_3 is the time interval measured using the connection 3 – i. e., the time interval measured with the connection 1 once again.

- Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects:

The results of measurements obtained with their standard and expanded uncertainties for the TIGen standard and the InLambda standards are presented in Tables 1 and 2, correspondingly. Uncertainty budgets are given in the Tables 3-9.

Table 1. Measurement results with uncertainties for the TIGen standard:

Number of the measured time interval	Determined value of the measured time interval (ns)	Its standard uncertainty (ns)	Its expanded uncertainty (p ≈ 95 %, in ns)
"dn0"	22.6	± 0.52	± 1.04
"dn3"	250.0	± 0.52	± 1.04
"dn7"	1509.0	± 0.52	± 1.04
"dn126"	12039.5	± 0.52	± 1.04

Table 2. Measurement results with uncertainties for the InLambda standards:

The source of the measured time interval	Determined value of the measured time interval (ns)	Its standard uncertainty (ns)	Its expanded uncertainty (p ≈ 95 %, in ns)
Inλ 20	24.2	± 0.52	± 1.04
Inλ 100	104.5	± 0.52	± 1.04
Inλ 300	307.3	± 0.52	± 1.04

Table 3. Uncertainty budget for the measurement D0

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 $c_i \cdot u(x_i)$, ns	Degrees of freedom ν_i
T_1	22.723	0.52	Not stated	B	0.25	0.13	N/A
T_2	22.543	0.52	Not stated	B	0.5	0.26	N/A
T_3	22.722	0.52	Not stated	B	0.25	0.13	N/A
		Combined standard uncertainty			u_c	0.52 ns	
		Effective degrees of freedom			ν_{eff}	N/A	
		Expanded uncertainty ($p \approx 95\%$)			U	1.04 ns	

Note concerning the evaluation of the measurement uncertainty. According to the specification of the TIC, its measurement $|Error| = \text{R}esolution + t\Delta_L + \Delta_{trig1} + \Delta_{trig2} + 0.5ns$, where t is the time interval measured, Δ_L is the relative error of the time base frequency (in our case – of atomic clock), $\Delta_{trig\,i}$ is the trigger error of the channel A (B). In our case, $\Delta_{trig1} = \Delta_{trig2} = \dfrac{15mV + 0.5\%\,(\text{trigger level})}{\partial u / \partial t}$, where $\partial u / \partial t$ is the slope of the pulse, which was estimated as $4 \cdot 10^9$ V/s, the level for both triggers was set to 0.5 V. Therefore, $\Delta_{trig1} = \Delta_{trig2} =$ 4.4 ps.

Finally, the resolution is expressed as follows:

$\text{Resolution} = \sqrt{\dfrac{(25ps)^2 + (t\sigma(t))^2 + (s_{trig1})^2 + (s_{trig2})^2}{n}}$, where n is the number of measurements, $\sigma(t)$ is the short-term stability of the TIC's time-base, $s_{trig1} = s_{trig2}$ is the trigger jitter, which is estimated as $s_{trig} = \dfrac{\sqrt{E^2_{internal} + E^2_{signal}}}{\partial u / \partial t}$, where $E_{internal}$ and E_{signal} are the noise levels of the trigger inputs and the signal, which can be estimated as 350 μV = $3.5 \cdot 10^{-4}$ V. Now,

$\text{Resolution} = \sqrt{\dfrac{6.25 \cdot 10^{-22}s + \sigma(t)t^2 + 3.06 \cdot 10^{-26}s}{n}}$. The problem is that we don't have an estimate of $\sigma(t)$ for such short intervals. On the other hand, experimental standard deviation of the results is up to 43 ps for the "dn126" measurements, and up to 12 ps for measurements of shorter intervals – the value smaller than a single 25 ps term presented in the specification. Anyway, the standard deviation of the mean is up to about 1 ps.

Another issue to be considered is the repeatability of the measurement results. Having repeated the measurements after reconnecting the cables back, we have obtained results differing by up to about 10 ps from the initial ones. Keeping in mind that the error of the time-base (i., e., atomic clock) Δ_L is of the order of 10^{-13} to 10^{-12} in our measurement conditions, and the associated contribution $t\Delta_L$ is infinitesimal, we obtain a safe estimate of the standard uncertainty $u(x_i)$ for all the measurements:

$u(x_i) = 1ps + 10ps + 8.8ps + 500ps \approx 520ps.$ The value is determined mostly by systematic effects, which cannot be eliminated by averaging measurements in similar conditions. The conventional law of error propagation, which assumes that input quantities are statistically independent and states that their contributions can be added in quadrature, doesn't apply here. It is why the combined standard uncertainty u_c is the same as $u(x_i)$.

Table 4. Uncertainty budget for the measurement D3

Quantity	Estimate	Standard	Probability	Method of	Sensitivity	Uncertainty	Degrees of

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 $c_i \cdot u(x_i)$, ns	Degrees of freedom ν_i
T_1	250.09	0.52	Not stated	B	0.25	0.13	N/A
T_2	249.918	0.52	Not stated	B	0.5	0.26	N/A
T_3	250.091	0.52	Not stated	B	0.25	0.13	N/A
		Combined standard uncertainty			u_c	0.52 ns	
		Effective degrees of freedom			ν_{eff}	N/A	
		Expanded uncertainty ($p \approx 95\%$)			U	1.04 ns	

Table 5. Uncertainty budget for the measurement D7

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 $c_i \cdot u(x_i)$, ns	Degrees of freedom ν_i
T_1	1509.11	0.52	Not stated	B	0.25	0.13	N/A
T_2	1508.94	0.52	Not stated	B	0.5	0.26	N/A
T_3	1509.11	0.52	Not stated	B	0.25	0.13	N/A
		Combined standard uncertainty			u_c	0.52 ns	
		Effective degrees of freedom			ν_{eff}	N/A	
		Expanded uncertainty ($p \approx 95\%$)			U	1.04 ns	

Table 6. Uncertainty budget for the measurement D126

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 $c_i \cdot u(x_i)$, ns	Degrees of freedom ν_i
T_1	12039.6	0.52	Not stated	B	0.25	0.13	N/A
T_2	12039.4	0.52	Not stated	B	0.5	0.26	N/A
T_3	12039.6	0.52	Not stated	B	0.25	0.13	N/A
		Combined standard uncertainty			u_c	0.52 ns	
		Effective degrees of freedom			ν_{eff}	N/A	
		Expanded uncertainty ($p \approx 95\%$)			U	1.04 ns	

Table 7. Uncertainty budget for the measurement λ20

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 $c_i \cdot u(x_i)$, ns	Degrees of freedom ν_i
T_1	24.261	0.52	Not stated	B	0.25	0.13	N/A
T_2	24.07	0.52	Not stated	B	0.5	0.26	N/A
T_3	24.253	0.52	Not stated	B	0.25	0.13	N/A
		Combined standard uncertainty			u_c	0.52 ns	
		Effective degrees of freedom			ν_{eff}	N/A	
		Expanded uncertainty ($p \approx 95\%$)			U	1.04 ns	

Table 8. Uncertainty budget for the measurement λ100

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 $c_i \cdot u(x_i)$, ns	Degrees of freedom ν_i
T_1	104.58	0.52	Not stated	B	0.25	0.13	N/A
T_2	104.403	0.52	Not stated	B	0.5	0.26	N/A
T_3	104.586	0.52	Not stated	B	0.25	0.13	N/A

Combined standard uncertainty	u_c	0.52 ns
Effective degrees of freedom	ν_{eff}	N/A
Expanded uncertainty ($p \approx 95\%$)	U	1.04 ns

Table 9. Uncertainty budget for the measurement λ300

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 $c_i \cdot u(x_i)$, ns	Degrees of freedom ν_i
T_1	307.384	0.52	Not stated	B	0.25	0.13	N/A
T_2	307.179	0.52	Not stated	B	0.5	0.26	N/A
T_3	307.382	0.52	Not stated	B	0.25	0.13	N/A

Combined standard uncertainty	u_c	0.52 ns
Effective degrees of freedom	ν_{eff}	N/A
Expanded uncertainty ($p \approx 95\%$)	U	1.04 ns

Note: the value of uncertainty is determined mostly by a systematic effect – the residual nonlinearity of the time interval counter, which estimate is given in the specification. Therefore, the number of degrees of freedom is not applicable. Probability distribution has not been provided by the manufacturer. As the systematic effects can not be reduced by repeating the measurements under similar conditions, we state the value of the combined standard uncertainty the same as that of the measured quantities.

- Identification and description of the source of 10 MHz reference frequency for TIGen standard:
a HP5071A caesium atomic clock, S. N.: US39301362. Amplitude of the 10 MHz signal (at 50 Ω): 1.8 V.

- Description of the input pulse signals used for InLambda standards:

Low level: 0 V, high level (amplitude): 2.2 V, frequency: 1 Hz, pulse width: 20 µs, rise time (20% to 80 %): < 1.5 ns, duty cycle: 0.002 %.

- Ambient conditions were the same during all the measurements (for both the TIGen standard and every InLambda standard): ambient temperature was (25 ± 1) °C, and ambient humidity was (25 ± 5) %.

- Date and signature:

Emilis Urba 2020.01.17

Appendix C

VTT report

Annex 7: measurement report

This report should be considered together with Annex 3 and Annex 4.

1.1 - Identification of the participating laboratory

VTT MIKES

1.2 - Description of the calibration method

The Pivot-method [Rovera2019] was used. The start-input of the time-interval counter was permanently connected to a 1PPS distribution amplifier. The stop-input of the time-interval counter was first connected the DUT-start, a measurement of N=60...100 taken, then moved to the DUT-stop, and another N=60...100 measurements taken. The unconnected DUT-port was terminated at 50 Ohm. The DUT time-interval was determined as the difference between the readings in the two measurement configurations.

[Rovera2019] G. D. Rovera *et al.* 2019 Metrologia 56 035004

1.3 - Description of the calibration set-up and equipment

An FDA/PDA distribution amplifier [Wallin] representing UTC(MIKE) 1PPS and 10 MHz, with BNC-outputs, was used for the set-up.

The time interval-counter, Keysight 53230A, had the external time-base connected to the UTC(MIKE) 10 MHz signal. The CH1 input was permanently connected to one PDA 1PPS output.

The TIGen was connected to a 10 MHz output of the FDA.

Standard BNC-BNC RG58 cables were used. SMA-connectors were finger-tightened.

Either the internal averaging function of the counter, or an external python script that controlled the counter over Ethernet, was used to gather the mean and standard deviation of N=60...100 measurements in each configuration.

[Wallin] https://ohwr.org/project/pda-8ch-fda-8ch

1.4 - Traceability chart

1PPS and 10 MHz signals representing UTC(MIKE) were used. UTC(MIKE) is currently based on MIKES Active Hydrogen Maser nr1 (AHM1) frequency output at 5 MHz. This frequency is doubled to 10 MHz and used as the reference input frequency for a SpectraDynamics HROG-10 phase-micro-stepper. The phase-micro-stepper produces 10MHz and 1PPS outputs representing UTC(MIKE) - based on steering commands that are computed each time a new Circular-T is issued. The results of the computation are published as MIKES "Atomic Bulletin" on our ftp site: ftp://monitor.mikes.fi/time-scale/

Traceability is through Circular-T. MIKES participates in Circular-T via GNSS PPP link using our main receiver MI04, Dicom GTR51.

1.5 - Used relationship/ equation for obtaining estimates of results and uncertainty budget

See Annex 3.

1.6 - Obtained results of measurements

See Annex 4.

1.7 - Identification and description of the source 10 MHz reference frequency for TIGen standard.

10 MHz representing UTC(MIKE), See Annex 4.

1.8 - Description of the used input pulse signals for InLambda standards (low level, high level (amplitude), frequency, pulse width, rise time (20% to 80 %), duty cycle),

See Annex 4.

1.9 - Ambient conditions of measurements (the temperature and the relative humidity) – the temperature for every InLambda standard separately,

See Annex 4.

1.10 - Average date of performing measurements,

See Annex 4.

1.11 - Date and signature.

Anders Wallin 2020-02-04

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: .....VTT Country: .....FINLAND

Average date of measurements: ...2020-01-17

Remarks: When tightening SMA/BNC-adapters to the TIGen front SMA-connectors with a SMA torque wrench the connectors became loose. Consequently the TIGen connectors were hand-tightened (a torque-wrench was not used).

....

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

<table>
<tr><td colspan="4">External standard 10 MHz reference frequency applied for TIGen standard</td><td>Required reference conditions</td><td>Meet requirements?
yes / no</td></tr>
<tr><td colspan="3">Source
(Cs clock, HM, ...)</td><td>Active hydrogen maser</td><td>10 MHz ± 1 Hz</td><td>yes</td></tr>
<tr><td colspan="3">Amplitude (at 50 Ω)</td><td>2.81 Vpp</td><td>within (0,5 ÷ 2) V_{p-p}</td><td>slightly over higher limit</td></tr>
<tr><td colspan="3">Ambient temperature during measurements</td><td>Unit of measure</td><td>Required reference conditions</td><td>Meet requirements?
yes / no</td></tr>
<tr><td>22.4</td><td>±</td><td>0.1</td><td>°C</td><td>within (22 ± 4) °C</td><td>yes</td></tr>
<tr><td colspan="3">Ambient humidity during measurements</td><td>Unit of measure</td><td>Required reference conditions</td><td>Meet requirements?
yes / no</td></tr>
<tr><td>40</td><td>±</td><td>1</td><td>%</td><td>within (50 ± 30) %</td><td>yes</td></tr>
<tr><td colspan="6">The base equipment used for time interval measurements</td></tr>
<tr><td colspan="4">The type / brand of time interval counter/ digital oscilloscope
(eg. SR620, 53230A, ...)</td><td colspan="2">Keysight 53230A. MIKES inventory nr. 13228. Serial nr. MY59190170</td></tr>
<tr><td colspan="4">Applied trigger level (50 Ω)
(Required: 0,5 V)</td><td colspan="2">DC-coupled, 0.5 V, into 50 Ohm.</td></tr>
<tr><td colspan="4">Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results
(eg. 0,150 ns/2 for SR620, unknown, ≤ ..., ...)</td><td colspan="2">The TIGen device showed repeatability at 0.1 ns level, therefore we add an uncertainty component of 0.1 ns to the uncertainty budget in Annex 3.</td></tr>
</table>

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22.66	±	0.24	ns
"dn3"	250.01	±	0.24	ns
"dn7"	1508.95	±	0.24	ns
"dn126"	12039.50	±	0.24	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Active hydrogen maser		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2.77 V	(1,75 ÷ 2,25) V	slightly over the high limit
Rise time (20% to 80 %)	< 1 ns	< 10 ns	yes
Duty cycle	200ns/1s = 0.00002 %	≤ 50 %	yes
Pulse width	200 ns	to avoid the pulse widths close (**<± 10 ns**) to the measured time intervals	no measured interval seems close to 200 ns.
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100, start output	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 20, start output	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 20, start output	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.4	±	0.1	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
40	±	1	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements

The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, ...)	Keysight 53230A. MIKES inventory nr. 13228. Serial nr. MY59190170
Applied trigger level (50 Ω) (Required: 0,5 V)	DC-coupled, Trigger 0.5 V, into 50 Ohm.
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ ..., ...)	The in-lambda standard showed good repeatability, no additional uncertainty wrt. to Annex 3 description.

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.17	±	0.14	ns	22.4	±	0.1	°C
Inλ 100	104.48	±	0.14	ns	22.4	±	0.1	°C
Inλ 300	307.29	±	0.14	ns	22.4	±	0.1	°C

.....
Anders Wallin

..2020-01-22....
(Date)

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: .....VTT Country: ..Finland...

Average date of measurements: 2020-01-17

Remarks: The Pivot-method [Rovera2019] was used. The start-input of the time-interval counter was permanently connected to a 1PPS distribution amplifier. The stop-input of the time-interval counter was first connected the DUT-start, a measurement of N=60…100 taken, then moved to the DUT-stop, and another N=60…100 measurements taken. The unconnected DUT-port was terminated at 50 Ohm.

Model equation that follows from the measurement setup:

TI = Y_UTC* (TI_stop - TI_start)

Description of the quantities in the model equation:

Quantity X_i	Description
Y_UTC	Fractional frequency error of the UTC(MIKE) 10 MHz reference signal.
TI_stop	N=60…100 average of time-interval counter reading with counter Ch2 = DUT_stop
TI_start	N=60…100 average of time-interval counter reading with Ch2 = DUT_start

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Y_UTC	0	1e-14	-	-	1, for time-interval of length 1s	<0.01 ps	
TI_stop	0	50 ps			1	50 ps	
TI_start	0	50 ps			1	50 ps	

Combined standard uncertainty	u_c	70 ps
Effective degrees of freedom	ν_{eff}	
Expanded uncertainty ($p \approx 95\%$)	U	140 ps

repeatability of measurements was 100 ps with the TIGen. Therefore we add a standard uncertainty of 100 ps to the TIGen results.

References

[Rovera2019] G. D. Rovera *et al.* 2019 Metrologia 56 035004

Anders Wallin

..2020-01-22.......
(Date)

Appendix D

RISE report

REPORT

issued by Notified Body No. 0402

Contact person RISE	Date	Reference	Page
Kenneth Jaldehag Measurement Science and Technology +46 10 516 54 08 kenneth.jaldehag@ri.se	2020-02-25	Euramet.TF.S1	1 (7)

Measurement report

Preface

This document reports on the measurements and results obtained at RISE in the EURAMET.TF.S1 Supplementary Comparison "Comparison of time interval measurements" (performed within EURAMET Project #1485) organized by the Pilot laboratory GUM (Central Office of Measures), Poland. Measurement instructions were given in the Technical Protocol "EURAMET_TF_S1_Time interval measurements Technical protocol_v_fin.pdf".

Identification

Objects	TIGen, Time Interval Generator, 1 generator InLambda, Time Interval Standard TIE-10, 3 standards (20, 100, 300 ns)
Objects state	Upon arrival the objects had no visual damage. TIGen front end SMA connectors somewhat loose.
Calibration location	Borås, Room 7:116 laboratory
Calibration date	2020-01-29

Measurement methods and procedures

The calibration was performed by measuring the time interval generated by the device under test (DUT). Two short cables of arbitrary length were connected between the DUT and the time interval counter (TIC). One cable between the start trigger output of the DUT and the start trigger input of the TIC, and one cable between the stop trigger output of the DUT and the stop trigger input of the TIC. The trigger level of the TIC was chosen according to the instructions given in the Technical Protocol.

The systematic time delay caused by the difference in length of the connecting cables as well as the internal time delay of the TIC was measured and corrected for.

See also SP-Metod 2816 "Calibration of time interval using a time interval counter" for further details of the used method as well as measurement uncertainty calculations.

Measurement conditions

Room temperature	23.0 ± 1.0 °C
Relative humidity	30 ± 10%
Equipment heat up time	> 24 h

Traceability

RISE is National Laboratory for electrical quantities and time and frequency by appointment of the Swedish government. RISE realizes fundamental units such as volt, ohm and second from primary standards. Traceability for other units is established from these realizations by means of in-house calibrations and scientific analyses. To ensure international equivalence and acceptance of the established traceability, interlaboratory comparisons are made between national laboratories.

Model Equation

Model equation that follows from the measurement setup:

$$TI = y_s + \delta y_{\text{tbe}} + \delta y_{\text{decal\_a}} + \delta y_{\text{decal\_b}} + \delta y_{\text{lcd}}$$

Description of the quantities in the model equation:

Quantity X_i	Description
y_s	is the measured time interval calculated as the arithmetic mean of individual measurements
δy_{tbe}	is a correction for the systematic time base error
$\delta y_{\text{decal\_a}}$	is a correction for the measured systematic delay due to internal counter asymmetry, connecting cables, and trigger level setting errors, calculated as the arithmetic mean of individual measurements
$\delta y_{\text{decal\_b}}$	is a correction for the systematic error in the calculation of $\delta y_{\text{decal\_a}}$
δy_{lcd}	is a correction for the least significant digit available

The systematic time delay caused by the difference in length of the connecting cables as well as the internal time delay of the TIC is measured and corrected for with the quantity $\delta y_{\text{decal\_a}}$. Any systematic uncertainty that remains is included in the quantity $\delta y_{\text{decal\_b}}$.

Results

The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%. The standard uncertainty has been determined in accordance with EA Publication EA-4/02. The long term stability of the calibrated object is not included in the reported expanded uncertainty of measurement.

Summary of the results:

DUT	Measured time interval /ns	Expanded measurement uncertainty /ns
Inλ 20	24.2	±0.4
Inλ 100	104.5	±0.4
Inλ 300	307.4	±0.4
TIGen dn0	22.7	±0.4
TIGen dn3	250.1	±0.4
TIGen dn7	1509.1	±0.4
TIGen dn126	12039.4	±0.4

Uncertainty budget tables for Inλ 20:

Quantity X_i	Estimate /s x_i	Standard uncertainty /s $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution /s $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	29.30E-9	1.92E-12	Normal	A	1	1.92E-12	99
δy_{tbe}	0	2.03E-21	Rectangular	B	1	2.03E-21	100
δy_{decal_a}	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
δy_{decal_b}	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	24.17E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Uncertainty budget tables for Inλ 100:

Quantity X_i	Estimate /s x_i	Standard uncertainty /s $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution /s $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	109.63E-9	2.12E-12	Normal	A	1	2.12E-12	99
δy_{tbe}	0	7.60E-21	Rectangular	B	1	7.60E-21	100
δy_{decal_a}	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
δy_{decal_b}	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	104.50E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Uncertainty budget tables for Inλ 300:

Quantity X_i	Estimate /s x_i	Standard uncertainty /s $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution /s $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	312.48E-9	1.84E-12	Normal	A	1	1.84E-12	99
δy_{tbe}	0	2.16E-20	Rectangular	B	1	2.16E-20	100
δy_{decal_a}	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
δy_{decal_b}	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	307.35E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Uncertainty budget tables for TIGen dn0:

Quantity X_i	Estimate /s x_i	Standard uncertainty /s $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution /s $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	27.79E-9	1.90E-12	Normal	A	1	1.90E-12	99
δy_{tbe}	0	1.93E-21	Rectangular	B	1	1.93E-21	100
δy_{decal_a}	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
δy_{decal_b}	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	22.66E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Uncertainty budget tables for TIGen dn3:

Quantity X_i	Estimate /s x_i	Standard uncertainty /s $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution /s $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	255.18E-9	1.92E-12	Normal	A	1	1.92E-12	99
δy_{tbe}	0	1.77E-20	Rectangular	B	1	1.77E-20	100
δy_{decal_a}	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
δy_{decal_b}	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	250.05E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Uncertainty budget tables for TIGen dn7:

Quantity X_i	Estimate /s x_i	Standard uncertainty /s $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution /s $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	1514.19E-9	2.13E-12	Normal	A	1	2.13E-12	99
δy_{tbe}	0	1.05E-19	Rectangular	B	1	1.05E-19	100
δy_{decal_a}	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
δy_{decal_b}	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	1509.06E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Uncertainty budget tables for TIGen dn126:

Quantity X_i	Estimate /s x_i	Standard uncertainty /s $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution /s $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	12044.57E-9	1.52E-12	Normal	A	1	1.52E-12	99
δy_{tbe}	0	8.34E-19	Rectangular	B	1	8.34E-19	100
δy_{decal_a}	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
δy_{decal_b}	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	12039.45E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Equipment

Frequency standard (Vremya VCH-1003M, RISE inv. no. BX91872)
Auxiliary Output Generator (Datum AOG-110, RISE inv. no. 602734)
Frequency distribution amplifier (TimeTech 10273, RISE inv. no. 901616)
Frequency distribution amplifier (Agilent 5087A, RISE inv. no. 603141)
Frequency distribution amplifier (Hewlett Packard 5087A, RISE inv. no. 502906)
Pulse distribution amplifier (TimeTech 10188, RISE inv. no. 901624)
Pulse distribution amplifier (TimeTech 10188, RISE inv. no. 901622)
Time interval counter (Fluke/Phillips PM6681, RISE inv. no. 502484)

External standard 10 MHz reference frequency applied for TIGen standard		**External input pulses applied to an auxiliary InLambda standard**	
Source (Cs clock, HM, …)	UTC(SP)	Source (Cs clock, HM, frequency generator, ..)	UTC(SP)
Amplitude (at 50 Ω)	1.9 $V_{p\text{-}p}$	1 pps (yes / no)	yes
		Frequency	1 Hz
		Low level	0 V
		High level (at 50 Ω)	1.8 V
		Rise time (20% to 80 %)	< 5 ns
		Duty cycle	0.005 %
		Pulse width	50 µs

RISE Research Institutes of Sweden AB
Measurement Science and Technology - Time and Optics

Performed by

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Kenneth Jaldehag

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: RISE Country: Sweden

Average date of measurements: 2020-01-29

Remarks:

TIGen SMA front end connector somewhat loose

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)		UTC(SP)		10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)		$1.9\ V_{p\text{-}p}$		within (0,5 ÷ 2) $V_{p\text{-}p}$	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	1	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
30	±	10	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Fluke/Phillips PM6681
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	Unknown

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22.7	±	0.4	ns
"dn3"	250.1	±	0.4	ns
"dn7"	1509.1	±	0.4	ns
"dn126"	12039.4	±	0.4	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	UTC(SP)		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	1.8 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	< 5 ns	< 10 ns	yes
Duty cycle	0.005 %	≤ 50 %	yes
Pulse width	50 μs	to avoid the pulse widths close **(<± 10 ns)** to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 20	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 20	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	1	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
30	±	10	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Fluke/Phillips PM6681
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	Unknown

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.2	±	0.4	ns	23	±	1	°C
Inλ 100	104.5	±	0.4	ns	23	±	1	°C
Inλ 300	307.4	±	0.4	ns	23	±	1	°C

Kenneth Jaldehag 2020-02-25

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Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: RISE Country: Sweden

Average date of measurements: 2020-01-29

Remarks: TIGen SMA front end connectors somewhat loose

Model equation that follows from the measurement setup:

$$TI = y_s + \delta y_{\mathrm{tbe}} + \delta y_{\mathrm{decal\_a}} + \delta y_{\mathrm{decal\_b}} + \delta y_{\mathrm{lcd}}$$

Description of the quantities in the model equation:

Quantity X_i	Description
y_s	is the measured time interval calculated as the arithmetic mean of individual measurements
δy_{tbe}	is a correction for the systematic time base error
$\delta y_{\mathrm{decal\_a}}$	is a correction for the measured systematic delay due to internal counter asymmetry, connecting cables, and trigger level setting errors, calculated as the arithmetic mean of individual measurements
$\delta y_{\mathrm{decal\_b}}$	is a correction for the systematic error in the calculation of $\delta y_{\mathrm{decal\_a}}$
δy_{lcd}	is a correction for the least significant digit available

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
y_s	27.79E-9	1.90E-12	Normal	A	1	1.90E-12	99
δy_{tbe}	0	1.93E-21	Rectangular	B	1	1.93E-21	100
$\delta y_{\mathrm{decal\_a}}$	-5.13E-9	2.03E-12	Normal	A	1	2.03E-12	99
$\delta y_{\mathrm{decal\_b}}$	0	1.73E-10	Rectangular	B	1	1.73E-10	100
δy_{lcd}	0	2.89E-13	Rectangular	A	1	2.89E-13	100
TI	22.66E-9	Combined standard uncertainty			u_c	1.73E-10	
		Effective degrees of freedom			ν_{eff}	2.03	
		Expanded uncertainty ($p \approx 95\%$)			U	3.51E-10	

Kenneth Jaldehag 2020-02-17

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Appendix E

PTB report

SUPPLEMENTARY COMPARISON: TIME INTERVAL MEASUREMENTS

REPORT PTB 2020

Prepared by: Andreas Bauch (PTB)
Head, Time Dissemination
Working Group

Supported by: Dirk Piester
Time Dissemination
Working Group

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, BRAUNSCHWEIG, FEBRUARY 2020

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY 3
1.1. IDENTIFICATION OF PARTICIPANTS 3
2. DESCRIPTION OF THE CALIBRATION METHOD, SET-UP AND EQUIPMENT USED 4
2.1 METHOD 4
2.2 SET-UP 4
3. DESCRIPTION OF OBSERVABLES AND DEFINITION OF THE UNCERTAINTY BUDGET 6
4. RESULTS 8

1. EXECUTIVE SUMMARY

PTB participated in the EURAMET Supplementary Comparison EURAMET.TF-S1. The travelling equipment was in operation in PTB between 18. and 20. February 2020.

This Report details installation and results obtained, following the instructions contained in the Technical Protocol.

1.1. IDENTIFICATION OF PARTICIPANTS

No of participant	Name and function	Institute	Address	Phone	e-Mail
5	Dirk Piester, Data collection	PTB (DE)	AG 4.42 Bundesallee 100 38116 Braunschweig	+49 531 592 4421	dirk.piester @ptb.de
5	Andreas Bauch, Author of report	PTB (DE)	AG 4.42 Bundesallee 100 38116 Braunschweig	+49 531 592 4420	andreas.bauch @ptb.de

2. DESCRIPTION OF THE CALIBRATION METHOD, SET-UP AND EQUIPMENT USED

2.1 METHOD

Both kinds of signal generators provided in the frame of the project generate two output pulses of 1PPS with a well-defined delay between them. In Figure 1, the two output signals are named Start and Stop. The measurement quantity is the delay between them. It was determined using a counter type SR620 S/N 6096.

External time base 10 MHz representing UTC(PTB) is used in the counter. The mean relative frequency offset from SI definition was < $2x10^{-13}$ for all averaging times.

Figure 1 shows the sequence of installation for the measurement of two time intervals needed, called TI1(left part in Fig. 1) and TI2 (right part in Fig. 1) in equation (1) below. The auxiliary 1PPS signal is generated with a Stanford Digital Delay Generator DG645 which in turn has 10 MHz UTC(PTB) as its time base. The delay is adjusted in a way that the measurement quantity TI2 (Stop vs. AUX) is a time interval < 100 ns.

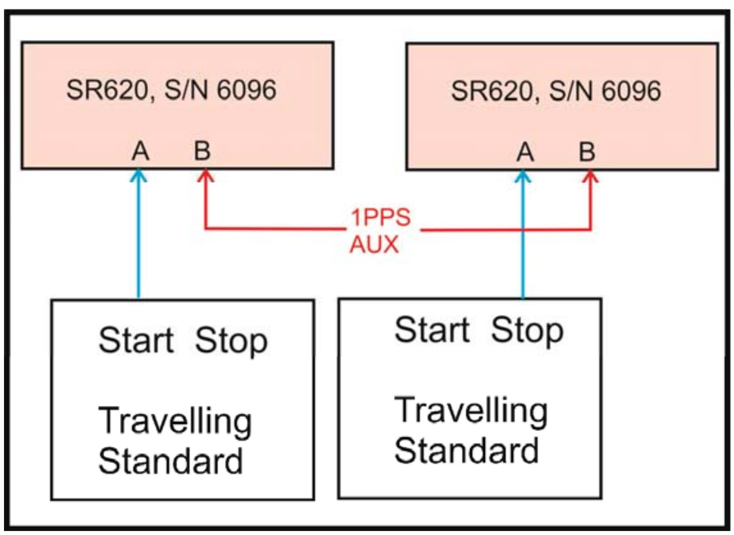


Figure 1 Method of differential time interval measurement

2.2 SET-UP

The TIGen standard is connected to 10 MHz UTC(PTB). 1PPS UTC(PTB) was used as Trigger Seed Input to the respective InLambda device. The InLambda devices were operated as prescribed in the Technical Protocol in a way that the output of the device under test receives a 1PPS output from a neigbouring device as input to its Trigger Seed Input. Figure 2 shows the installation of the devices next to the counter. All devices were kept in running condition for several hours before the data taking commenced.

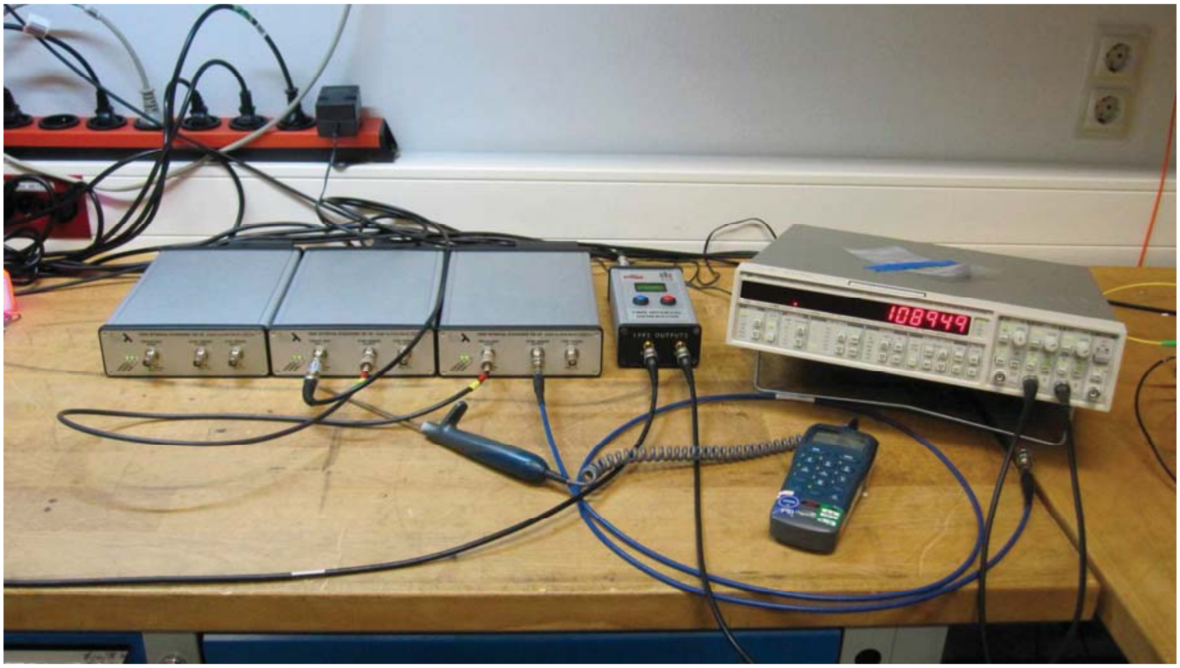


Figure 2 Set-up of delay generators in PTB#S time laboratory

Temperature recording in the room is made with a fixed installation sensor some meters away from the set-up and a data logger. Recordings during the period of data taking are shown in Section 4. The temperature close to the set-up was determined with a calibrated electronic thermometer, laying in front of the counter, device type Digitron 2084T, last calibration 2019, re-calibration 06/2024. Values stated in report tables refer to the calibrated meter.

3. DESCRIPTION OF OBSERVABLES AND DEFINITION OF THE UNCERTAINTY BUDGET

Model equation that follows from the measurement setup:

$$TI = \text{TI1} + \delta\text{B1\_1} + \delta\text{B2\_1} - \{\text{TI2} + \delta\text{uB1\_2} + \delta\text{uB2\_2}\} + \delta\text{uB3} \quad (1)$$

Description of the quantities in the model equation:

Quantity X_i	Description
TI1	Time interval measurement no. 1
δB1_1	Time base uncertainty of measurement no. 1
δB2_1	Trigger level timing uncertainty of measurement no. 1
TI2	Time interval measurement no. 2
δB1_2	Time base uncertainty of measurement no. 2
δB2_2	Trigger level timing uncertainty of measurement no. 2
δB3	Differential non-linearity

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
TI1	83.378ns	33 ps	N	A	1	33 ps	99
δB1_1	0 ns	1 ps	N	B	1	1 ps	∞
δB2_1	0 ns	20 ps	N	B	1	20 ps	∞
TI2	60.720 ns	29 ps	N	A	1	29 ps	99
δB1_2	0ns	1 ps	N	B	1	1 ps	∞
δB2_2	0 ns	20 ps	N	B	1	20 ps	∞
δB3	0 ns	50 ps	N	B	1	50 ps	∞

Combined standard uncertainty	u_c	80 ps
Effective degrees of freedom	ν_{eff}	> 50
Expanded uncertainty ($p \approx 95\%$)	U	160 ps

The estimated measurement values and the statistical uncertainty values stated above are examples, for details see Section 4. In the following, explanations are given for the determination of the numerical values of the uncertainty contributions.

The measurement consists of two subsequent time interval measurements:

TI1 = 1ppsStart – 1ppsAUX, TI2 = 1ppsStop – 1ppsAUX, TI = (TI1 – TI2).

Contribution	Description	This work (ps)	Feldmann PhD thesis	
uA_I	standard uncertainty	40[1]		
uA_II	standard uncertainty	40[1]		
uB1_I	timebase uncertainty	1[2]		
uB1_II	timebase uncertainty	1[2]		
uB2_I	trigger level timing unc.	20[3]	40[5]	
uB2_II	trigger level timing unc.	20[3]	40[5]	
uB3	differential non-linearity	50[4]	100[6]	
U		81		

1) typical standard deviation of 100 measurements ≤ 40 ps.

2) The timebase uncertainty is derived from the combined uncertainty of the difference UTC – UTC(PTB) and the UTC frequency offset to the SI second (10^{-15}) multiplied by an maximum time interval of 1 s. As in this EURAMET experiment the generated time intervals are derived from the same clock as the external reference signal of the used TIC, this contribution is negligible.

3) trigger level timing uncertainty (TLTU) is determined according to

TLTU = (15 mV+0.5% of trigger level)/(1pps slew rate)

We assume a maximum 1pps slew rate of 1V/ns and a trigger level = 1V. If the input bandwidth of a time interval counter is in the range of 300 MHz, the slew rates of input 1pps signals at the start gate are limited to that value.

The actual 1pps slew rate is higher (0.9V/0.4ns) and the trigger level is 0.5 V.

4) the differential non-linearity is specified as the maximum time error for any given relative measurement. The SR620’s differential non-linearity is typically ±50ps. That means if the time interval is changed by some amount the SR620 will report that change to within ±50ps. [SR620 Operating Manual]

5) Same equation as in 3) but 1pps slew rate = 0.5V/ns.

6) non-linearity observed by changing external reference frequency from 5 MHz to 10 MHz and by changing the phase of the reference frequency signal. The observed differences were always below 100 ps [Feldmann PhD Thesis: Advances in GPS based Time and Frequency Comparisons for Metrological Use, PTB 2011]. If this observation has the same origin as the differential non-linearity, the stated uncertainty in the SR620 manual seems to be reasonable.

4. RESULTS

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	UTC(PTB)	10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)	2 Vpp	within (0,5 ÷ 2) V_{p-p}	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23.3	±	1	°C	within (22 ± 4) °C	yes

Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
24.8	±	3	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620, S/N 6096
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	Differential non-linearity: 50 ps Trigger level timing uncertainty: 20 ps

A2. TIGen standard - measurement results with uncertainty:

Period of data taking: 2020-02-19 13:00 – 15:00 UTC

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”	22.66	±	0.16	ns
“dn3”	250.00	±	0.16	ns
“dn7”	1508.97	±	0.16	ns
“dn126”	12039.48	±	0.16	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	UTC(PTB)		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	< 2ns	< 10 ns	yes
Duty cycle	50 µs / 1 s	≤ 50 %	yes
Pulse width	50 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 300	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 300	Inλ 20 or Inλ 300	yes

Inλ 300			Inλ 100	Inλ 20 or Inλ 100	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23.6	±	1	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
25.6	±	3	%	within (50 ± 30) %	yes
The base equipment used for time interval measurements					
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)			SR620, S/N 6096		
Applied trigger level (50 Ω) (Required: 0,5 V)			0.5 V		
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)			Differential non-linearity: 50 ps Trigger level timing uncertainty: 20 ps		

B2. InLambda standards - measurement results with uncertainty:

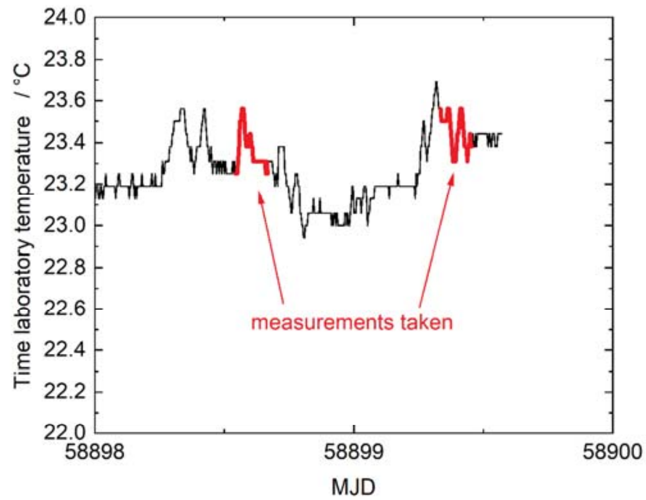
Period of data taking: 2020-02-20, 08:00 – 10:00 UTC

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.19	±	0.16	ns	23.6	±	1	°C
Inλ 100	104.51	±	0.16	ns	23.6	±	1	°C
Inλ 300	307.29	±	0.16	ns	23.6	±	1	°C

For completeness, the results of individual measurements are presented in the following table.

DUT	Configuration	TI1 (ns)	uA (ps)	TI2 (ns)	uA (ps)	TI (ns)	uB1_1 (ps)	uB1_2 (ps)	uB2_1 (ps)	uB2_2 (ps)	uB3 (ps)	TI (ns)	u (ns)
TIGen	dn0	83.378	33	60.72	29	22.658	1	1	20	20	50	22.66	0.16
	dn3	341.254	38	91.255	36	249.999	1	1	20	20	50	250	0.16
	dn7	1564.968	30	56.002	27	1508.966	1	1	20	20	50	1508.97	0.16
	dn126	12094.406	33	54.925	30	12039.481	1	1	20	20	50	12039.48	0.16
													0.16
inLambda 20		75.144	37	50.959	32	24.185	1	1	20	20	50	24.19	0.16
inLambda 100		175.078	34	70.57	40	104.508	1	1	20	20	50	104.51	0.16
inLambda 300		374.921	37	67.632	38	307.289	1	1	20	20	50	307.29	0.16

C. Recording of temperature and humidity



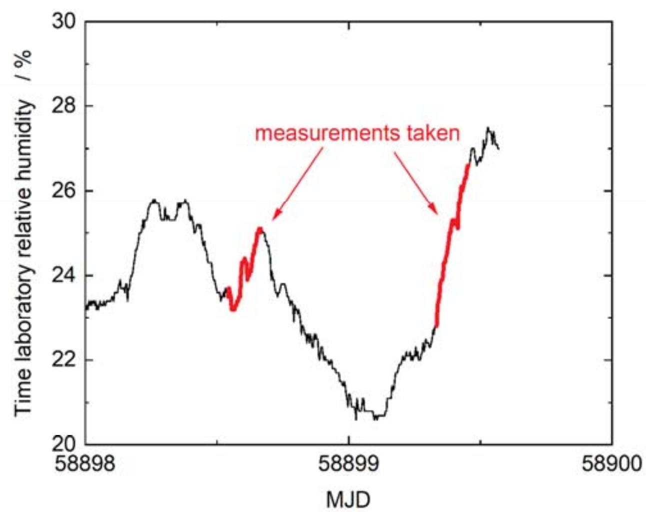


Figure 3 Recording of temperature and humidity in the PTB time lab during the campaign

END of DOCUMENT

Appendix F

VSL report

Comparison of time interval measurements

EURAMET.TF-S1 Supplementary Comparison
VSL results
Report number: S/TF/20-01ED

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Table of contents

Table of contents 3
1 Introduction 4
2 Method of measurement 5
2.1 Calibration method 5
2.2 Calibration set-up and equipment 5
2.3 Identification of the devices under test 8
2.4 Identfication of the reference standards 8
3 Calculation of the results 9
3.1 Equations for obtaining the results 9
3.2 Uncertainty budget 9
4 Traceability 12
5 Results 13
5.1 Average date of performing measurements 13
5.2 Ambient conditions 13
5.3 Reference signals, etc. 13
5.4 Results 14
6 Conclusion 15
6.1 General conclusion 15
6.2 CMC statement 15
Annex 1: VSL uncertainty budget 16
Annex 2: Summary of VSL results 17

1 Introduction

In this document, the results of VSL are reported for the participation in EURAMET supplementary comparison TF-S1 on Time Interval Measurements (EURAMET project #1485).

The quantity to be measured in this comparison is time interval, defined as the time delay between the rising edges of a start and stop pulse generated by the traveling standards, measured at a trigger level of 0.5 V.

In this comparison, there are four traveling standards. Three of them generate fixed time intervals of 20 ns, 100 ns and 300 ns respectively. The fourth traveling standard can be set to generate time intervals from 20 ns up to 12 μs, but for this comparison, only 20 ns, 250 ns, 1.5 μs and 12 μs are measured.

The measurements at VSL have been carried out from the 28th of February 2020 till the 10th of March 2020.

2 Method of measurement

2.1 Calibration method

The time interval generated between the start and stop output of the generator has been measured with a time interval counter of which the internal timebase was locked to the 10 MHz reference frequency of UTC(VSL).

Before the measurement, the "automatic calibration" of the time interval counter was performed.

Then, the remaining delay offset between the start and stop channel of the time interval counter was determined by applying a pulse via a power splitter and 2 coaxial cables of (nearly) identical length (about 20 cm) to the inputs of the counter (Figure 1). To eliminate the delay asymmetry from the power splitter and the coaxial cables, the measurement is repeated with reversed connections at the start and stop channels of the time interval counter (Figure 2).

For connecting the time interval generator to the time interval counter a pair of coaxial cables of (nearly) identical length (about 1.00 m) is used. The delay asymmetry of the cables is determined by applying a pulse via a power splitter and the two coaxial cables to the inputs of the counter (Figure 3).

To eliminate the effect of the delay asymmetry of the power splitter and of the time interval counter, the measurement is repeated with the cables in swapped positions (Figure 4).

Now that the time interval counter offset and the cable asymmetry has been determined, the calibration of the time interval generator can start. The start output from the generator is connected to the start input from the counter, and the stop output from the generator is connected to stop input from the counter Figure 5.

The pulses from the generator are applied to the counter at a rate of 1 pulse per second.

For each time interval measurement, the average was taken from a series of 300 seconds.

During the measurements, the trigger level of the time interval counter on both the start and the stop channel was set to 0.5 V.

2.2 Calibration set-up and equipment

The set-up for calibrating the offset of the time interval counter is shown in Figure 1 and Figure 2. The pulse generator used in this measurement is the 1PPS output from a digital divider that divides a 10 MHz reference signal from UTC(VSL) into a 1PPS signal.

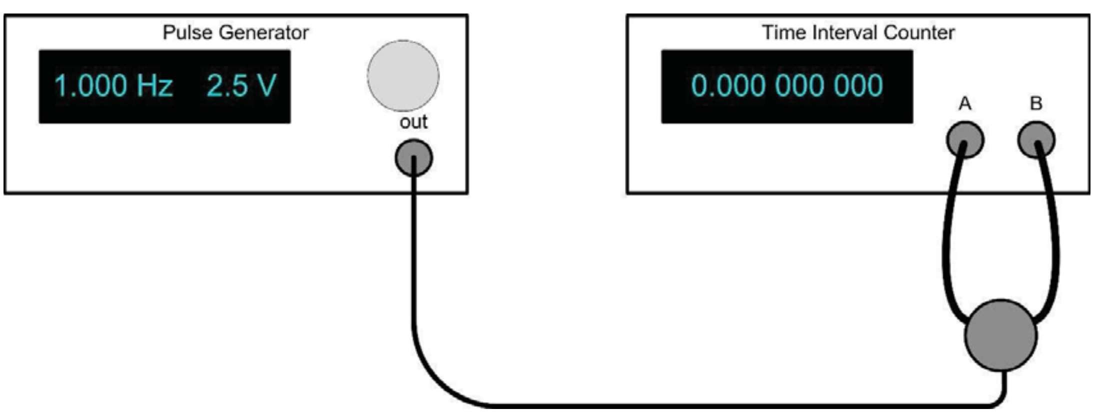


Figure 1. TIC offset calibration; first measurement

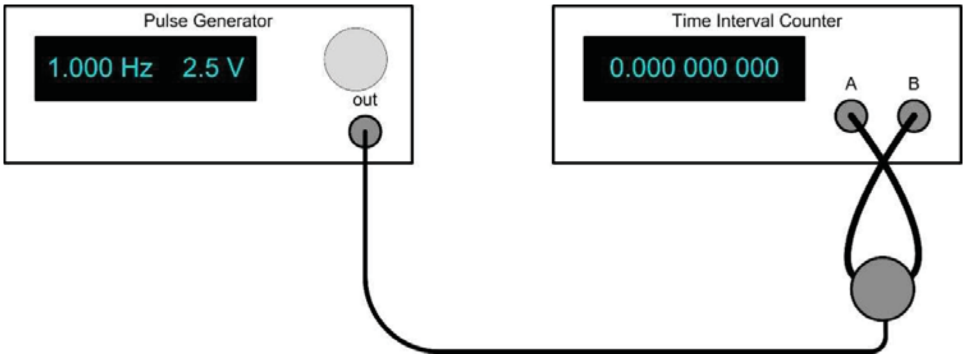


Figure 2. TIC offset calibration; second measurement

The set-up for calibrating the delay asymmetry of the coaxial cables is shown in Figure 3 and Figure 4.

The pulse generator used in this measurement is the 1PPS output from a digital divider that divides a 10 MHz reference signal from UTC(VSL) into a 1PPS signal.

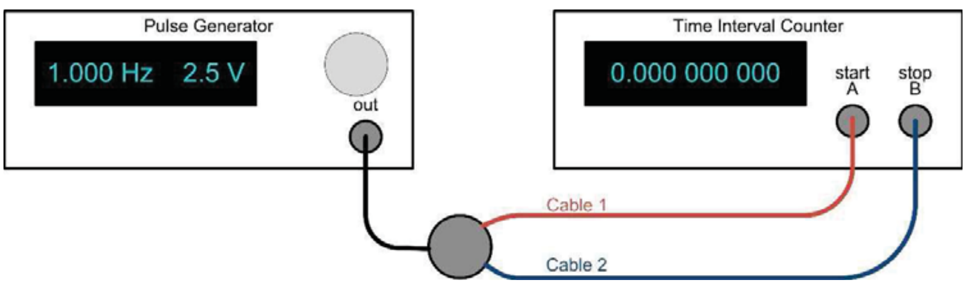


Figure 3. Delay asymmetry calibration of the coaxial cables; first measurement

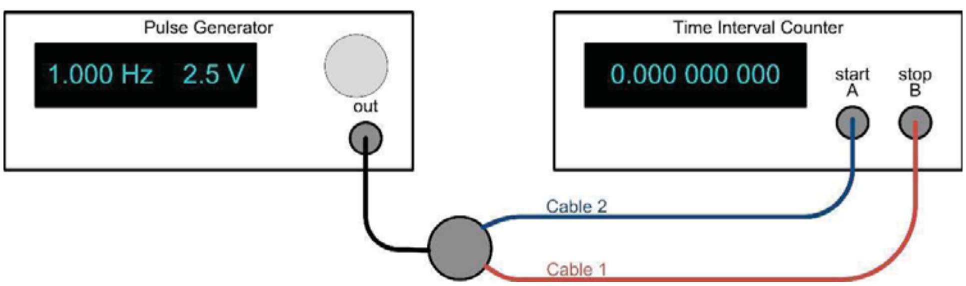


Figure 4. Delay asymmetry calibration of the coaxial cables; second measurement

The setup for the calibration of time interval generators is shown in Figure 5.

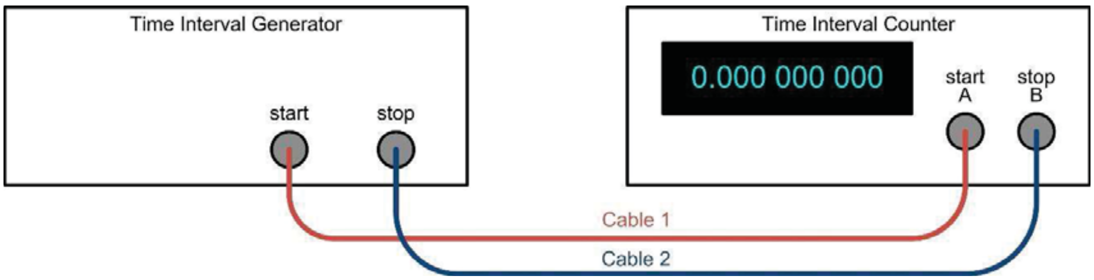


Figure 5. Calibration set-up for the time interval generator

Note 1: The TiGen standard was connected to the 10 MHz reference from UTC(VSL).

Note 2: The InLambda 20 ns standard was triggered by the InLambda 100 ns standard, the InLambda 100 ns standard was triggered by the InLambda 20 ns standard and the InLambda 300 ns standard was triggered by the InLambda 20 ns standard. The auxiliary InLambda trigger device was triggered by a 1PPS derived from the 10 MHz reference from UTC(VSL) via a digital frequency divider.

2.3 Identification of the devices under test

There are four devices under test in this comparison:

A. TIGen:

- Time Interval Generator, Ser. No. n/a

This standard can be set to multiple values of time interval. The selected values for this comparison are: 20 ns, 250 ns, 1.5 μs and 12 μs.

B. InLambda Time Interval Standard TIE-10

- InLambda 20 (nominal value of delay: 20 ns) Ser. No. n/a

- InLambda 100 (nominal value of delay: 100 ns) Ser. No. n/a

- InLambda 300 (nominal value of delay: 300 ns) Ser. No. n/a

2.4 Identfication of the reference standards

The measurements for this comparison have been performed with two time interval counters.

A. Stanford Research, type 620 counters, serial number 4819.

B. Stanford Research, type 620 counters, serial number 4821.

Both counters were locked to the 10 MHz reference frequency of UTC(VSL) during calibration of the devices under test in this comparison.

3 Calculation of the results

3.1 Equations for obtaining the results

The time interval *TI* generated by the generator under test is measured by the time interval counter T_{meas}, and corrected for the offset of the time interval counter, $d_{TIC\ offset}$, and the delay asymmetry of the coaxial cables, (d_{Cable2} - d_{Cable1}):

$$TI = T_{meas} - d_{TIC\ offset} - (d_{Cable2} - d_{Cable1}) \quad (1)$$

It is assumed that the offset of the time interval counter is a constant value related to internal signal path asymmetry in the counter. The offset can, however, be affected by the "AutoCal". Therefore, this offset measurement needs to be repeated after each "AutoCal".

The offset of the time interval counter is determined with the measurement configurations as shown in Figure 1 and Figure 2 respectively.

$$T_{meas1} = d_{TIC\ offset} + \left((d_{Cable2} + d_{splitter2}) - (d_{Cable1} + d_{splitter1}) \right) \quad (2)$$

$$T_{meas2} = d_{TIC\ offset} + \left((d_{Cable1} + d_{splitter1}) - (d_{Cable2} + d_{splitter2}) \right) \quad (3)$$

$$d_{TIC\ offset} = \frac{T_{meas1} + T_{meas2}}{2} \quad (4)$$

The delay asymmetry of the coaxial cables is determined from the measurements in the configurations in Figure 3 and Figure 4.

$$T_{meas3} = TI + d_{TIC\ offset} + (d_{Cable2} - d_{Cable1}) \quad (5)$$

$$T_{meas4} = TI + d_{TIC\ offset} + (d_{Cable1} - d_{Cable2}) \quad (6)$$

$$(d_{Cable2} - d_{Cable1}) = \frac{T_{meas3} - T_{meas4}}{2} \quad (7)$$

3.2 Uncertainty budget

The uncertainty evaluation is based on equation (1):

$$TI = T_{meas} - d_{TIC\ offset} - (d_{Cable2} - d_{Cable1}) \quad (1) \text{ repeated}$$

The uncertainty in T_{meas} consists of several components:

$u_1(T_{meas})$: contribution from the fluctuation in the reading of the time interval counter

The standard deviation in the measurements varies for the time interval generators under test:

Table I. Standard deviation in the measurements for each time interval generator

Generator	Standard deviation (ps)
InLambda 20 ns	9
InLambda 100 ns	23
InLambda 300 ns	38
TIGEN DN=000 20 ns	26
TIGEN DN=003 250 ns	52
TIGEN DN=007 1.5 µs	31
TIGEN DN=126 12 µs	35

$u_2(T_{meas})$: contribution from the resolution of the time interval counter

The resolution of the time interval counter is 2.7 ps; determined as the average interval between sorted measurement samples from a set of 1000 samples.

$u_3(T_{meas})$: contribution from reference frequency of the time interval counter

The timebase of the time interval counter is locked to the 10 MHz reference frequency of UTC(VSL). The uncertainty from the reference frequency is dominated by its short-term stability. This uncertainty contribution is estimated to be 1×10^{-11} Hz/Hz $\cdot$ T_{meas}.

$u_4(T_{meas})$: contribution from the non-linearity of the time interval counter

For resolving the least significant digits of the time interval measurement, the counter uses a time to amplitude converter. The contribution from the non-linearity of this converter is estimated to be less than 10x the resolution which corresponds to approximately 27 ps.

$u_5(d_{TICoffset})$: contribution from the internal offset of the time interval counter

The time interval counter has an internal offset due to unequal signal paths from the start and stop connector to the internal latching points. The effect of the internal offset can be reduced by performing the "AutoCal" before the measurements. The remaining offset of the counter has been determined with an uncertainty of 50 ps, which is the standard deviation in repeated offset measurements.

$u_6(d_{Cable2} - d_{Cable1})$: contribution from the delay asymmetry of the coaxial cables

The coaxial cables used to connect the time interval generator to the time interval counter have slightly unequal lengths. The uncertainty with which this delay asymmetry has been determined is 10 ps, which is the standard deviation in repeated measurements of the delay asymmetry.

The total uncertainty is computed as the root sum square of all contributions converted to standard uncertainties and multiplied with their respective sensitivity coefficient.

An example of the uncertainty budget calculation of the InLambda 20 ns generator is shown in Table II.

Table II. Uncertainty budget table

quantity	value		unc		distribution	std unc		sensitivity		contribution	
Tmeas Std dev	24190	ps	9	ps	normal	9	ps	1		9.0	ps
Tmeas Resolution	0	ps	2.7	ps	rectangular	1.56	ps	1		1.6	ps
Tmeas Ref frequency	0	ps	1.00E-11	Hz/Hz	normal	1.00E-11	Hz/Hz	1E+12	ps	10.0	ps
Tmeas Non-linearity	0	ps	27	ps	rectangular	15.6	ps	1		15.6	ps
TIC offset	0	ps	50	ps	normal	50	ps	1		50.0	ps
Cable asymmetry	0	ps	10	ps	normal	10	ps	1		10.0	ps
TI	24190	ps						*k* = 1		55.0	ps
								k = 2		110.0	ps

The total expanded uncertainty (*k* = 2) for each of the time interval generators in the comparison is given in Table III:

Table III. Total expanded uncertainty (*k* = 2) for each of the time interval generators

Time interval generator	Total Expanded Uncertainty (ns)
InLambda 20	0.11
InLambda 100	0.12
InLambda 300	0.13
TIGEN DN=000 20 ns	0.12
TIGEN DN=003 250 ns	0.15
TIGEN DN=007 1.5 μs	0.13
TIGEN DN=126 12 μs	0.13

4 Traceability

The traceability chart for the calibration performed in this comparison is shown in Figure 6.

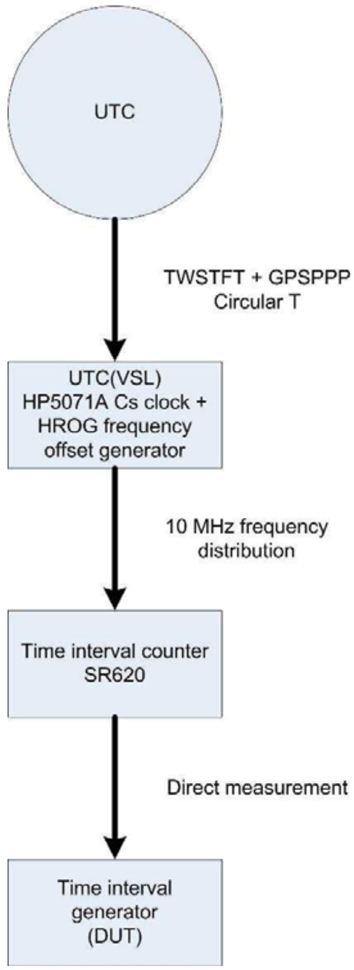


Figure 6. Traceability chart for time interval calibrations at VSL

5 Results

5.1 Average date of performing measurements

The measurements have been carried out from the 28th of February 2020 till the 10th of March 2020.

The average date of the measurements for each of the devices under test is reported in Table IV.

Table IV. Average date of measurements

Time interval generator	average date (dd-mm-yyyy)
InLambda 20	04-03-2020
InLambda 100	05-03-2020
InLambda 300	05-03-2020
TIGEN DN=000 20 ns	03-03-2020
TIGEN DN=003 250 ns	05-03-2020
TIGEN DN=007 1.5 µs	05-03-2020
TIGEN DN=126 12 µs	05-03-2020

5.2 Ambient conditions

The measurements for this comparison have been performed in the VSL Time and Frequency laboratory, room 6.1.35.
The ambient conditions are the same for all time interval generators calibrated in this comparison.
The ambient temperature in the laboratory during the measurements was (22.8 ± 0.5) °C.
The relative humidity in the laboratory during the measurements was (44 ± 5) %.

5.3 Reference signals, etc.

- The 10 MHz reference frequency for the TIGen standard was derived directly from the 10 MHz frequency of UTC(VSL). The deviation of UTC(VSL) with respect to UTC is less than 2 x 10^{-14} Hz/Hz

The 10 MHz frequency is a sine wave with an amplitude of 1 Vrms (2.8 V_{p-p}) with 50 Ω input impedance.

- The input pulse signals for the auxiliary InLambda standard was a 1PPS signal derived from the 10 MHz frequency of UTC(VSL) via a digital frequency divider.

The pulse shape with 50 Ω input impedance is described as follows:
low level: -0.36 V
high level: +2.46 V
frequency: 1 Hz
pulse width: 0.5 s
rise time (20 % to 80 %): 1.8 ns
duty cycle: 50 %

5.4 Results

The measurement results with their corresponding expanded uncertainties are reported in Table V.

Table V. Measurement results with uncertainty

Device under test	Measured Time Interval with expanded uncertainty (p ≈ 95 %)			Unit
InLambda 20	24.19	±	0.11	ns
InLambda 100	104.53	±	0.12	ns
InLambda 300	307.31	±	0.13	ns
TIGen “dn0” 20 ns	22.72	±	0.12	ns
TIGen “dn3” 250 ns	250.08	±	0.15	ns
TIGen “dn7” 1.5 μs	1509.05	±	0.13	ns
TIGen “dn126” 12 μs	12039.54	±	0.13	ns

6 Conclusion

6.1 General conclusion

VSL has calibrated the time interval generators that serve as traveling standard in the EURAMET TF-S1 supplementary comparison of time interval measurements.

The performed measurements are in the range between 20 ns and 12 µs.

The reference standard used to perform this calibration was a time interval counter of which the internal frequency reference was locked to the 10 MHz reference frequency of UTC(VSL).

The reported uncertainties are less than or equal to 0.15 ns, which is well below the VSL CMC claim for this quantity. The dominant contribution in the uncertainty budget is the determination of the offset of the time interval counter.

6.2 CMC statement

The measurements in this comparison correspond with the VSL Time and Frequency service categories 3.2.3 and 3.2.4 from the Calibration Measurement Capabilities (version 15 March 2011):

Calibration Service			Measurand Range			Expanded Uncertainty	
Quantity	Instrument or Artifact	Instrument type or Method	Minimum value	Maximum value	Unit	Value	Unit
Time interval	Time difference source	Time interval counter	-1E-09	+1000	s	1	ns
Time interval	Delay source	Time interval counter	0	+1000	s	1	ns

The uncertainties reported by VSL in this comparison are well below the CMC claim.

Therefore, if the reported results agree with the comparison reference values, the VSL results support the current CMC claim for time interval calibrations.

Annex 1: VSL uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM
e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: VSL Country: The Netherlands

Average date of measurements: 5 March 2020

Remarks: The given uncertainty budget is for the InLambda 20 standard. Other standards have slightly different uncertainties, depending on the fluctuations in the measurements

Model equation that follows from the measurement setup:

$$TI = (T_{meas} \cdot (1 + df/f)) + d_{TIC\ non\text{-}lineartiy} + d_{TIC\ resolution} - d_{TIC\ offset} - (d_{Cable2} - d_{Cable1})$$

Description of the quantities in the model equation:

Quantity X_i	Description
T_{meas}	Measured value of the time interval counter
df/f	relative frequency offset of the external reference frequency of the counter
$d_{TIC\ non\text{-}lineartiy}$	non-linearity of the counter
$d_{TIC\ resolution}$	resolution of the counter
$d_{TIC\ offset}$	internal delay offset of the counter
d_{Cable2} - d_{Cable1}	delay asymmetry of the cables used to connect the generator to the counter

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_{meas}	24190 ps	9 ps	normal	A	1	9.0 ps	300
df/f	0 ps	1.0E-11 Hz/Hz	normal	B	1E+12 ps	10.0 ps	100
non-lin.	0 ps	27 ps	rectangular	B	1	15.6 ps	100
resol.	0 ps	2.7 ps	rectangular	B	1	1.6 ps	100
$d_{TIC\ offset}$	0 ps	50 ps	normal	B	1	50.0 ps	100
d_{Cable2} - d_{Cable1}	0 ps	10 ps	normal	B	1	10.0 ps	100

Combined standard uncertainty	u_c	55.0 ps
Effective degrees of freedom	ν_{eff}	145
Expanded uncertainty ($p \approx 95\%$)	U	110.0 ps

Erik Dierikx 15 May 2020
(Name) (Date)

Annex 2: Summary of VSL results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: VSL Country: The Netherlands

Average date of measurements: 5 March 2020

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	Cs clock	10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)	1,0 V_{rms}	within (0,5 ÷ 2) V_{p-p}	no

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,8	±	0,5	°C	within (22 ± 4) °C	yes

Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
44	±	5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0,027 ns

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22,72	±	0,12	ns
"dn3"	250,08	±	0,15	ns
"dn7"	1509,05	±	0,13	ns
"dn126"	12039,54	±	0,13	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)			Cs clock		
1 pps (yes / no)			yes		
Frequency			1 Hz	≤ 200 Hz	yes
Low level			-0,36 V	0 V	no
High level (at 50 Ω)			2,46	(1,75 ÷ 2,25) V	no
Rise time (20% to 80 %)			1,8 ns	< 10 ns	yes
Duty cycle			50 %	≤ 50 %	yes
Pulse width			0,5 s	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration					
DUT – Device Under Test			Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20			Inλ 100	Inλ 100 or Inλ 300	yes
Inλ 100			Inλ 20	Inλ 20 or Inλ 300	yes
Inλ 300			Inλ 20	Inλ 20 or Inλ 100	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,8	±	0,5	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
44	±	5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0,027 ns

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty ($p \approx 95$ %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24,19	±	0,11	ns	22,8	±	0,5	°C
Inλ 100	104,53	±	0,12	ns	22,8	±	0,5	°C
Inλ 300	307,31	±	0,13	ns	22,8	±	0,5	°C

Erik Dierikx
(Name)

15 May 2020
(Date)

Appendix G

SMD report

1. Participant

Name	Institute	Acronym	Delivery address
Frank Coutereel	FPS Economy, S.M.E.s, Self-employed and Energy Directorate-general: Quality and Safety – Metrology	SMD	Boulevard du Roi Albert II, 16 BE 1000 Brussels

Country	Telephone	e-mail
Belgium	+32 277 91 72	frank.coutereel@economie.fgov.be

2. Schedule of measurements

First loop

Measurements				Transport
Start date	End date	Stabilization	Measurement	
2020-06-08	2020-06-12	1 day	5 days	4 days

3 Report

3.1 Introduction

The purpose of this Supplementary Comparison (SC) is to support CMC claims in time interval (TI) measurements. Since a cable-delay as TI is not a well-defined measured quantity and its value is significantly dependent on the shape of signals used for cable delay measurements, another method was preferred in order to measure well-defined TI's.

The method is based on direct measurement of 4 of the 127 different TI's generated by a TI Generator (TIGen) with PLL loops and programmable logic and counters within a range from 20 ns to 12 µs and 3 Delay Standards (InLambda - Inλ – standards) based on stabilised fibre delays of 20 ns, 100 ns and 300 ns respectively.

As stated in the conditions for participation that each participant was allowed to use his own method we did not use, for practical reasons, the pivot method described in metrologia 56 (2019) "Time delay measurements: estimation of the error budget (G D Rovera, M Siccardi, S Römisch and M Abgrall)".

For the comparison, following TI's have been measured:

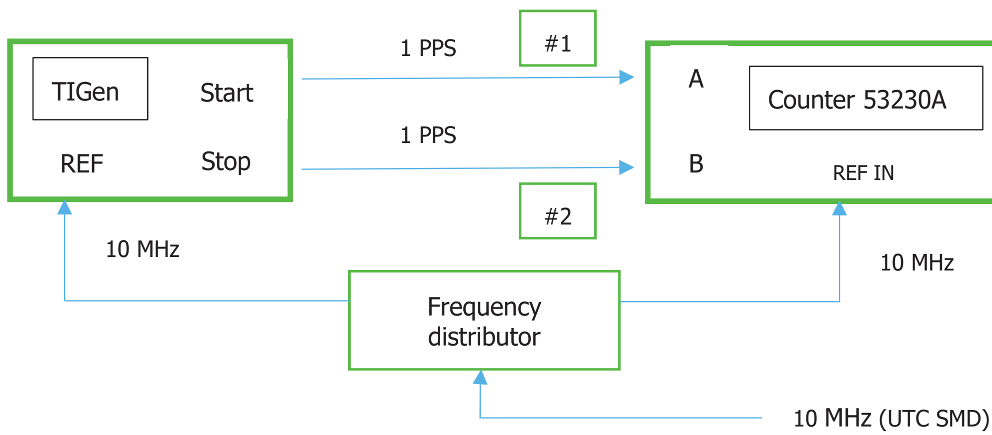
- 20 ns, 250 ns, 1,5 µs and 12 µs generated by the TIGen
- 20 ns, 100 ns and 300 ns for the Inλ-standards

Measuring equipment:

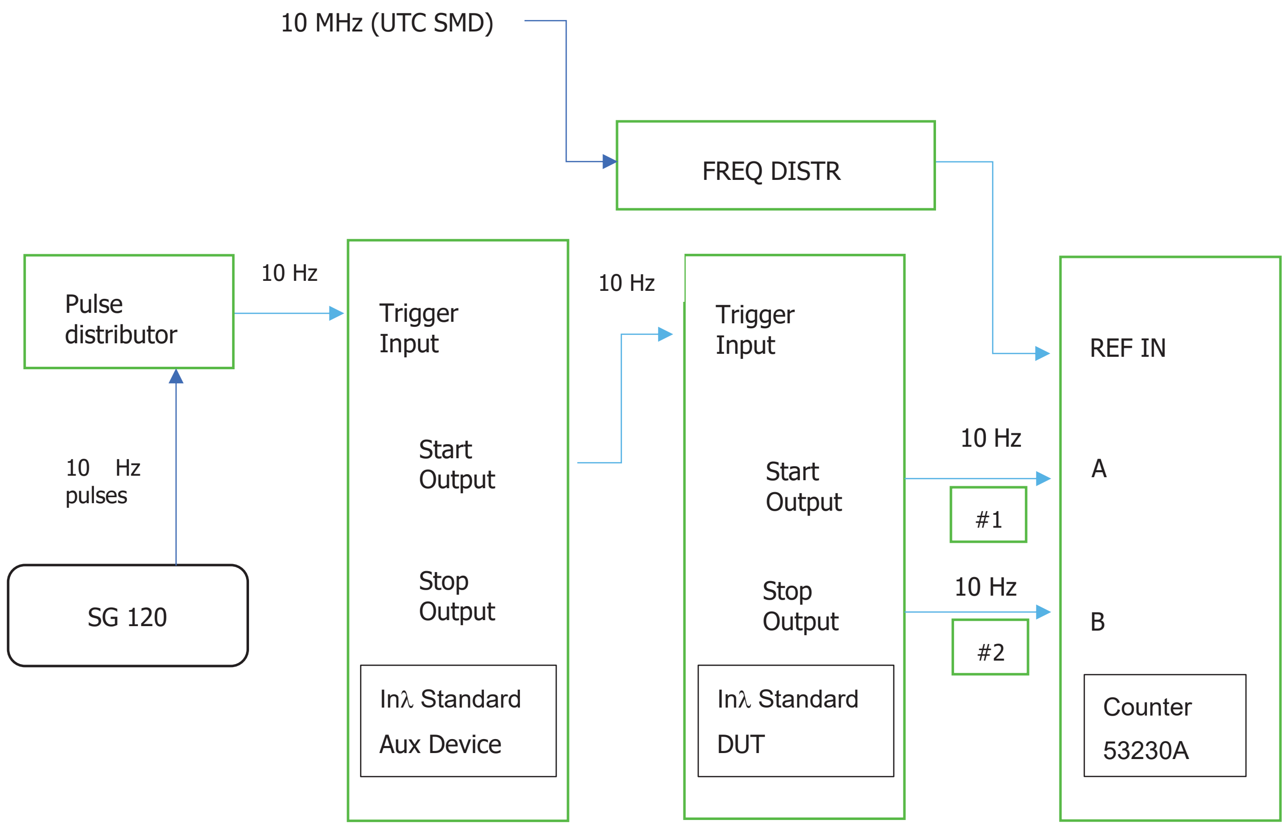
- 10 MHz UTC(SMD), derived from a H MASER frequency standard VCH 1003 A
- Time Interval Counter 53230A
- Time interval counter CNT 91
- Pulse distributor
- Frequency distributor
- FG 120, function generator Yokogawa
- Calibrated connecting cables
- InLambda standards used as DUT (device under test) and auxiliary device
- TiGen as DUT

3.2 Set-up

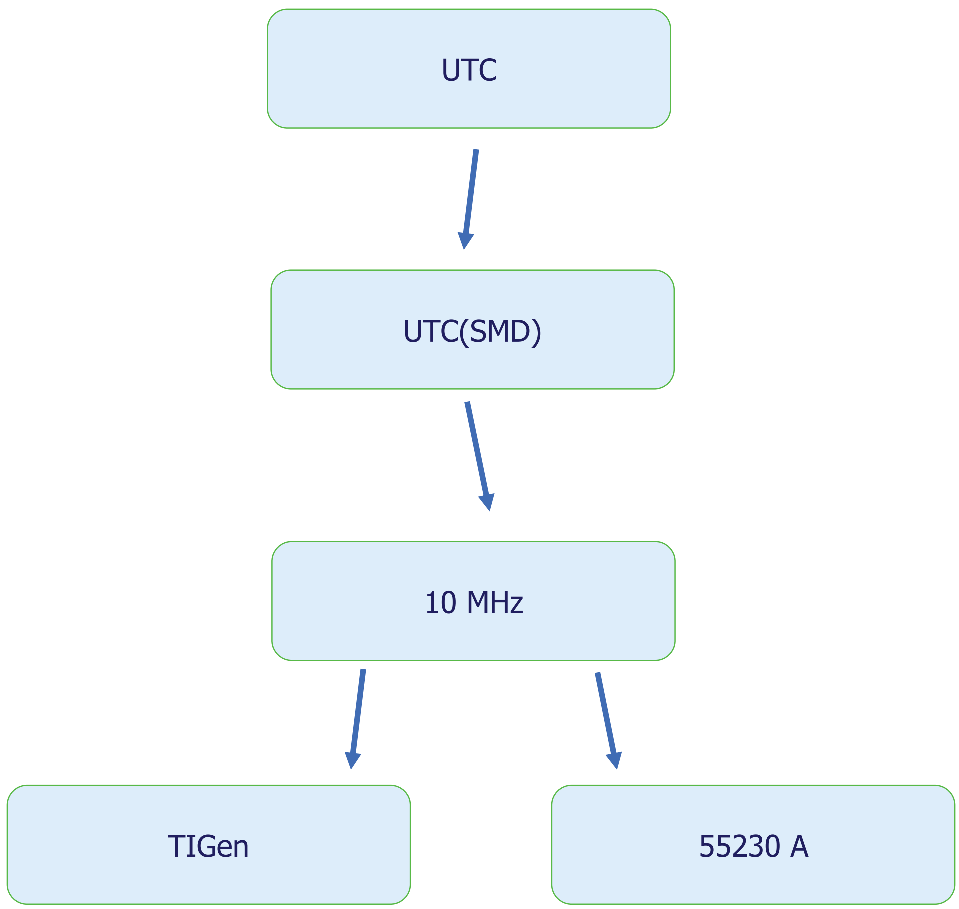
3.2.1 TIGen:



3.2.2 InLambda



3.3 Tracebility chart



3.4 Method

3.4.1 Description

The time intervals between the 1 PPS pulses at start and stop of the TIgen standard and the 10 Hz pulses at start and stop of the InLambda standards have been measured with two interval counters (TIC), respectively CNT 91 and a Agilent 53230A. We reported only the measurements with 53230A. Calibrated coax cables serve as connection between Start and Stop of the DUT and the inputs of the TIC. The nominal values of the time intervals were respectively 20 ns, 250 ns, 1,5 µs and 12 µs for the TIgen and 20 ns, 100 ns and 300 ns for the InLambda S. The external references for the TIC's and TIgen have been connected to the 10 MHz derived from UTC(SMD).The trigger levels for both TIC inputs were 0,5 VDC, input impedance = 50 ohm.
5 sessions (one per day) of 100 measurements each have been made for each time interval

3.4.2 Equation

The equation for the obtained unknown time interval is:

$$TI_x = TI + \delta TB + \delta Lin + \delta Trig + \delta CableDelay + \delta Quant + \delta Offset + \delta Temp$$

Where:

TI	**-** mean value of the different measurement values by the TIC
δTB	- time base error
δLin	- non-linearity error
$\delta Trig$	- trigger error
$\delta CableDelay$	- correction for the additional delay due to cables #1 and #2
$\delta Quant$	- error due to TIC resolution
$\delta offset$	- error due to reversing input channels counter
$\delta Temp$	- error due to temperature influence
TI_x	**-** result (x = dn0, dn3, dn7, dn126, InLa20, InLa100, inLa300)

3.4.3 Uncertainties

- **Indicated Time Interval** (TI):
  Average from 5 daily measurements performed by TIC with associated standard uncertainty.
  We consider this quantity to have a normal probability distribution
- **Time base error** (δTB):
  The time base error is proportional to the measured TI and depends on the frequency stability of the time base of the TC. Since the TI is much smaller than 1 s and 0.1 s, and the TC time base is disciplined with 10 MHz from UTC (SMD) this error can be neglected, with no correction and limits of +/- 1 ps.
- **Non-linearity error** (δLin):
  Evaluation based on experiment since this error depends on the type of interpolation technique.
  The manufacturer reports this type of error as the accuracy error and estimates it to be 100 ps.
  By smoothing out the noise with $1/\sqrt{n}$, the standard uncertainty for the residual non–linearity is supposed not be more than 10 ps which we consider to have a rectangular probability distribution.
  An experimental setup with pulses from a stepper disciplined with the frequency of a Maser had shown that the noise and residuals were limited to be less than 1 ps.
- **Trigger error** ($\delta Trig$):
  Type B uncertainty proportional to the inverse of the pulse slew rate.
  The trigger error consists of:

a. The threshold error:

$$T_E = \frac{(V^2{}_{noise-input} + V^2{}_{noise-signal})^{0,5}}{SR_{Trig\ point}}$$

$V_{noise-input}$: internal noise from TIC (approx. 500 µV)

$V_{noise-signal}$: rms noise of applied signal (approx. <= 1 mV)

$SR_{Trig\ point}$: slewrate at the triggerpoint.

b. Threshold level timing error

$$T_{TLT} = TLSE\ x\ \left(\frac{1}{S_x} + \frac{1}{S_y}\right) + 0,5(\frac{Vhyst}{Sx} - \frac{Vhyst}{Sy})$$

S_x = Slew rate at start trigger point (V/s)

S_y = Slew rate at stop trigger point (V/s)

$TLSE$ = Trigger level setting error (V) = +/- (0,2 % of setting + 0,1% of range)

$Vhyst = 20\ mV\ hysteresis\ with\ noise\ reject\ on\ OFF$

- **Cable delay** ($\boldsymbol{\delta CableDelay}$):
  Error due to the difference in delay between the two connecting cables (equal length). We assumed the adapters used for the TIgen are identical and should not contribute to the results. We performed two cable delay measurements, before and during the measurement sessions.
  To determine the cable delays we applied the double weight method in four steps.
  The measurements gave a zero bias and standard uncertainty of 31 ps with a assumed normal probability distribution.
- **Quantization error** ($\boldsymbol{\delta Quant}$):
  Error due to the TIC resolution as a combination of the quantization and time base jitter. We estimated this error with experiential set-up to be no more than +/- 5 ps.
  The TIC manufacturer gives for single shot resolution the value of 20 ps. After averaging, we can reduce this error to 2 ps. Based on our experimental set-up, the uncertainty associated with this type of error is estimated to have limits +/- 5 ps with a rectangular distribution.
- **Offset error** ($\boldsymbol{\delta offset}$):
  Is the difference when reversing counter input channels A and B
  Measurements showed that there was a systematic difference.
  We estimated the uncertainties associated with the biases to have limits of +/- 20 ps with triangular distribution.
- **Temperature error** ($\boldsymbol{\delta Temp}$):
  Error due to the uncertainty of the temperature. Measurements by the pilot institutes whereby the temperature changed, showed that the TIGen for temperature changes from 18 °C to 30 °C during the day, the influence on the measured timed interval did not change by more than 10 ps. Therefore since the TIGen is disciplined to our UTC(SMD) 10 MHz we assumes no more than +/- 1 ps error associated with a rectangular distribution. On the other hand the influence for temperature of the InLambda standards showed that there is an dependence of about 0,6 ps/K for the smallest standard to 1,4 ps/K for the 100 ns standards and finally 2,5 ps/K for the 300 ns standard.
  Taking into account the stabilization of the FG 120 in the temperature range 5 to 40 °C to be 10 ppm, we can assume for the lambda_20 limits of +/- 2 ps, for lambda_100 +/- 3 ps, and for lambda_300 +/- 4 ps, all associated with a rectangular distribution.
- **Correlation**: We considered no correlation of the input quantities to any significant extent.

3.5 Measurement results and uncertainty budget

DN0									
Quantity Xi	Estimate xi	Uncertainty value	Divisor	Standard uncertainty u(xi)	Probability distribution A or B	Sensitivity Coefficient ci	Uncertainty contribution ui(y)	Degree of freedom vi	Index
TI	22,628 ns	0,0030 ns	1,000	0,0030 ns	A Normal	1	0,0030 ns	4	3,49%
δTB	0,000 ns	0,0010 ns	1,732	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,13%
δLin	0,000 ns	0,0100 ns	1,732	0,0058 ns	B Rectangular	1	0,0058 ns	∞	12,50%
δTE	0,000 ns	0,0012 ns	1,732	0,0007 ns	B Rectangular	1	0,0007 ns	∞	0,19%
δLTE	0,000 ns	0,0068 ns	1,732	0,0039 ns	B Rectangular	1	0,0039 ns	∞	5,84%
$\delta CableDelay$	0,000 ns	0,0115 ns	1	0,0115 ns	B Normal	1	0,0115 ns	∞	49,60%
$\delta Quant$	0,000 ns	0,0050 ns	1,73205	0,0029 ns	B Rectangular	1	0,0029 ns	∞	3,13%
$\delta Temp$	0,000 ns	0,0010 ns	1,73205	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,13%
$\delta Offset$	0,020 ns	0,0200 ns	2,44949	0,0082 ns	B Triangular	1	0,0082 ns	∞	25,00%
					Combined standard uncertainty uc(y)		0,0163 ns	Veff	3292
Tdn0	**22,648 ns**		*k*	**1,96**	**Expanded uncertainty**		**0,032 ns**		
			P	**95%**					

DN3									
Quantity	Estimate	Uncertainty	Divisor	Standard	Probability	Sensitivity	Uncertainty	Degree of	Index
TI	249,980 ns	0,0034 ns	1,000	0,0034 ns	A Normal	1	0,0034 ns	4	4,39%
δTB	0,000 ns	0,0010 ns	1,732	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,12%
δLin	0,000 ns	0,0100 ns	1,732	0,0058 ns	B Rectangular	1	0,0058 ns	∞	12,42%
δTE	0,000 ns	0,0012 ns	1,732	0,0007 ns	B Rectangular	1	0,0007 ns	∞	0,19%
δLTE	0,000 ns	0,0067 ns	1,732	0,0039 ns	B Rectangular	1	0,0039 ns	∞	5,55%
$\delta CableDelay$	0,000 ns	0,0115 ns	1	0,0115 ns	B Normal	1	0,0115 ns	∞	49,27%
$\delta Quant$	0,000 ns	0,0050 ns	1,73205	0,0029 ns	B Rectangular	1	0,0029 ns	∞	3,10%
$\delta Temp$	0,000 ns	0,0010 ns	1,73205	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,12%
$\delta Offset$	0,018 ns	0,0200 ns	2,44949	0,0082 ns	B Triangular	1	0,0082 ns	∞	24,83%
					Combined standard uncertainty uc(y)		0,0164 ns	Veff	2076
Tdn3	**249,998 ns**		*k*	**1,96**	**Expanded uncertainty**		**0,032 ns**		
			P	**95%**					

DN7

Quantity Xi	Estimate xi	Uncertainty value	Divisor	Standard uncertainty u(xi)	Probability distribution A or B	Sensitivity Coefficient ci	Uncertainty contribution ui(y)	Degree of freedom vi	Index
TI	1508,930 ns	0,0051 ns	1,000	0,0051 ns	A Normal	1	0,0051 ns	4	9,36%
δTB	0,000 ns	0,0010 ns	1,732	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,12%
δLin	0,000 ns	0,0100 ns	1,732	0,0058 ns	B Rectangular	1	0,0058 ns	∞	11,78%
δTE	0,000 ns	0,0012 ns	1,732	0,0007 ns	B Rectangular	1	0,0007 ns	∞	0,17%
δLTE	0,000 ns	0,0067 ns	1,732	0,0039 ns	B Rectangular	1	0,0039 ns	∞	5,24%
$\delta CableDelay$	0,000 ns	0,0115 ns	1	0,0115 ns	B Normal	1	0,0115 ns	∞	46,72%
$\delta Quant$	0,000 ns	0,0050 ns	1,73205	0,0029 ns	B Rectangular	1	0,0029 ns	∞	2,94%
$\delta Temp$	0,000 ns	0,0010 ns	1,73205	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,12%
$\delta Offset$	0,018 ns	0,0200 ns	2,44949	0,0082 ns	B Triangular	1	0,0082 ns	∞	23,55%
					Combined standard uncertainty uc(y)		0,0168 ns	Veff	457
Tdn7	1508,948 ns		k	1,97	Expanded uncertainty		0,033 ns		
			P	95%					

DN126

Quantity Xi	Estimate xi	Uncertainty value	Divisor	Standard uncertainty u(xi)	Probability distribution A or B	Sensitivity Coefficient ci	Uncertainty contribution ui(y)	Degree of freedom vi	Index
TI	12039,458 ns	0,0044 ns	1,000	0,0044 ns	A Normal	1	0,0044 ns	4	7,00%
δTB	0,000 ns	0,0010 ns	1,732	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,12%
δLin	0,000 ns	0,0100 ns	1,732	0,0058 ns	B Rectangular	1	0,0058 ns	∞	12,05%
δTE	0,000 ns	0,0012 ns	1,732	0,0007 ns	B Rectangular	1	0,0007 ns	∞	0,18%
δLTE	0,000 ns	0,0068 ns	1,732	0,0039 ns	B Rectangular	1	0,0039 ns	∞	5,60%
$\delta CableDelay$	0,000 ns	0,0115 ns	1	0,0115 ns	B Normal	1	0,0115 ns	∞	47,82%
$\delta Quant$	0,000 ns	0,0050 ns	1,73205	0,0029 ns	B Rectangular	1	0,0029 ns	∞	3,01%
$\delta Temp$	0,000 ns	0,0010 ns	1,73205	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,12%
$\delta Offset$	0,019 ns	0,0200 ns	2,44949	0,0082 ns	B Triangular	1	0,0082 ns	∞	24,10%
					Combined standard uncertainty uc(y)		0,0166 ns	Veff	817
Tdn126	12039,477 ns		k	1,96	Expanded uncertainty		0,033 ns		
			P	95%					

InLambda20

Quantity Xi	Estimate xi	Uncertainty value	Divisor	Standard uncertainty u(xi)	Probability distribution A or B	Sensitivity Coefficient ci	Uncertainty contribution ui(y)	Degree of freedom vi	Index
TI	24,166 ns	0,0016 ns	1,000	0,0016 ns	A Normal	1	0,0016 ns	4	0,96%
δTB	0,000 ns	0,0010 ns	1,732	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,13%
δLin	0,000 ns	0,0100 ns	1,732	0,0058 ns	B Rectangular	1	0,0058 ns	∞	12,54%
δTE	0,000 ns	0,0014 ns	1,732	0,0008 ns	B Rectangular	1	0,0008 ns	∞	0,25%
δLTE	0,000 ns	0,0078 ns	1,732	0,0045 ns	B Rectangular	1	0,0045 ns	∞	7,63%
$\delta CableDelay$	0,000 ns	0,0115 ns	1	0,0115 ns	B Normal	1	0,0115 ns	∞	49,77%
$\delta Quant$	0,000 ns	0,0050 ns	1,73205	0,0029 ns	B Rectangular	1	0,0029 ns	∞	3,14%
$\delta Temp$	0,000 ns	0,0020 ns	1,73205	0,0012 ns	B Rectangular	1	0,0012 ns	∞	0,50%
$\delta Offset$	0,018 ns	0,0200 ns	2,44949	0,0082 ns	B Triangular	1	0,0082 ns	∞	25,09%
					Combined standard uncertainty uc(y)		0,0163 ns	Veff	43168
InLa_20	**24,184 ns**		*k*	**1,96**	**Expanded uncertainty**		**0,032 ns**		
			P	**95%**					

InLambda100

Quantity Xi	Estimate xi	Uncertainty value	Divisor	Standard uncertainty u(xi)	Probability distribution A or B	Sensitivity Coefficient ci	Uncertainty contribution ui(y)	Degree of freedom vi	Index
TI	104,474 ns	0,0018 ns	1,000	0,0018 ns	A Normal	1	0,0018 ns	4	1,18%
δTB	0,000 ns	0,0010 ns	1,732	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,13%
δLin	0,000 ns	0,0100 ns	1,732	0,0058 ns	B Rectangular	1	0,0058 ns	∞	12,50%
δTE	0,000 ns	0,0014 ns	1,732	0,0008 ns	B Rectangular	1	0,0008 ns	∞	0,24%
δLTE	0,000 ns	0,0075 ns	1,732	0,0043 ns	B Rectangular	1	0,0043 ns	∞	7,08%
$\delta CableDelay$	0,000 ns	0,0115 ns	1	0,0115 ns	B Normal	1	0,0115 ns	∞	49,61%
$\delta Quant$	0,000 ns	0,0050 ns	1,73205	0,0029 ns	B Rectangular	1	0,0029 ns	∞	3,13%
$\delta Temp$	0,000 ns	0,0030 ns	1,73205	0,0017 ns	B Rectangular	1	0,0017 ns	∞	1,13%
$\delta Offset$	0,018 ns	0,0200 ns	2,44949	0,0082 ns	B Triangular	1	0,0082 ns	∞	25,01%
					Combined standard uncertainty uc(y)		0,0163 ns	Veff	28557
InLa_100	**104,492 ns**		*k*	**1,96**	**Expanded uncertainty**		**0,032 ns**		
			P	**95%**					

InLambda300

Quantity Xi	Estimate xi	Uncertainty value	Divisor	Standard uncertainty u(xi)	Probability distribution A or B	Sensitivity Coefficient ci	Uncertainty contribution ui(y)	Degree of freedom vi	Index
TI	307,272 ns	0,0032 ns	1,000	0,0032 ns	A Normal	1	0,0032 ns	4	3,75%
δTB	0,000 ns	0,0010 ns	1,732	0,0006 ns	B Rectangular	1	0,0006 ns	∞	0,12%
δLin	0,000 ns	0,0100 ns	1,732	0,0058 ns	B Rectangular	1	0,0058 ns	∞	12,05%
δTE	0,000 ns	0,0014 ns	1,732	0,0008 ns	B Rectangular	1	0,0008 ns	∞	0,24%
δLTE	0,000 ns	0,0076 ns	1,732	0,0044 ns	B Rectangular	1	0,0044 ns	∞	7,01%
$\delta CableDelay$	0,000 ns	0,0115 ns	1	0,0115 ns	B Normal	1	0,0115 ns	∞	47,80%
$\delta Quant$	0,000 ns	0,0050 ns	1,73205	0,0029 ns	B Rectangular	1	0,0029 ns	∞	3,01%
$\delta Temp$	0,000 ns	0,0040 ns	1,73205	0,0023 ns	B Rectangular	1	0,0023 ns	∞	1,93%
$\delta Offset$	0,018 ns	0,0200 ns	2,44949	0,0082 ns	B Triangular	1	0,0082 ns	∞	24,10%
					Combined standard uncertainty uc(y)		0,0166 ns	Veff	2851
InLa_300	**307,290 ns**		*k*	**1,96**	**Expanded uncertainty**		**0,033 ns**		
			P	**95%**					

Frank Coutereel. 2020-07-17

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM
e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: **SMD** Country: **Belgium**

Average date of measurements: **2020-06-08 till 2020-06-12**

Remarks:

As a result of a virus outbreak, a general lockdown was issued in Belgium so that the measurements were started with a delay of three months in SMD at Brussels.

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)		**10 MHz from UTC(SMD)**		10 MHz ± 1 Hz	**yes**
Amplitude (at 50 Ω)		**1,2 V**		within (0,5 ÷ 2) V_{p-p}	**yes**
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,0	±	**0,3**	°C	within (22 ± 4) °C	**yes**
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
47,5	±	**6,0**	%	within (50 ± 30) %	**yes**

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	**53230A**
Applied trigger level (50 Ω) (Required: 0,5 V)	**0,5 V**
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	< 10 ps

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	**22,648**	**±**	**0,032**	**ns**
"dn3"	**249,998**	**±**	**0,032**	**ns**
"dn7"	**1508,948**	**±**	**0,033**	**ns**
"dn126"	**12039,477**	**±**	**0,033**	**ns**

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Generator + Pulse Distributor		
1 pps (yes / no)	**no**		
Frequency	**10 Hz**	≤ 200 Hz	**yes**
Low level	**0V**	0 V	**yes**
High level (at 50 Ω)	**1.9 V**	(1,75 ÷ 2,25) V	**yes**
Rise time (20% to 80 %)	**< 1 ns**	< 10 ns	**yes**
Duty cycle	**10 %**	≤ 50 %	**yes**
Pulse width	**10 ms**	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	**yes**
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	**Inλ 100**	Inλ 100 or Inλ 300	**yes**
Inλ 100	**Inλ 20**	Inλ 20 or Inλ 300	**yes**
Inλ 300	**Inλ 100**	Inλ 20 or Inλ 100	**yes**

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,0	**±**	**0,3**	°C	within (22 ± 4) °C	**yes**
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
47,5	**±**	**6,0**	%	within (50 ± 30) %	**yes**

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	**53230A**
Applied trigger level (50 Ω) (Required: 0,5 V)	**0,5 V**
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	< 10 ps

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	**24,184**	**±**	**0,032**	**ns**	**22,0**	**±**	**0,3**	**°C**
Inλ 100	**104,492**	**±**	**0,032**	**ns**	**22,0**	**±**	**0,3**	**°C**
Inλ 300	**307,290**	**±**	**0,033**	**ns**	**22,0**	**±**	**0,3**	**°C**

Frank Coutereel 17 July 2020

Appendix G

SMD report - Addendum

Addendum to the SMD's Report Supplementary Comparison: EURAMET.TF-S1

1. Non-Linearity Behaviour

Evaluation is based on experiments, as this error depends on the type of interpolation technique. The manufacturer reports this type of error as the accuracy error and estimates it to be 100 ps. By smoothing out the noise with the number of measurements (division by the square root of the number of measurements during one session), the standard uncertainty for the residual non-linearity is not supposed to be more than 10 ps, which we consider to have a rectangular probability distribution.

However, the estimate of reducing the uncertainty by dividing by 10 (the square root of the number of measurements during one session) was too optimistic.

Measurements conducted on March 20, 2020, before the actual measurements, in the range from 1 to 100 ns using a stepper (HROG 10) showed a different approach. Measurements were taken in steps of 1 ns in the range of 1 to 10 ns, and in steps of 10 ns in the range of 10 to 100 ns. The conclusion was that a peak-to-peak error of approximately 140 ps in the range of 1-100 ns could be considered (with no correction), which can lead to a uniform distribution with limits of ± 70 ps for this type of error. Thus, the standard error will be reduced to 40 ps.

Measurements Summary

Delay(/ns)	Random error not corrected(/s)	/ps	Rounded /ps
1	**2,05078E-11**	**20,508**	**21**
2	**2,44141E-11**	**24,414**	**24**
3	**3,56445E-11**	**35,645**	**36**
4	**2,53906E-11**	**25,391**	**25**
5	**4,00391E-11**	**40,039**	**40**
6	**3,75977E-11**	**37,598**	**38**
7	**5,66406E-11**	**56,641**	**57**
8	**3,17383E-11**	**31,738**	**32**
10	**2,05078E-11**	**20,508**	**21**
20	**-8,05664E-11**	**-80,566**	**-81**
30	**-2,92969E-12**	**-2,930**	**-3**
50	**2,53906E-11**	**25,391**	**25**
70	**-1,75781E-11**	**-17,578**	**-18**
90	**5,27344E-11**	**52,734**	**53**

	/ps
MIN	-81
MAX	57
span	137
span/2	69
Std Unc (uniform)	40

Based on the above, the modification in the SMD's Report Supplementary Comparison: EURAMET.TF-S1 should be as follows:

Standard uncertainty component related to residual non-linearities or other non-reduced systematic effects and included in the uncertainty budget of measurement results (e.g., 0.150 ns/2 for SR620, unknown, ≤ …, …) is < = 40 ps.

This brings the total uncertainty to 84 ps (95% coverage) for the measurements for both “DN” and “InLambda” standards.

2. Offset Calculation

For clarification, the uncertainty for the offset was determined with a measurement conducted on the last day, yielding the following results:

Offset_Quantity				
Offset_Quantity	**Value**	**Uncertainty**	**Distr**	**Veff**
DN0	**+ 0,020 ns**	**+/- 0,020 ns**	**Triang**	∞
DN3	**+ 0,018 ns**	**+/- 0,020 ns**	**Triang**	∞
DN7	**+ 0,018 ns**	**+/- 0,020 ns**	**Triang**	∞
DN126	**+ 0,019 ns**	**+/- 0,020 ns**	**Triang**	∞
La_20	**+ 0,018 ns**	**+/- 0,020 ns**	**Triang**	∞
La_100	**+ 0,016 ns**	**+/- 0,020 ns**	**Triang**	∞
La_300	**+ 0,015 ns**	**+/- 0,020 ns**	**Triang**	∞

Average	**+ 0,018 ns**

Frank Coutereel

Frank Coutereel (Signature)

Frank Coutereel (Signature) 2024.07.11 14:30:20 +02'00'

Appendix H

IPQ report

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: IPQ Country: Portugal

Average date of measurements: 2020-06-30

Remarks:

Model equation that follows from the measurement setup:

$TI = f(X_1 + X_2 + X_3 + X_4)$

Description of the quantities in the model equation:

Quantity X_i	Description
Med	Measurements (100 measurements in 3 different days)
Res(SR620)	Resolution of the Time Interval Counter (SR620)
SR620	Time Interval Counter
UTC(IPQ)	UTC(IPQ) during measurements
Em	Influence of wrong measurements

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Med	5,8185 E-05	$\frac{\sqrt{5{,}8185 \times 10^{-5}}}{\sqrt{240}}$	Gaussian	A	1	0,0005	237
Res(SR620)	0,001	$\frac{0{,}001}{\sqrt{12}}$	Rectangular	B	1	0,0003	∞
SR620	0,150	0,150/2	Rectangular	B	1	0,0750	∞
UTC(IPQ)	0,5	$\frac{0{,}5}{\sqrt{12}}$	Rectangular	B	1	0,1443	∞
Em	1	$\frac{1}{\sqrt{12}}$	Rectangular	B	1	0,2887	∞

Combined standard uncertainty	u_c	0,3313
Effective degrees of freedom	ν_{eff}	∞
Expanded uncertainty ($p \approx 95\%$)	U	0,66

Carlos Pires 2020-07-31

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: IPQ Country: Portugal

Average date of measurements: 2020-06-30

Remarks:

….

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

<table>
<tr><th colspan="4">External standard 10 MHz reference frequency applied for TIGen standard</th><th>Required reference conditions</th><th>Meet requirements? yes / no</th></tr>
<tr><td colspan="3">Source (Cs clock, HM, …)</td><td>Cs clock</td><td>10 MHz ± 1 Hz</td><td>yes</td></tr>
<tr><td colspan="3">Amplitude (at 50 Ω)</td><td>0.5</td><td>within (0,5 ÷ 2) $V_{p\text{-}p}$</td><td>yes</td></tr>
<tr><th colspan="3">Ambient temperature during measurements</th><th>Unit of measure</th><th>Required reference conditions</th><th>Meet requirements? yes / no</th></tr>
<tr><td>22,3</td><td>±</td><td>0,4</td><td>°C</td><td>within (22 ± 4) °C</td><td>yes</td></tr>
<tr><th colspan="3">Ambient humidity during measurements</th><th>Unit of measure</th><th>Required reference conditions</th><th>Meet requirements? yes / no</th></tr>
<tr><td>41,9</td><td>±</td><td>0,2</td><td>%</td><td>within (50 ± 30) %</td><td>yes</td></tr>
<tr><th colspan="6">The base equipment used for time interval measurements</th></tr>
<tr><td colspan="4">The type / brand of time interval counter/ digital oscilloscope
(eg. SR620, 53230A, …)</td><td colspan="2">SR620
SN: 5014</td></tr>
<tr><td colspan="4">Applied trigger level (50 Ω)
(Required: 0,5 V)</td><td colspan="2">0.5</td></tr>
<tr><td colspan="4">Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results
(eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)</td><td colspan="2"></td></tr>
</table>

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22,999	±	0,66	ns
"dn3"	250,390	±	0,66	ns
"dn7"	1509,361	±	0,66	ns
"dn126"	12039,839	±	0,66	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	n		
Frequency	200	≤ 200 Hz	yes
Low level	0	0 V	yes
High level (at 50 Ω)	2	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)		< 10 ns	
Duty cycle	50	≤ 50 %	yes
Pulse width		to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 300	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 300	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
24,9	±	0,4	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
42,4	±	0,4	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620 SN: 5014
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24,531	±	0,66	ns	24,9	±	0,1	°C
Inλ 100	104,876	±	0,66	ns	24,8	±	0,1	°C
Inλ 300	307,691	±	0,66	ns	25,0	±	0,1	°C

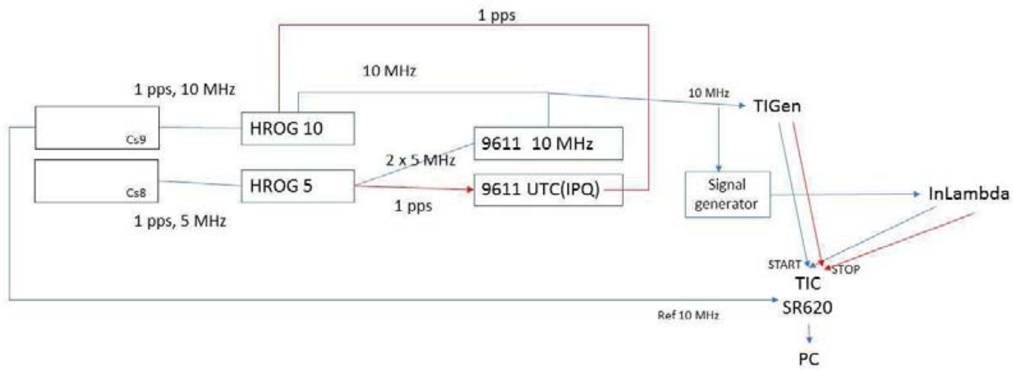
Carlos Pires 2020-07-31

Supplementary comparison EURAMET.TF-S1
Time interval measurements

Participating laboratory: Instituto Português da Qualidade

Calibration method:

Calibration set-up and equipment:



Equipment:

- 2 Cs clocks (Microsemi 5071A high performance tube);
- 2 Phase And Frequency Offset Generator from SpectraDynamics, HROG10 and HROG5;
- 2 SYMMETRICOM 9611 control distribution (12 channels), 1 for 1pps, and the other for 10 MHz;
- 1 Time Interval Counter from Stanford Research Systems, model SR620;
- Signal generator Tektronix model AFG1022.

Traceability chart:

As described in the set-up, the Time Interval Counter is traceable to the Cs clock (Cs9), UTC(IPQ) is traceable to Circular-T.

Uncertainty budget

Model equation that follows from the measurement setup:

$$TI = f(X_1 + X_2 + X_3 + X_4)$$

Description of the quantities in the model equation:

Quantity X_i	Description
Med	Average value of 3 different days, with more than 75 measurements per day
Res(SR620)	Resolution of the Time Interval Counter (SR620)
SR620	Time Interval Counter
UTC(IPQ)	UTC(IPQ) during measurements
Em	Influence of wrong measurements

Uncertainty budget for dn0:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Med	5,8185E-05	$\frac{\sqrt{5{,}8185 \times 10^{-5}}}{\sqrt{240}}$	Gaussian	A	1	0,0005	237
Res(SR620)	0,001	$\frac{0{,}001}{\sqrt{12}}$	Rectangular	B	1	0,0003	∞
SR620	0,150	0,150/2	Rectangular	B	1	0,0750	∞
UTC(IPQ)	1	$\frac{1}{\sqrt{12}}$	Rectangular	B	1	0,2887	∞
Em	1	1/√12	Rectangular	B	1	0,2887	∞
		Combined standard uncertainty			u_c	0,3313	
		Effective degrees of freedom			ν_{eff}	∞	
		Expanded uncertainty ($p \approx 95\%$)			U	0,66	

Obtained results of measurements:

Results in the Excel file named "Trat dados IPQ.xlsx"

10 MHz reference frequency for TIGen standard:

The 10 MHz signal for the TIGen standard comes from the HROG10, subsequently from the cesium clock with internal number Cs9

Input pulse signals for InLambda standards:

The signal comes from a signal generator with the specifications:

- Frequency 200 Hz;
- Low level 0 V;
- High level 2 V;
- Rise time not specified;
- Duty cycle 50 %;
- Pulse width not specified.

Ambient conditions of measurements

22,3 ± 0,4 °C and 41,9 ± 0,2 %RH for the TIGen standard measurements.
24,9 ± 0,4 °C and 42,4 ± 0,4 %RH for the InLambda standards measurements.

Average date of performing measurements:

Measurements made in 3 days: 2020-06-29, 2020-06-30 and 2020-07-02

Carlos Pires 2020-07-31

Appendix I

ROA report

SUBJECT:

EURAMET.TF-S1 Supplementary Comparison ”Comparison of time interval measurements”, report of the Real Instituto y Observatorio de la Armada (ROA). (performed within EURAMET Project #1485)

	NAME	SIGNATURE	DATE
PREPARED BY:	Ildefonso García Fraga	ILDEFONSO GARCÍA FRAGA 2020.07.31 09:23:18 +02'00'	July 2020
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Edition	**Date**	**Information**
01	July, 2020	Initial edition

REAL INSTITUTO Y OBSERVATORIO DE LA ARMADA
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INDEX

1. Identification of the participating laboratory 3

2. Description of the calibration methods and associated measurement systems. 3

3. Generalities 3

4. First calibration of travelling standards 6

4.1. Simplified method for evaluating asymmetries 6

4.1.1. Uncertainty budget 7

4.2. Measurements on travelling standards 8

5. Second calibration method of travelling standards 9

6. Description of the 1 PPS signal used for the calibration, as well as the one generated by the InLambda and TiGen. Amplitude and rise time (from 20% to 80 %) can be directly obtained. 11

7. Methods I and II comparison and final result 13

7.1. Measurement results with uncertainty: Method I 16

7.2. Measurement results with uncertainty: Method II 17

7.3. Measurement results with uncertainty: Oscilloscope method 17

8. Ambient conditions of measurements (the temperature and the relative humidity) 18

9. Average date of performing measurements 18

1. Identification of the participating laboratory

The *Real Instituto y Observatorio de la Armada* (ROA) is the Designated Institute (DI) responsible for maintaining the Spanish National Standards for time and frequency. The activities appertaining to these standards are performed under the supervision and co-ordination of *the Centro Español de Metrología* (CEM), within the Associated Laboratories Commission, of the *Consejo Superior de Metrología*.

Both designations as well as details of the standards, have been published in the Spanish Official State Gazette *(Boletín Oficial del Estado, BOE)*.

2. Description of the calibration methods and associated measurement systems.

The calibration method employs a time interval counter (TIC) to carry out the measurements on the time difference source or device under test (DUT); for both instruments is applied a 10 MHz reference frequency from the UTC(ROA) scale. Time interval (TI) measurements are corrected by system asymmetries.

The TIC is the widely used SR620 which takes the frequency of the UTC(ROA) scale as external time base. UTC(ROA) is generated by a MHM 2010 active hydrogen maser and an Auxiliary Output Generator AOG-110. The measurement system is graphically described in the Figure 1.

In the calibration process have been used two different measurement methods. Method I previously computes non-linearities of the measurement system and Method II removes existing non-linearities between TIC channels and cables involved. For each time interval (TI) standard to calibrate, 100 measurements are carried out. All of them have been made with a trigger setting value of 0.5 V.

To ensure the validity of the results, the measurements are performed on two counters called TIC # 1 (SR620-01, s/n: 6467) and TIC # 2 (SR620-01, s/n: 6468).

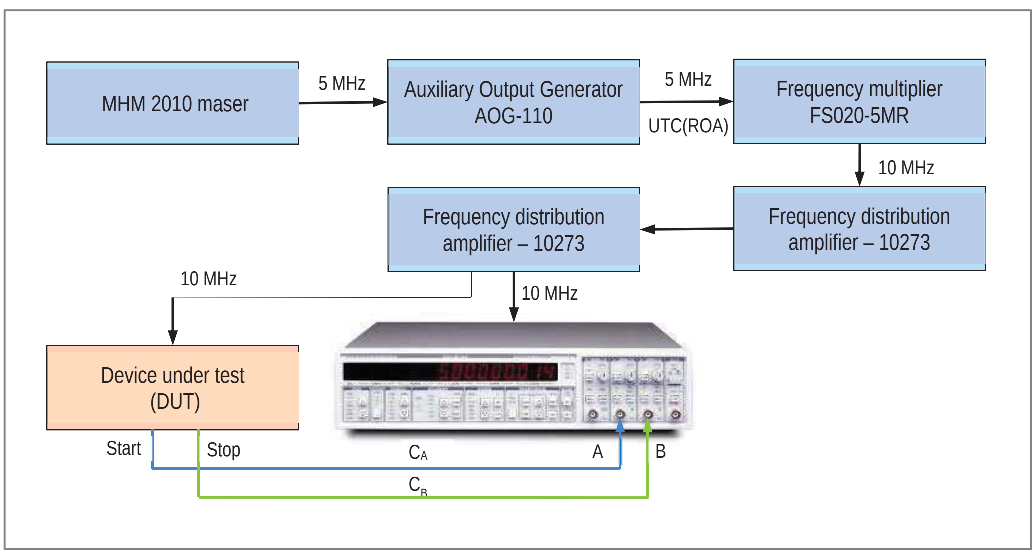


Figure 1. General diagram of the measurement system and distribution chain of the reference frequency.

3. Generalities

In the model for computing the uncertainty of the time interval measurements, are considered the contributions from the UTC(ROA) frequency distribution chain (through the TIC external timebase input), together with the time interval resolution expressions provided by the counter manufacturer.

Formal traceability of the UTC(ROA) scale to UTC is assured through the monthly BIPM publication of Circular T.

Magnitudes involved in the uncertainty budget affecting the timebase error:

1) UTC(ROA) uncertainty @ 1 day. (Obtained from Circular T extrapolation and considering UTCr)

$$UTC(ROA)\ uncertainty\ @\ 1\ day = \sqrt{\left(\frac{\Delta f}{f}\right)^2 + (\sigma_y)^2} = \pm\, 7{,}5\times 10^{-15}$$

2) SR620's short-term timebase stability @ 1 s. (Stability obtained by calibration on the signal from SR620's 10 MHz output connector).

$$short - term\ timebase\ stability\ @\ 1\ s < \ 2\times 10^{-12}$$

3) Maser Temperature sensitivity: < 1.0×10^{-14} / °C

4) AOG temperature sensitivity: < 10 ps / ºC

For an integration time of 100 s and a temperature variation of ± 0.5 ºC during measurements:

$$\frac{10\times 10^{-12}}{100}\cdot \Delta T = 1\times 10^{-13}$$

5) FS020-5MR temperature sensitivity: < 50 ps / ºC

$$\frac{50\times 10^{-12}}{100}\cdot \Delta T = 5\times 10^{-13}$$

6) Frequency distribution amplifier 10273 Temperature sensitivity: < 6 ps / ºC

$$\frac{6\times 10^{-12}}{100}\cdot \Delta T = 6\times 10^{-14}$$

Frequency distributors used: 2

Quantity X_i	Estimate x_i	Standart uncertainty (Hz/Hz) $u(x_i)$	Probability Distribution	Conversion Factor	Uncertainty Contribution $u_i(y)$
UTC(ROA) Accuracy @ 1 day	-	7.50E-15	Normal	1.0	7.50E-15
Short term stability Timebase @ 1 s		2.00E-12	Normal	1.0	2.00E-12
Maser Temperature sensitivity		1.00E-14	Rectangular	0.6	5.77E-15
AOG Temperature sensitivity	-	1.00E-13	Rectangular	0.6	5.77E-14
FS020-5MR temperature sensitivity		5.00E-13	Rectangular	0.6	2.89E-13
10273 temperature sensitivity		6.00E-14	Rectangular	0.6	3.46E-14
10273 temperature sensitivity		6.00E-14	Rectangular	0.6	3.46E-14
Timebase error	-			Combined Uncertainty u_C:	2.02E-12

Table 1. Timebase error, uncertainty budget.

Other contributions to uncertainty budget:

7) SR620's Uncertainty.

In this document, the accuracy and short-term stability of the counter's timebase are considered equal in value.

$$Error_{SR620} = \pm Resolution \pm (timebase\ error\ \cdot TI) \pm start\ trigger\ level\ error \pm stop\ trigger\ level\ error$$

Counter errors are treated as uncertainties and their terms are quadratically summed:

$$u_{SR620} = \sqrt{Resol^2 + (timebase\ error\ \cdot TI)^2 + (start\ trigger\ level\ error)^2 + (stop\ trigger\ level\ error)^2}$$

Where:

$$Resolution = \pm \sqrt{\frac{(25ps)^2 + (TI \cdot short\ term\ stability)^2 + (start\ trigger\ jitter)^2 + (stop\ trigger\ jitter)^2}{N}}$$

$$(start/stop)\ trigger\ jitter = \sqrt{\left(\frac{E_{internal}}{Input\ Slew\ Rate}\right)^2 + \left(jitter_{DUT}\right)^2}$$

$E_{internal}(TIC\ internal\ input\ noise) = 350\ \mu V\ (rms\ typical)$

$Jitter_{10545}$ = 2×10^{-12} s

$Jitter_{TIGen}$ = 3×10^{-12} s

$Jitter_{In\lambda}$ = 10×10^{-12} s

$Jitter_{aux\ In\lambda+\ In\lambda}$ = 14.1×10^{-12} s

DUT's *input slew rate (start/stop)* at 0.5 V is 2.94E+9 V/s. Jitter of the signals used in the calibration can be seen in section 6. In the case of the TIGen, $Jitter_{TIGen}$ = 3×10^{-12} *s*.

$$(start/stop)\ trigger\ jitter = \sqrt{\left(\frac{350 \times 10^{-6}}{2.94 \times 10^{+9}}\right)^2 + (3 \times 10^{-12})^2} \cong 3 \times 10^{-12} s$$

Then:

$$Resolution^{(*)} = \pm \sqrt{\frac{(25 \times 10^{-12})^2 + (TI_{mean} \cdot 2 \times 10^{-12})^2 + 2 \cdot (3 \times 10^{-12})^2}{100}} \cong 2.54\ \times 10^{-12}\ s$$

(*) The same *resolution* is obtained in all TI_{mean} measurements carry out on the DUT.

$$(start/stop)\ trigger\ level\ error = \frac{15\ mV + 0.5\%\ of\ setting}{Input\ Slew\ Rate}$$

$$(start/stop)\ trigger\ level\ error = \frac{15\ \times 10^{-3} + 0.5 \cdot \frac{0.5}{100}}{2.94 \times 10^{+9}} \cong 6\ \times 10^{-12}\ s$$

$$u_{SR620}{}^{(**)} = \sqrt{(2.54 \times 10^{-12})^2 + (TI_{mean} \cdot 2.76 \times 10^{-13})^2 + 2 \cdot (6 \times 10^{-12})^2} \cong 8.79 \times 10^{-12}\ s$$

(**) The same u_{SR620} is obtained in all TI_{mean} measurements carry out on the DUT.

8) SR620 Differential Non-Linearity: 5×10^{-11} s

9) Display (LSD) SR620 Resolution: 1×10^{-12} s

4. First calibration of travelling standards

4.1. Simplified method for evaluating asymmetries

Before performing the TI measurements on the DUT, the differential delay introduced due to asymmetry existing between the TIC's channels is determined. The measurement system for this purpose is shown below.

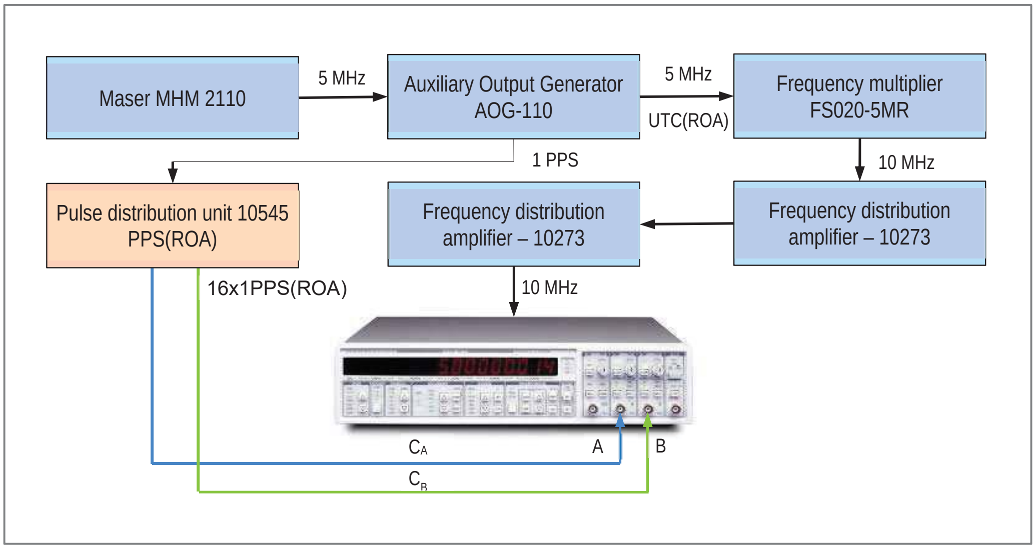


Figure 2. Diagram of the measurement system for the measurement of the asymmetry by simplified method.

Cables C_A and C_B and pulse distributor outputs are selected with practically the same delays, so the differential delay they produce is considered negligible.

The pulse distribution unit 10545 has an output to output skew < 20 ps (P_B-P_A). The rise time of the pulses can be seen in Figure 7 (Timetech PDU). Pulse width 20 µs.

The model to determine the asymmetry of the measurement system follows the following expression:

$$TI_{asy} = P_B - P_A + C_B - C_A + R_B - R_A = P_{BA} + C_{BA} + R_{BA}$$

Where:

$P_{BA} = P_B - P_A$: Differential delay due to output to output skew of the pulses used. The difference delay is treated as an uncertainty, therefore considering that the delay is zero.

$C_{BA} = C_B - C_A$: Delay due to the asymmetry of the cables used. It is considering null and its value added to the delay between channels of the counter R_{BA}.

$R_{BA} = R_B - R_A$: Delay due to the asymmetry of the SR620 channels.

Therefore:

$$TI_{asy} = R_{BA} \pm u(TI_{asy})$$

To ensure the validity of the results, the delay measurements are performed on two counters called TIC # 1 and TIC # 2. The average delay of 100 observations is taken as the best estimate of the delay in each of them.

$$\bar{R}_{BA} = \overline{TI}_{asy} \pm u(TI_{asy})$$

Differential delay readings:

$$TIC\#1:\ \overline{TI}_{asy} = 87 \times 10^{-12}\ s, \qquad jitter = 7 \times 10^{-12}\ s$$

$$TIC\#2:\ \overline{TI}_{asy} = 171 \times 10^{-12}\ s, \qquad jitter = 7 \times 10^{-12}\ s$$

4.1.1.Uncertainty budget

Lab. temperature variation: ± 0.5 ºC

1) Pulse distribution unit 10545 Temperature sensitivity: 6 ps/K

$$6 \times 10^{-12} \cdot \Delta T = 6 \times 10^{-12}\ \mathrm{s}$$

2) Pulse distribution unit 10545 Output intrinsic jitter: < 2 ps
3) Pulse distribution unit 10545 Output to output skew: < 20 ps
4) SR620's Uncertainty

   SR620's timebase error and short term stability @ 1s: 2.02×10^{-12}

$$\boldsymbol{u}_{SR620} = \sqrt{Resol^2 + (timebase\ error\ \cdot TI)^2 + (start\ trigger\ level\ error)^2 + (stop\ trigger\ level\ error)^2} \cong 8.78 \times 10^{-12}\ s$$

5) SR620 Differential Non-Linearity: 50×10^{-12} s
6) Display (LSD) SR620 Resolution: 1×10^{-12} s
7) Type A uncertainty:

$$\frac{TI\ jitter}{\sqrt{100}} = 7 \times 10^{-13}\ \mathrm{s}$$

Combined Uncertainty:

$$\boldsymbol{u}_c(TI_{asy}) = \sqrt{(1)^2 + (2)^2 + (3)^2 + (4)^2 + (5)^2 + (6)^2 + (7)^2} = 52.2\ \times 10^{-12}\ s$$

Quantity X_i	Estimate x_i	Standart uncertainty (s) $u(x_i)$	Probability Distribution	Conversion Factor	Uncertainty Contribution $u_i(y)$
10545 Temperature sensitivity		6.00E-12	Rectangular	0.6	3.46E-12
10545 Output to output Skew	-	2.00E-11	Rectangular	0.6	1.15E-11
10545 jitter		2.00E-12	Rectangular	0.6	1.15E-12
SR620 Differential Non-Linearity		5.00E-11	Normal	1.0	5.00E-11
Display (LSD) SR620 Resolution		1.00E-12	Rectangular	0.6	5.77E-13
u_{sr620} (DelayTIC#1)		8.78E-12	Normal	1.0	8.78E-12
uncert (type A) DelayTIC#1		7.00E-13	Normal	1.0	7.00E-13
TIC#1 Asym	8.73E-11			Combined Uncertainty u_c:	5.22E-11
u_{sr620} (DelayTIC#2)		8.78E-12	Normal	1.0	8.78E-12
uncert (type A) DelayTIC#2		7.00E-13	Normal	1.0	7.00E-13
TIC#2 Asym	1.71E-10			Combined Uncertainty u_c:	5.22E-11

Table 2. Delay TICs, uncertainties budget.

4.2. Measurements on travelling standards

The rise time of TIGen and InLambda travelling standards pulses can be seen in Figures 3 and 4. To perform the process a pair of RG-58 cables of equal length is used. The results for the first calibration method are detailed below.

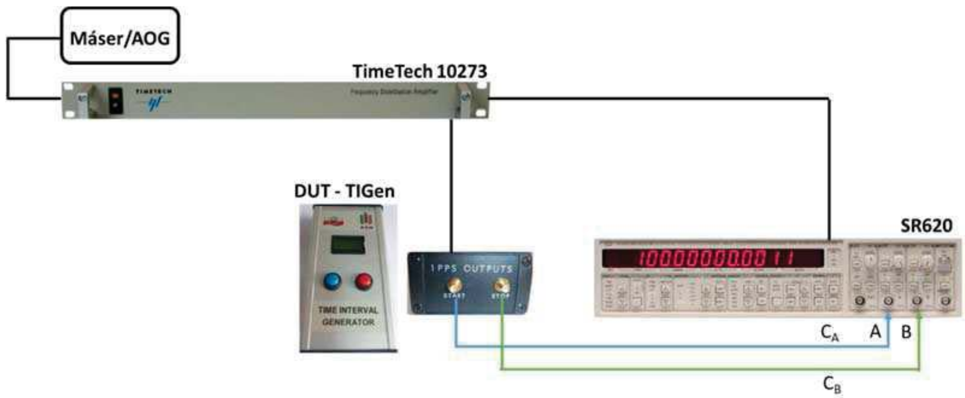


Figure 3. TIGen measurement

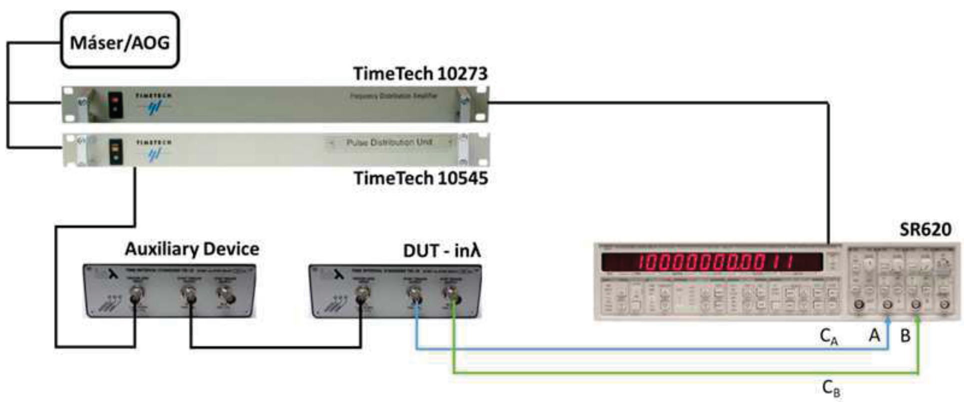


Figure 4. Inλ measurement

In this case, it is necessary to take into account the asymmetry due to the counter channels. Therefore, the measurement obtained for the travelling standards M1 evaluation (Figure 6 and Figure 7) with the starting time on channel A is given by:

$$\overline{TI}_{DUT} = \overline{TI}_{measured} - \overline{TI}_{asy}$$

The uncertainty budged is shown in Table 3:

Magnitude X_i	Estimation (s) x_i	Standard uncertainty (s) $u(x_i)$	Probability distribution	Conversion factor	Uncertainty contribution $u_i(y)$
SR620 Differential Non-linearity		5.000E-11	Normal	1.0	5.00E-11
Resol. display (LSD)		1.000E-12	Rectangular	0.6	5.77E-13
(1) u_{SR620}		9.003E-12	Normal	1.0	9.00E-12
(2) TI mean	2.276E-08	5.000E-13	Normal	1.0	5.00E-13
(3) TI Asymmetry TIC#1	8.733E-11	5.220E-11	Normal	1.0	5.22E-11
TI_{DUT} TIGen dn0	2.267E-08			Combined Uncertainty u_C:	7.28E-11
				Expanded uncertainty U (k = 2)	1.46E-10

Table 3. Measurement TIGen dn0 uncertainty budget with Method I and TIC#1.

To determine the u_{sr620} uncertainty, Table 1 has been used (Timebase error, uncertainty budget).

(1)(2)(3) u_{SR620}, TI_{mean} and $TI_{asymmetry}$ in Table 3, correspond to the uncertainty budget of the TIGen dn0 measurement performed with TIC#1. The result of all the time interval measurements made with TIC#1 and TIC#2 are obtained proceeding in the same way. The results are presented below.

Results			
Measurement	**TI_{DUT}**	**$u_c(TI)$**	**U (k=2)**
TIGen dn0	2.267E-08	7.28E-11	1.46E-10
TIGen dn3	2.5005E-07	7.28E-11	1.46E-10
TIGen dn7	1.50893E-06	7.28E-11	1.46E-10
TIGen dn126	1.203951E-05	7.28E-11	1.46E-10
Inλ 20 ns	2.423E-08	7.28E-11	1.46E-10
Inλ 100 ns	1.0452E-07	7.28E-11	1.46E-10
Inλ 300 ns	3.0731E-07	7.28E-11	1.46E-10

Table 4. TI_{DUT} results and expanded uncertainties with TIC#1 (SR620-01, s/n: 6467)

Results			
Measurement	**TI_{DUT}**	**$u_c(TI)$**	**U (k=2)**
TIGen dn0	2.272E-08	7.28E-11	1.46E-10
TIGen dn3	2.5000E-07	7.28E-11	1.46E-10
TIGen dn7	1.50899E-06	7.28E-11	1.46E-10
TIGen dn126	1.203946E-05	7.28E-11	1.46E-10
Inλ 20 ns	2.426E-08	7.28E-11	1.46E-10
Inλ 100 ns	1.0451E-07	7.28E-11	1.46E-10
Inλ 300 ns	3.07300E-07	7.28E-11	1.46E-10

Table 5. TI_{DUT} results and expanded uncertainties with TIC#2 (SR620-01, s/n: 6468)

5. Second calibration method of travelling standards

The purpose of this second calibration is to take two measurements for every characterized Time Interval and to cancel the delay due to the counter channel asymmetry. To perform this method, the first measurement M1 (Figure 5a and 6a), is configured with the starting time on channel A. Then, the cables are swapped and the starting time set on channel B (Figure 5b and 6b). The comparison is realized with the SR620 counter for an averaging time of 100 s (number of samples N= 100).

The method of the Time Interval measurement is shown in Figures 5 to 6:

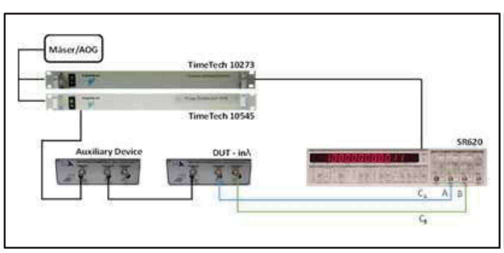


Figure 5a. Inλ M1 measurement.

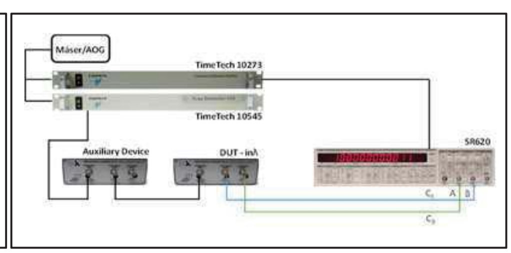


Figure 5b. Inλ M2 measurement.

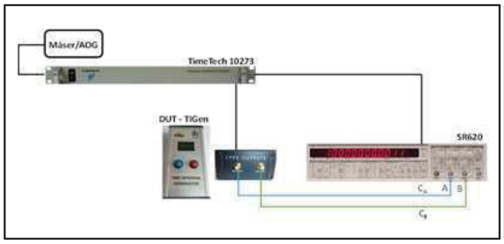


Figure 6a. TIGen M1 measurement.

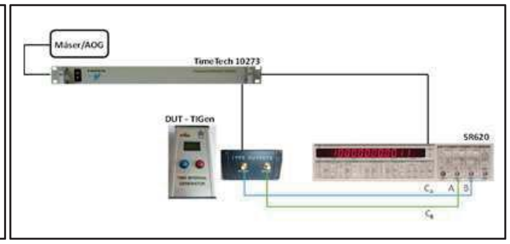


Figure 6b. TIGen M2 measurement.

The model function is expressed as:

$$\overline{M_1}_{DUT} = \overline{TI}_{DUT} + \overline{R}_{BA} + \overline{C}_{BA}$$

$$\overline{M_2}_{DUT} = \overline{TI}_{DUT} - \overline{R}_{BA} - \overline{C}_{BA}$$

$$\overline{TI}_{DUT} = \frac{\overline{M_1}_{DUT} + \overline{M_2}_{DUT}}{2}$$

Applying the law of propagation of uncertainties to the model function, assuming that the quantities are strongly correlated:

$$u(\overline{TI}_{DUT}) = \sqrt{\left(\frac{1}{2}\right)^2 u^2(\overline{M_1}_{DUT}) + \left(\frac{1}{2}\right)^2 u^2(\overline{M_2}_{DUT}) + 2\cdot\frac{1}{2}\cdot\frac{1}{2}u(\overline{M_1}_{DUT})u(\overline{M_2}_{DUT})}$$

The result for the TIGen dn0 measurement using the second calibration method ant TIC#1 is detailed below:

Magnitude X_i	Estimation (s) x_i	Standard uncertainty (s) $u(x_i)$	Probability distribution	Conversion factor	Uncertainty contribution $u_i(y)$
SR620 Differential Non-linearity		5.000E-11	Normal	1.0	5.00E-11
Resol. display (LSD)		1.000E-12	Rectangular	0.6	5.77E-13
$u_{SR620\ M1}$		8.788E-12	Normal	1.0	8.79E-12
u_{M1} (Type A)		5.000E-13	Normal	1.0	5.00E-13
$M1_{DUT}$	2.2764E-08			Combined Uncertainty u_C:	5.08E-11

Table 7. Method II, $M1_{DUT}$ uncertainty budget. Measurement TIGen dn0 with TIC#1.

Magnitude X_i	Estimation (s) x_i	Standard uncertainty (s) $u(x_i)$	Probability distribution	Conversion factor	Uncertainty contribution $u_i(y)$
SR620 Differential Non-linearity		5.000E-11	Normal	1.0	5.00E-11
Resol. display (LSD)		1.000E-12	Rectangular	0.6	5.77E-13
$u_{SR620\ M2}$		8.788E-12	Normal	1.0	8.79E-12
u_{M2} (Type A)		5.000E-13	Normal	1.0	5.00E-13
$M2_{DUT}$	2.2625E-08			Combined Uncertainty u_C:	5.08E-11

Table 8. Method II, $M2_{DUT}$ uncertainty budget. Measurement TIGen dn0 with TIC#1.

To determine the u_{sr620} uncertainties, Table 1 has been used (Timebase error, uncertainty budget).

Magnitude X_i	Estimation (s) x_i	Standard uncertainty (s) $u(x_i)$	Probability distribution	Conversion factor	Uncertainty contribution $u_i(y)$
$M1_{DUT}$	2.2764E-08	5.077E-11	Normal	0.5	2.54E-11
$M2_{DUT}$	2.2625E-08	5.077E-11	Normal	0.5	2.54E-11
$u(M1_{DUT}, M2_{DUT})$		5.077E-11	Normal	0.7	3.59E-11
TI_{DUT} = (M1+M2)/2	2.2695E-08			Combined Uncertainty u_C:	5.08E-11
				Expanded uncertainty U (k = 2)	1.02E-10

Table 9. Method II, uncertainty budget. Measurement TIGen dn0 with TIC#1.

The results of all time interval measurements made with TIC#1 and TIC#2 are obtained proceeding in the same way, as presented below.

TIC#1 Results					
Measurement	TI_{DUT} = (M1+M2)/2	u_c(M1)	u_c(M2)	$u_c(TI_{DUT})$	U (k=2)
TIGen dn0	2.269E-08	5.08E-11	5.08E-11	5.08E-11	1.02E-10
TIGen dn3	2.4999E-07	5.08E-11	5.08E-11	5.08E-11	1.02E-10
TIGen dn7	1.50893E-06	5.08E-11	5.08E-11	5.08E-11	1.02E-10
TIGen dn126	1.203950E-05	5.08E-11	5.08E-11	5.08E-11	1.02E-10
Inλ 20 ns	2.418E-08	5.08E-11	5.08E-11	5.08E-11	1.02E-10
Inλ 100 ns	1.0455E-07	5.08E-11	5.08E-11	5.08E-11	1.02E-10
Inλ 300 ns	3.0734E-07	5.08E-11	5.08E-11	5.08E-11	1.02E-10

Table 10. Method II, Results with TIC#1.

TIC#2 Results					
Measurement	TI_{DUT} = (M1+M2)/2	u_c(M1)	u_c(M2)	$u_c(TI_{DUT})$	U (k=2)
TIGen dn0	2.267E-08	5.08E-11	5.08E-11	5.08E-11	1.02E-10
TIGen dn3	2.5000E-07	5.08E-11	5.08E-11	5.08E-11	1.02E-10
TIGen dn7	1.50900E-06	5.08E-11	5.08E-11	5.08E-11	1.02E-10
TIGen dn126	1.203947E-05	5.08E-11	5.08E-11	5.08E-11	1.02E-10
Inλ 20 ns	2.422E-08	5.08E-11	5.08E-11	5.08E-11	1.02E-10
Inλ 100 ns	1.0452E-07	5.08E-11	5.08E-11	5.08E-11	1.02E-10
Inλ 300 ns	3.0729E-07	5.08E-11	5.08E-11	5.08E-11	1.02E-10

Table 11. Method II, Results with TIC#2.

6. Description of the 1 PPS signal used for the calibration, as well as the one generated by the InLambda and TiGen.

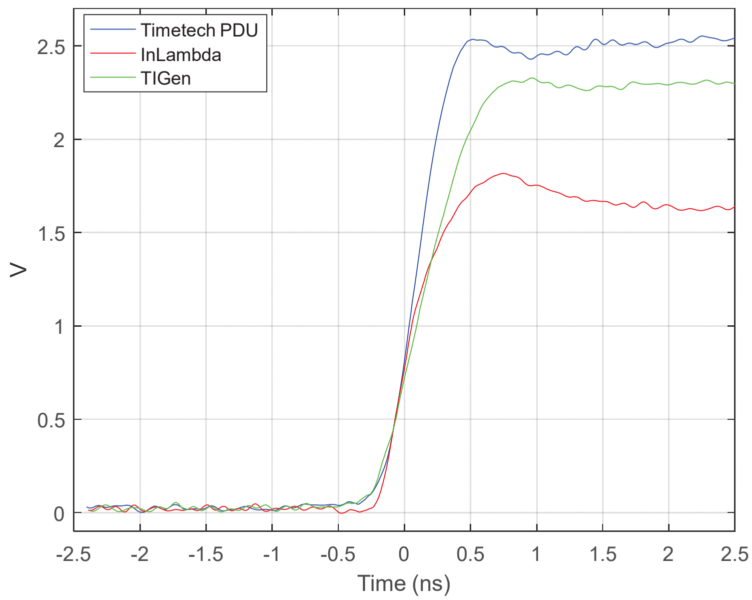


Figure 7. Rise time of the pulses used in the calibration.

Auxiliary InLambda input pulse (Graph with blue line): 1 PPS from 10545 Pulse Distribution Unit

Low level = 0 V, amplitude = 2.5 V, pulse width = 20 µs, rise time (20 % to 80 %) = 350 ps, jitter = 2 ps.

InLambda output (Graph with red line):

Low level = 0 V, amplitude = 1.84 V, rise time (20 % to 80 %) = 460 ps, jitter = 10 ps.

TIGen output (Graph with green line):

Low level = 0 V, amplitude = 2.34 V, rise time (20 % to 80 %) = 420 ps, jitter = 3 ps.

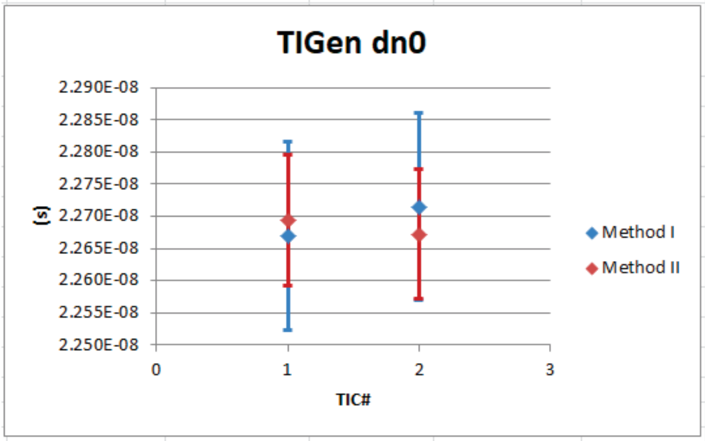
Device:	TimeTech	TIGen	InLambda	Unit
Amplitude:	2.5	2.34	1.84	(V)
80%	2	1.87	1.47	(V)
20%	0.5	0.47	0.37	(V)
Rise time @ 20% - 80%:	3.50E-10	4.20E-10	4.60E-10	(s)
Slew rate @ 20% - 80%:	4.29E+09	3.34E+09	2.40E+09	(V/s)
Rise time @ 0.25 V - 0.75 V:	1.70E-10	1.70E-10	1.70E-10	(s)
Slew rate @ 0.5 V:	2.94E+09	2.94E+09	2.94E+09	(V/s)
jitter:	2.00E-12	3.00E-12	1.00E-11	(s)

Table 12. Characteristics of the signals.

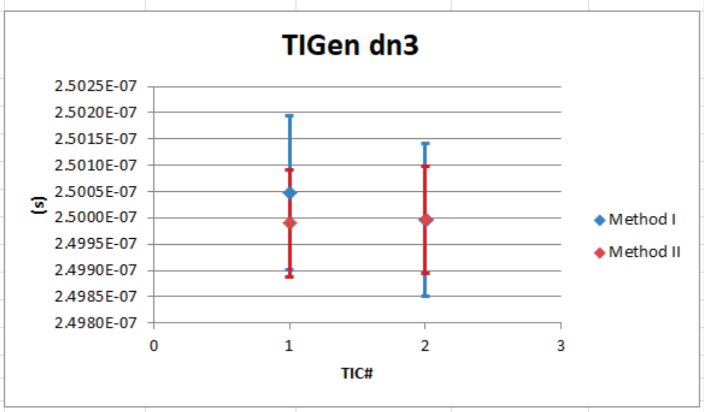
7. Methods I and II comparison and final result

Units are in seconds.

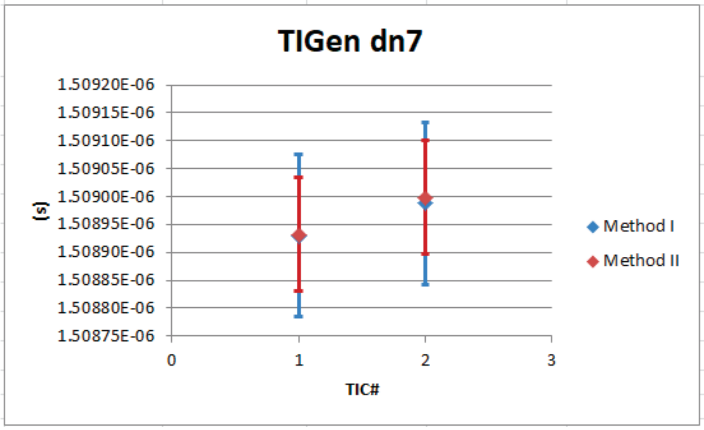
TIGen dn0	Method I		Method II	
	Measurement	U (k=2)	Measurement	U (k=2)
TC#1	2.267E-08	1.46E-10	2.269E-08	1.02E-10
TC#2	2.272E-08	1.46E-10	2.267E-08	1.02E-10
TC#1&2	**2.269E-08**	**1.03E-10**	**2.2684E-08**	**7.18E-11**



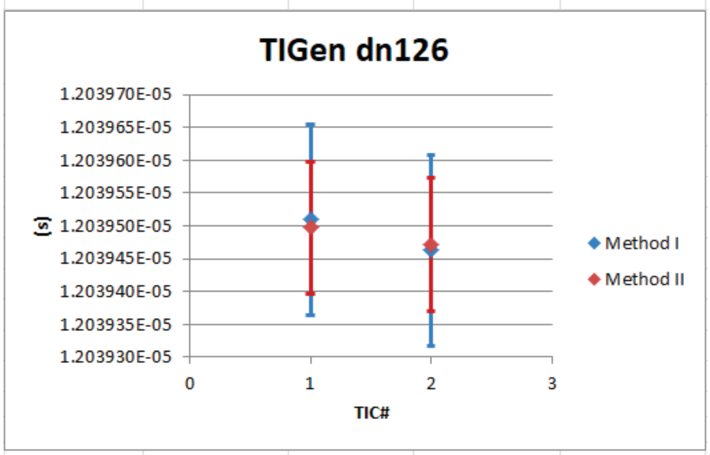
TIGen dn3	Method I		Method II	
	Measurement	U (k=2)	Measurement	U (k=2)
TC#1	2.5005E-07	1.46E-10	2.4999E-07	1.02E-10
TC#2	2.5000E-07	1.46E-10	2.5000E-07	1.02E-10
TC#1&2	**2.5002E-07**	**1.03E-10**	**2.49997E-07**	**7.18E-11**



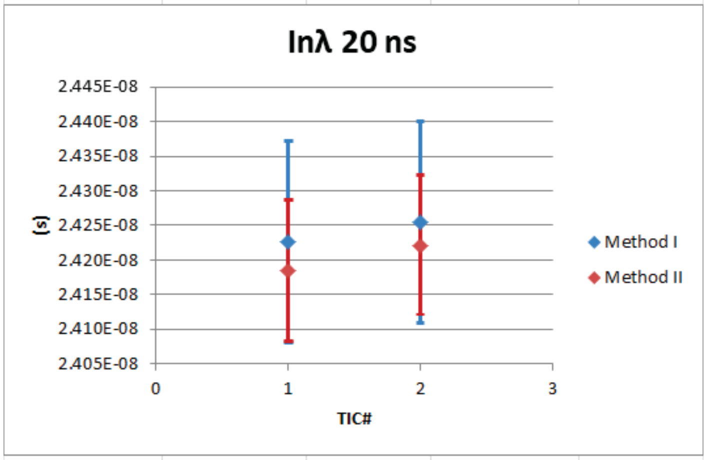
TIGen dn7	Method I		Method II	
	Measurement	U (k=2)	Measurement	U (k=2)
TC#1	1.50893E-06	1.46E-10	1.50893E-06	1.02E-10
TC#2	1.50899E-06	1.46E-10	1.50900E-06	1.02E-10
TC#1&2	**1.50896E-06**	**1.03E-10**	**1.508966E-06**	**7.18E-11**



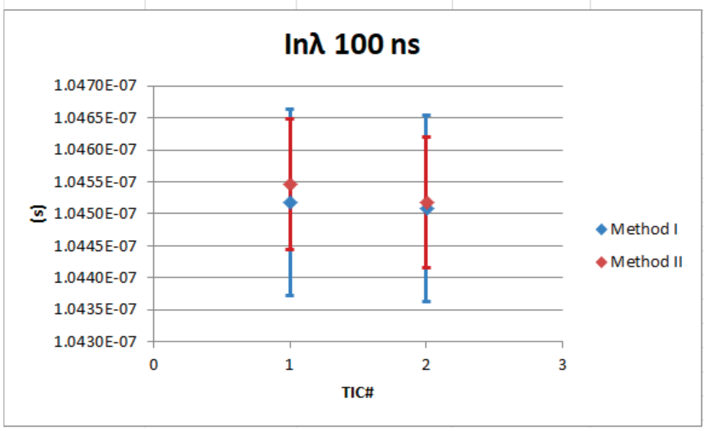
TIGen dn126	Method I		Method II	
	Measurement	U (k=2)	Measurement	U (k=2)
TC#1	1.203951E-05	1.46E-10	1.203950E-05	1.02E-10
TC#2	1.203946E-05	1.46E-10	1.203947E-05	1.02E-10
TC#1&2	**1.203949E-05**	**1.03E-10**	**1.2039484E-05**	**7.18E-11**



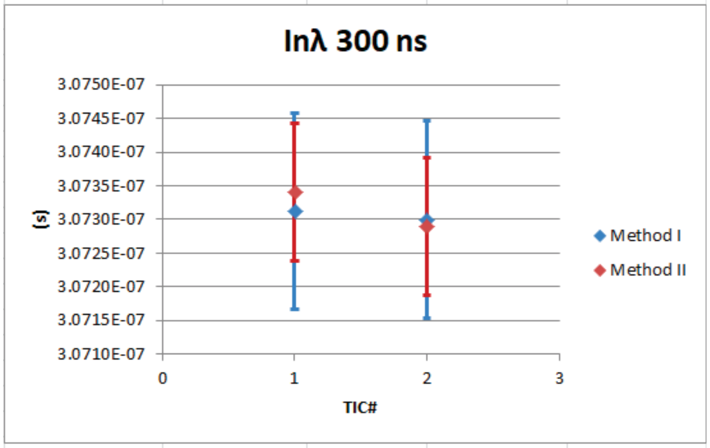
Inλ 20 ns	Method I		Method II	
	Measurement	U (k=2)	Measurement	U (k=2)
TC#1	2.423E-08	1.46E-10	2.418E-08	1.02E-10
TC#2	2.426E-08	1.46E-10	2.422E-08	1.02E-10
TC#1&2	**2.424E-08**	**1.03E-10**	**2.4203E-08**	**7.19E-11**



Inλ 100 ns	Method I		Method II	
	Measurement	U (k=2)	Measurement	U (k=2)
TC#1	1.0452E-07	1.46E-10	1.0455E-07	1.02E-10
TC#2	1.0451E-07	1.46E-10	1.0452E-07	1.02E-10
TC#1&2	**1.0451E-07**	**1.03E-10**	**1.04532E-07**	**7.19E-11**



Inλ 300 ns	Method I		Method II	
	Measurement	U (k=2)	Measurement	U (k=2)
TC#1	3.0731E-07	1.46E-10	3.0734E-07	1.02E-10
TC#2	3.0730E-07	1.46E-10	3.0729E-07	1.02E-10
TC#1&2	**3.0731E-07**	**1.03E-10**	**3.07315E-07**	**7.19E-11**



7.1. Measurement results with uncertainty: Method I

The following values have been obtained from the mean value of measurements carried out with Time Internal Counter #1 and #2. Therefore, the uncertainty has been reduced by a factor of 1/√2. Although it usually suffices to give *U* at most two significant digits, in this case additional digits have been preserved to avoid round-off errors in subsequent calculations.

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”	22.692	±	0.103	ns
“dn3”	250.022	±	0.103	ns
“dn7”	1508.959	±	0.103	ns
“dn126”	12039.486	±	0.103	ns

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.240	±	0.103	ns	21.94	±	0.59	°C
Inλ 100	104.513	±	0.103	ns	21.99	±	0.25	°C
Inλ 300	307.306	±	0.103	ns	21.97	±	0.31	°C

7.2. Measurement results with uncertainty: Method II

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”	22.684	±	0.072	ns
“dn3”	249.997	±	0.072	ns
“dn7”	1508.966	±	0.072	ns
“dn126”	12039.484	±	0.072	ns

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.203	±	0.072	ns	21.94	±	0.59	°C
Inλ 100	104.532	±	0.072	ns	21.99	±	0.25	°C
Inλ 300	307.315	±	0.072	ns	21.97	±	0.31	°C

7.3. Measurement results with uncertainty: Oscilloscope method

The results have been also obtained through the DSO9104A Oscilloscope (1 GHz analog bandwidth):

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”	22.640	±	-	ns
“dn3”	249.983	±	-	ns
“dn7”	1508.944	±	-	ns
“dn126”	12039.477	±	-	ns

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.193	±	-	ns	21.94	±	0.59	°C
Inλ 100	104.489	±	-	ns	21.99	±	0.25	°C
Inλ 300	307.304	±	-	ns	21.97	±	0.31	°C

Through the use of the channel-to-channel delta time automatic measurement function (ΔTime(1-2)), the time interval can be reliably determined from PPS signals between channels 1 and 2. This function does not allow to set a trigger level of 0.5 V on each channel, which is triggered by default to half of the PPS level. The associated uncertainty has not been estimated, but all the measurements performed are close in value to those obtained with TIC.

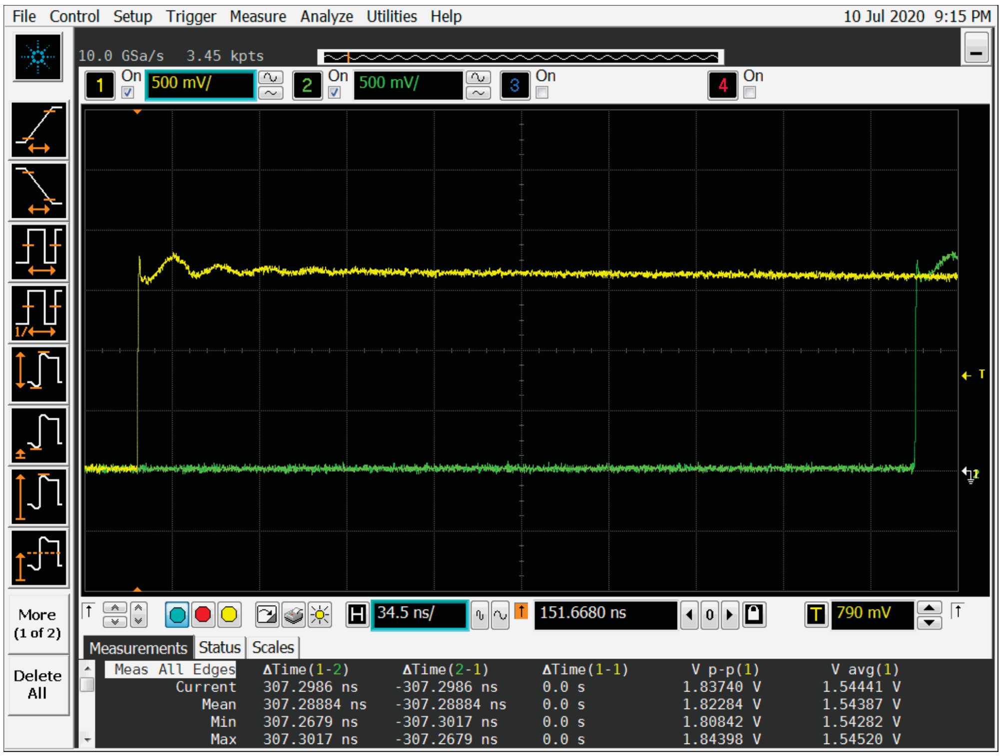


Figure 8. Time interval between channel 1 and 2, carried out with DSO9104A oscilloscope.

8. Ambient conditions of measurements (the temperature and the relative humidity)

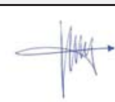
See annexes.

9. Average date of performing measurements

See annexes.

Appendix to the ROA report EURAMET.TF-S1_ROA/001.20 (EURAMET Project #1485): EURAMET.TF-S1 Supplementary Comparison "Comparison of time interval measurements", report of the Real Instituto y Observatorio de la Armada (ROA).

Method II of the aforementioned report should be used for determination of the reference values and for further analysis of equivalence within the EURAMET.TF-S1 comparison.

	NAME	SIGNATURE	DATE
PREPARED BY:	Juan Manuel González Sánchez	 Firmado digitalmente por Juan Manuel Gonzalez Sanchez Nombre de reconocimiento (DN): cn=Juan Manuel Gonzalez Sanchez, o=Real Instituto y Observatorio de la Armada, ou=Seccion de Hora, email=jmangon@roa.es, c=<n Fecha: 2021.06.09 12:38:39 +02'00'	June 2021
APPROVED BY:	Héctor Esteban Pinillos	 Firmado digitalmente por Héctor Esteban Fecha: 2021.06.09 12:40:06 +02'00'	June 2021

REAL INSTITUTO Y OBSERVATORIO DE LA ARMADA
Plaza de las Tres Marinas, s/n
11100 San Fernando (Cádiz), Spain

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: **ROA** Country: **SPAIN**

Average date of measurements: **on 8 and 9 July**

Remarks:

Information not provided in annexes can be found in the attached ROA report.

Model equation that follows from the measurement setup: **See attached ROA report**

$TI = ...$

Description of the quantities in the model equation:

Quantity X_i	Description

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
...							
...							
...							

Combined standard uncertainty	u_c	
Effective degrees of freedom	ν_{eff}	
Expanded uncertainty ($p \approx 95\%$)	U	

....
(Name) (Date)

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: **ROA** Country: **SPAIN**

Average date of measurements: **on 8 and 9 July**

Remarks:

Information not provided in annexes can be found in the attached ROA report.

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	MHM 2010	10 MHz ± 1 Hz	Yes
Amplitude (at 50 Ω)	2.825 V	within (0,5 ÷ 2) V_{p-p}	No

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22	±	2	°C	within (22 ± 4) °C	Yes

Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
50	±	10	%	within (50 ± 30) %	Yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	In report

A2. TIGen standard - measurement results with uncertainty: **In report**

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”		±		ns
“dn3”		±		ns
“dn7”		±		ns
“dn126”		±		ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	MHM 2010		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	Yes
Low level	0 V	0 V	Yes
High level (at 50 Ω)	2.5 V	(1,75 ÷ 2,25) V	No
Rise time (20% to 80 %)	300 ps	< 10 ns	Yes
Duty cycle	0.002 %	≤ 50 %	Yes
Pulse width	20 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	Yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	Yes
Inλ 100	Inλ 20	Inλ 20 or Inλ 300	Yes
Inλ 300	Inλ 20	Inλ 20 or Inλ 100	Yes
Ambient temperature during measurements	**Unit of measure**	Required reference conditions	Meet requirements?

					yes / no
22	±	2	°C	within (22 ± 4) °C	Yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
50	±	10	%	within (50 ± 30) %	Yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	In report

B2. InLambda standards - measurement results with uncertainty: **In report**

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20		±		ns	21.94	±	0.59	°C
Inλ 100		±		ns	21.99	±	0.25	°C
Inλ 300		±		ns	21.97	±	0.31	°C

....

(Name) (Date)

Appendix J

SIQ report

Supplementary Comparison: EURAMET.TF-S1

Contents

1 MEASUREMENT CONDITIONS AND IDENTIFICATION OF THE PARTICIPATING LABORATORY 2

2 CALIBRATION METHOD, EQUIPMENT, AND SET-UP 2

3 TRACEABILITY 6

4 UNCERTAINTY CALCULATION EXAMPLES 8

References used

1. EA-4/02, Expression of the Uncertainty of Measurement in Calibration, September 2013, (rev01)
2. SIQ internal procedures MN410000C, MN411000C

Prepared by: Klemen Starc 2021-06-15

Matjaž Lindič 2021-08-17

Digitally signed by Matjaž Lindič
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1 Measurement conditions and identification of the participating laboratory

All measurements were performed at SIQ Ljubljana, Mašera-Spasićeva ulica 10, 1000 Ljubljana on 21st and 22nd July 2020 under following environmental conditions:

Temperature: 23 °C ± 2 °C

Relative humidity: 50 % ± 20 %

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

Before commencing measurements, connectors and equipment were inspected.

2 Calibration method, equipment, and set-up

General

The calibration setups, shown in Fig. 1 and Fig. 2 were used for determining prescribed time intervals. A TIGen time interval generator developed by AGH University of Science and Technology, and GUM Poland was used for generating different time intervals. InLambda delay standards are based on temperature stabilized fibre delays of approximately 20 ns, 100 ns and 300 ns and are used as a part of measurement system. The time intervals between the pulse signals at the start and stop outputs of each delay standards mentioned above were measured with universal time interval counter Keysight 53230A.

In this comparison the following time intervals were measured:

- dno (20 ns)
- dn3 (250 ns)
- dn7 (1.5 µs)
- dn126 (12 µs)

generated by TIGen and

- three single time intervals generated by InLambda standards (lnλ 20 - 20 ns, lnλ 100 - 100 ns and lnλ 300 - 300 ns) in a double configuration

Calibration equipment

SIQ Ljubljana used the following reference equipment for the intercomparison:

- Keysight 53230A 350 MHz Universal Frequency Counter/ Timer with serial number MY50002220 and the corresponding calibration certificate C202000128,
- Hewlett Packard 5071A Primary Frequency Standard with serial number 3839A01268 and the corresponding calibration certificate C202000272,
- 3x SMA (m)- BNC(f) adapters included in travelling standards.

Calibration set-up

Initially we have measured time intervals of TIGen with Keysight 53230A on both channels. Rear 10 MHz time-base of the time interval counter Keysight 53230A was connected to Hewlett Packard 5071A Primary Frequency Standard. Primarily selected time interval was measured between CH1 and CH2. Furthermore, the cable connection to channels was exchanged to annihilate the effect of differential channel error. (Fig 1).

Additionally, a measurement of inLambda standards were performed correspondingly with configuration shown in Fig 2. Used input external pulse signals for InLambda standards are specified - low level 0 V, high level 1.75 ÷ 2.25 V, frequency $f \leq 200$ Hz, pulse width less than ±10 ns, rise time (20% to 80 %) < 10 ns and duty cycle ≤ 50%.We have used 1 PPS pulse from Cs clock HP 5071A with serial number 3839A01268.

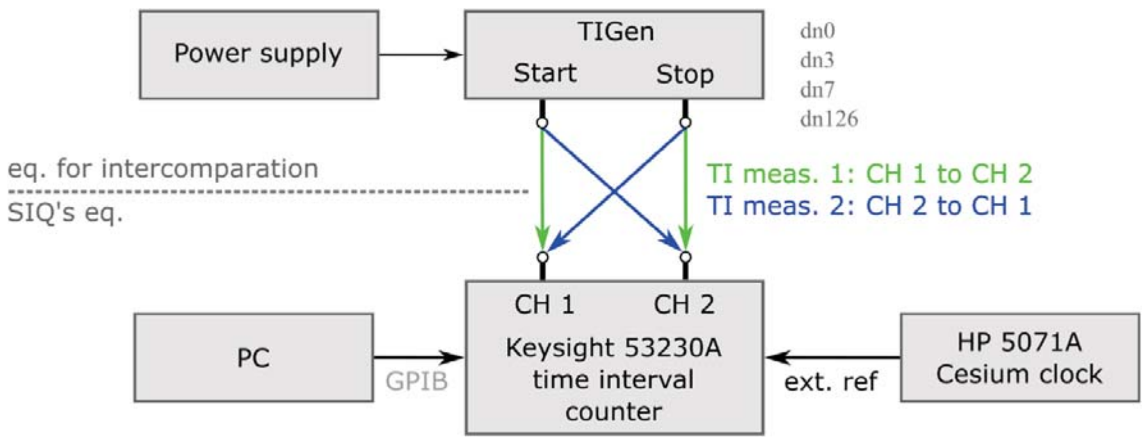


Figure 1: Measurement setup for time interval measurement of TIGen standard

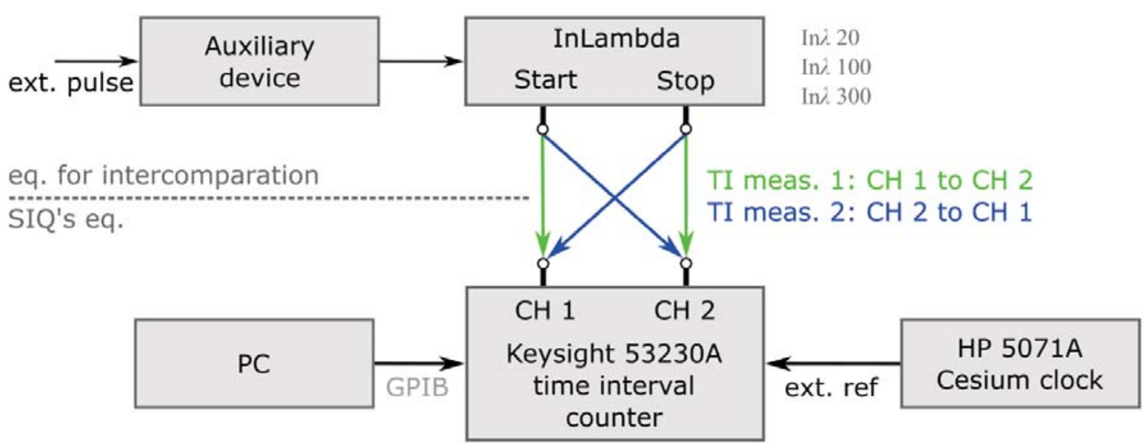


Figure 2: Measurement setup for time interval measurement of InLambda standards

For each time delay, 1000 measurements were made and each of these time intervals T_i had the following mathematical model for estimating the uncertainty:

$$T_i = \frac{t_{s1} + t_{s2}}{2} \quad (1)$$

where:

T_i measured time interval
ts_1 time interval measured at first setup (CH1-CH2)
ts_2 time interval measured at second setup (CH2-CH1)

The time interval t_s measured with time interval counter can be expressed with Eq. 2. According to the manufacturers recommendations these uncertainties are combined in the following manner (Eq. 3) to obtain the overall uncertainty $U\_ T_i$.

$$t_s = t_c + k_{\mathrm{Re}sRMS} + k_{Sys} + k_{\mathrm{DiffChErr}} \quad (2)$$

$$U\_t_i = \sqrt{U\_t_c^{\,2} + (U\_k_{\mathrm{ResRMS}} + U\_k_{\mathrm{Sys}} + U\_DiffChErr)^2} \quad (3)$$

where:

T_i time interval measured with time interval counter,
k_ResRMS correction due to RMS resolution of time interval counter
k_Sys correction due to systematic uncertainty of time interval counter
k_DiffChErr correction due to differential channel error of time interval counter

Contributions to standard uncertainty

Time interval measured with time interval counter (T_i)

This value is obtained as an average of all readings from time interval counter. The uncertainty associated with this value U_T_i is calculated as standard deviation of the mean of all readings used for calculation of the mean value. This uncertainty is assumed to has normal probability distribution. The sensitivity coefficient for this value is 0.5.

Correction due to RMS resolution of time interval counter(*k_ResRMS*)

This correction is taken to be 0 s with associated uncertainty *U_ResRMS* calculated using the Eq. 4 depending on the time interval counter used. This uncertainty is assumed to has normal probability distribution. The sensitivity coefficient for this value is 0.5.

$$U\_\mathrm{Re}sRMS = \frac{1.4 \cdot \sqrt{t_{res}^2 + TrigErr^2}}{|t_c|} \cdot t_c \quad (4)$$

where:

tres single shot resolution of the time interval counter
TrigErr trigger error of the time interval counter
T_i time interval measurement

Trigger error is calculated using Eq. 5.

$$TrigErr = \frac{\sqrt{(500\ \mu\text{V})^2 + E_{in}^2 + v_x^2}}{SR} \tag{5}$$

where

TrigErr	trigger error of the frequency counter
E_{in}	signal noise in measurement bandwidth
v_x	crosstalk between input channels
SR	slew rate of the input signal at trigger level.

Typically, v_x is -60 dB. And E_{in} is taken from specification and equals 0.35 mV.

Correction due to systematic uncertainty of time interval counter (*k_Sys*)

This uncertainty consists of uncertainty due to the time base error and stability and trigger level timing errors of time interval counter. Probability distribution of the uncertainty is normal. This value is calculated using Eq. 6 and Eq.7.

$$k_{Sys} = \frac{\Delta f}{f} \cdot t_c \tag{6}$$

$$U\_k_{Sys} = \left(U\_\frac{\Delta f}{f} + \sigma_A(t_c) \right) \cdot t_c + U\_TrigLevTim \tag{7}$$

Trigger level timing error is calculated using Eq. 8.

$$U\_TrigLevTim = 250\,ps \pm \frac{T_{LSE-start}}{SR_{start-}} \pm \frac{T_{LSE-stop}}{SR_{stop-}} \pm \left[\frac{0.5 \cdot HB}{SR_{start-}} - \frac{0.5 \cdot HB}{SR_{stop-}} \right] \tag{8}$$

HB	Input hysteresis band
$T_{LSEE-start}$	Start trigger level setting
$T_{LSE-stop}$	Stop trigger level setting
SR_{start-}	Slew rate at start trigger point
SR_{stop-}	Slew rate at stop trigger point
T_i	time interval measured with frequency counter.

where:

$\frac{\Delta f}{f}$	relative frequency deviation of the reference time-base
$U\_\frac{\Delta f}{f}$	uncertainty of relative frequency deviation of the time-base
T_i	time interval measured with time interval counter
U_TrigLevTim	trigger level timing error of time interval counter
$\sigma_A(t_c)$	short term stability of the reference frequency with averaging time equal to time interval.

Relative frequency deviation of the **external reference time-base** ($\Delta f/f$) together with its associated uncertainty ($U\_\Delta f/f$) are taken from the calibration certificate 20C00272 and are used for uncertainty calculation for each measurement (normal distribution with coverage factor 2). The uncertainty of the reference system given in the calibration certificate already contains the uncertainties associated with temperature stability and drift therefore these components are not considered separately. Short-term stability is taken from manufacturers specifications.

Correction due to differential channel error of time interval counter(*k_DiffChErr*)

This value is taken to be 0 s with associated uncertainty *U_DiffChErr*. Assuming that measurements are made where differences of measurements taken with the same time interval counter are subtracted, this correction is omitted for all performed measurements. This way also uncertainty due to differential channel error can be neglected.

3 Traceability chart

Traceability for frequency and time is assured by participation in on-going key comparison for Time&Frequency CCTF-K001.UTC. Results and data from this intercomparison are used at BIPM for calculation of reference time scales TAI and UTC. This is called “Circular-T” and results of this calculation are being calculated and distributed by BIPM every month for previous month. Data from GNSS CV is also used for calculating UTC(SIQ) time scale and relative frequency deviation of SIQ reference frequency standard relative to TAI/UTC and relative to PTB. Then calculation is done every month for quick analysis of measured data and to verify accuracy and stability of reference frequency standard. Once a year detailed analysis of all data is performed and based on that certificate is issued for reference T&F standard. Traceability of the time interval counter used (Keysight 53230A 350 MHz with serial number MY50002220) is assured through traceable calibration performed periodically (once a year) in house, based on reference T&F standard (Fig. 3).

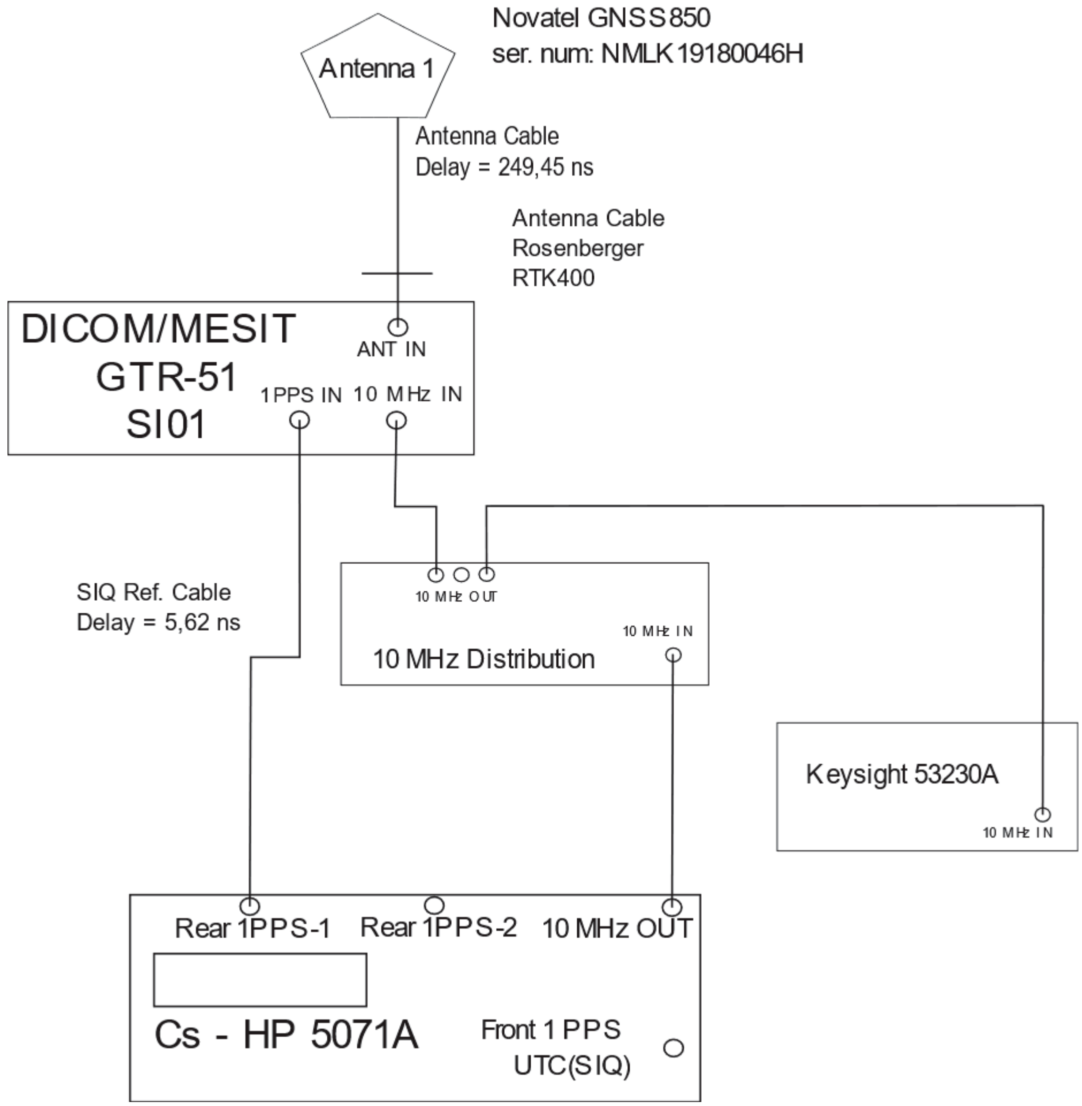


Figure 3: Measurement setup for traceability of time and frequency

4 Uncertainty calculation examples

In Table 1 to Table 7 calculations for seven different time intervals with uncertainties are fiven. Under each table is marked individual measured time interval and for consistency all values are shown in scientific format. Method of evaluation for t_{c1} and t_{c2} is type A and for all other quantities (k_{Sys1} k_{Sys2}, $k_{ResRMS1}$, $k_{ResRMS2}$, $k_{DiffChErr1}$, $k_{DiffChErr2}$) is type B.

Quantity X_i	x_i		Standard uncertainty $u(x_i)$		Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$		Effective degr. of freedom v_i
t_{c1}	2,26E-08	s	9,86E-12	s	normal	1	0,5	/	4,93E-12	s	999
t_{c2}	2,27E-08	s	1,08E-11	s	normal	1	0,5	/	5,40E-12	s	999
k_{Sys1}	-1,46E-22	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
k_{Sys2}	-1,46E-22	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
$k_{ResRMS1}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{ResRMS2}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{DiffChErr1}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
$k_{DiffChErr2}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
T_i	2,26E-08	s							2,09E-10	s	1E+09
			Expanded uncertainty of measurement:						4,18E-10	s	
			Relative expanded uncertainty of measurement:						1,8	%	

Table 1: Uncertainty calculation example for TIGen **dn0** time interval. The time interval was measured with Keysight 53230A frequency counter. 1000 measurements were made. Frequency deviation of the reference Cesium time-base $\Delta f/f$ and corresponding uncertainty were $-6.45 \cdot 10^{-15}$ and $1 \cdot 10^{-13}$ and were taken from last calibration certificate (*i.e.*, 20C00272). The value of $\sigma_A(t_g)$ was $8.5 \cdot 10^{-13}$ and it was taken from manufacturers specifications.

Quantity X_i	x_i		Standard uncertainty $u(x_i)$		Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$		Effective degr. of freedom v_i
t_{c1}	2,50E-07	s	9,97E-12	s	normal	1	0,5	/	4,98E-12	s	999
t_{c2}	2,50E-07	s	1,03E-11	s	normal	1	0,5	/	5,14E-12	s	999
k_{Sys1}	-1,61E-21	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
k_{Sys2}	-1,61E-21	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
$k_{ResRMS1}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{ResRMS2}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{DiffChErr1}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
$k_{DiffChErr2}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
T_i	2,50E-07	s							2,09E-10	s	1E+09
			Expanded uncertainty of measurement:						4,18E-10	s	
			Relative expanded uncertainty of measurement:						0,2	%	

Table 2: Uncertainty calculation example for TIGen **dn3** time interval. The time interval was measured with Keysight 53230A frequency counter. 1000 measurements were made. Frequency deviation of the reference Cesium time-base $\Delta f/f$ and corresponding uncertainty were $-6.45 \cdot 10^{-15}$ and $1 \cdot 10^{-13}$ and were taken from last calibration certificate (*i.e.*, 20C00272). The value of $\sigma_A(t_g)$ was $8.5 \cdot 10^{-13}$ and it was taken from manufacturers specifications.

Quantity *Xi*	*xi*		Standard uncertainty *u(xi)*		Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*		Effective degr. of freedom *vi*
t_{c1}	1,51E-06	s	1,01E-11	s	normal	1	0,5	/	5,05E-12	s	999
t_{c2}	1,51E-06	s	1,01E-11	s	normal	1	0,5	/	5,05E-12	s	999
k_{Sys1}	-9,73E-21	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
k_{Sys2}	-9,73E-21	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
$k_{ResRMS1}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{ResRMS2}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{DiffChErr1}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
$k_{DiffChErr2}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
T_i	1,51E-06	s							2,09E-10	s	1E+09
			Expanded uncertainty of measurement:						4,18E-10	s	
			Relative expanded uncertainty of measurement:						0,03	%	

Table 3: Uncertainty calculation example for TIGen **dn7** time interval. The time interval was measured with Keysight 53230A frequency counter. 1000 measurements were made. Frequency deviation of the reference Cesium time-base $\Delta f/f$ and corresponding uncertainty were $-6.45\cdot10^{-15}$ and $1\cdot10^{-13}$ and were taken from last calibration certificate (*i.e.*, 20C00272). The value of $\sigma_A(t_g)$ was $8.5\cdot10^{-13}$ and it was taken from manufacturers specifications.

Quantity *Xi*	*xi*		Standard uncertainty *u(xi)*		Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*		Effective degr. of freedom *vi*
t_{c1}	1,20E-05	s	1,27E-11	s	normal	1	0,5	/	6,36E-12	s	999
t_{c2}	1,20E-05	s	1,21E-11	s	normal	1	0,5	/	6,04E-12	s	999
k_{Sys1}	-7,76E-20	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
k_{Sys2}	-7,76E-20	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
$k_{ResRMS1}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{ResRMS2}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{DiffChErr1}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
$k_{DiffChErr2}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
T_i	1,20E-05	s							2,09E-10	s	6E+08
			Expanded uncertainty of measurement:						4,18E-10	s	
			Relative expanded uncertainty of measurement:						0,003	%	

Table 4: Uncertainty calculation example for TIGen **dn126** time interval. The time interval was measured with Keysight 53230A frequency counter. 1000 measurements were made. Frequency deviation of the reference Cesium time-base $\Delta f/f$ and corresponding uncertainty were $-6.45\cdot10^{-15}$ and $1\cdot10^{-13}$ and were taken from last calibration certificate (*i.e.*, 20C00272). The value of $\sigma_A(t_g)$ was $8.5\cdot10^{-13}$ and it was taken from manufacturers specifications.

Quantity		Standard uncertainty		Probability distribution	Div.	Sensitivity coefficient		Uncertainty contribution		Effective degr. of freedom
Xi	*xi*		*u(xi)*			*ci*		*ui(y)*		*vi*
t_{c1}	2,41E-08	s	1,14E-11	s	normal	1	0,5	/	5,70E-12	s	999
t_{c2}	2,42E-08	s	1,17E-11	s	normal	1	0,5	/	5,87E-12	s	999
k_{Sys1}	-1,56E-22	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
k_{Sys2}	-1,56E-22	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
$k_{ResRMS1}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{ResRMS2}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{DiffChErr1}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
$k_{DiffChErr2}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
T_i	2,42E-08	s							2,09E-10	s	9E+08
			Expanded uncertainty of measurement:						4,18E-10	s	
			Relative expanded uncertainty of measurement:						1,7	%	

Table 5: Uncertainty calculation example for inLambda **lnλ20** time interval. The time interval was measured with Keysight 53230A frequency counter. 1000 measurements were made. Frequency deviation of the reference Cesium time-base $\Delta f/f$ and corresponding uncertainty were $-6.45 \cdot 10^{-15}$ and $1 \cdot 10^{-13}$ and were taken from last calibration certificate (*i.e.*, 20C00272). The value of $\sigma_A(t_g)$ was $8.5 \cdot 10^{-13}$ and it was taken from manufacturers specifications.

Quantity		Standard uncertainty		Probability distribution	Div.	Sensitivity coefficient		Uncertainty contribution		Effective degr. of freedom
Xi	*xi*		*u(xi)*			*ci*		*ui(y)*		*vi*
t_{c1}	1,04E-07	s	1,10E-11	s	normal	1	0,5	/	5,49E-12	s	999
t_{c2}	1,05E-07	s	1,08E-11	s	normal	1	0,5	/	5,38E-12	s	999
k_{Sys1}	-6,73E-22	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
k_{Sys2}	-6,74E-22	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
$k_{ResRMS1}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{ResRMS2}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{DiffChErr1}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
$k_{DiffChErr2}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
T_i	1,04E-07	s							2,09E-10	s	1E+09
			Expanded uncertainty of measurement:						4,18E-10	s	
			Relative expanded uncertainty of measurement:						0,4	%	

Table 6: Uncertainty calculation example for inLambda **lnλ100** time interval. The time interval was measured with Keysight 53230A frequency counter. 1000 measurements were made. Frequency deviation of the reference Cesium time-base $\Delta f/f$ and corresponding uncertainty were $-6.45 \cdot 10^{-15}$ and $1 \cdot 10^{-13}$ and were taken from last calibration certificate (*i.e.*, 20C00272). The value of $\sigma_A(t_g)$ was $8.5 \cdot 10^{-13}$ and it was taken from manufacturers specifications.

Quantity			Standard uncertainty		Probability distribution	Div.	Sensitivity coefficient		Uncertainty contribution		Effective degr. of freedom
Xi	*xi*		*u(xi)*				*ci*		*ui(y)*		*vi*
t_{c1}	3,07E-07	s	1,35E-11	s	normal	1	0,5	/	6,76E-12	s	999
t_{c2}	3,07E-07	s	1,38E-11	s	normal	1	0,5	/	6,92E-12	s	999
k_{Sys1}	-1,98E-21	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
k_{Sys2}	-1,98E-21	s	2,67E-10	s	normal	1	0,5	/	1,34E-10	s	1E+99
$k_{ResRMS1}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{ResRMS2}$	0	s	2,80E-11	s	normal	1	0,5	/	1,40E-11	s	1E+99
$k_{DiffChErr1}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
$k_{DiffChErr2}$	0	s	0	s	normal	1	0,5	/	0	s	1E+99
T_i	3,07E-07	s							2,09E-10	s	4E+08
			Expanded uncertainty of measurement:						4,18E-10	s	
			Relative expanded uncertainty of measurement:						0,14	%	

Table 7: Uncertainty calculation example for inLambda **lnλ300** time interval. The time interval was measured with Keysight 53230A frequency counter. 1000 measurements were made. Frequency deviation of the reference Cesium time-base $\Delta f/f$ and corresponding uncertainty were $-6.45\cdot10^{-15}$ and $1\cdot10^{-13}$ and were taken from last calibration certificate (*i.e.*, 20C00272). The value of $\sigma_A(t_g)$ was $8.5\cdot10^{-13}$ and it was taken from manufacturers specifications.

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

Acronym of institute: **SIQ Ljubljana** Country: **Slovenia**

Average date of measurements: **2020-07-21; 2020-07-22**

Remarks:**/**

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	**Cs clock**	10 MHz ± 1 Hz	**YES**
Amplitude (at 50 Ω)		within (0,5 ÷ 2) $V_{p\text{-}p}$	**YES**

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	**2**	°C	within (22 ± 4) °C	**YES**

Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
50	±	**20**	%	within (50 ± 30) %	**YES**

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	**Keysight 53230A**
Applied trigger level (50 Ω) (Required: 0,5 V)	**0.5 V**
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	**unknown**

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22,64	±	0,42	ns
"dn3"	250,00	±	0,42	ns
"dn7"	1508,95	±	0,42	ns
"dn126"	12039,47	±	0,42	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	**Cs clock**		
1 pps (yes / no)	**YES**		
Frequency		≤ 200 Hz	**YES**
Low level		0 V	**YES**
High level (at 50 Ω)		(1.75 ÷ 2.25) V	**YES**
Rise time (20% to 80 %)		< 10 ns	**YES**
Duty cycle		≤ 50 %	**YES**
Pulse width		to avoid the pulse widths close **(<± 10 ns)** to the measured time intervals	**YES**
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20		Inλ 100 or Inλ 300	**YES**
Inλ 100		Inλ 20 or Inλ 300	**YES**
Inλ 300		Inλ 20 or Inλ 100	**YES**

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	**2**	°C	within (22 ± 4) °C	**YES**
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
50	±	**20**	%	within (50 ± 30) %	**YES**

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	**Keysight 53230A**
Applied trigger level (50 Ω) (Required: 0,5 V)	**0.5 V**
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	**unknown**

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24,18	±	0,42	ns	23	±	2	°C
Inλ 100	104,48	±	0,42	ns	23	±	2	°C
Inλ 300	307,28	±	0,42	ns	23	±	2	°C

Appendix K

SMU report

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM
e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: SMU Country: Slovakia

Average date of measurements: 20.8. – 24.8.2020

Remarks:

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	Cs clock	10 MHz ± 1 Hz	Yes
Amplitude (at 50 Ω)	2 V_{p-p}	within (0,5 ÷ 2) V_{p-p}	Yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	2	°C	within (22 ± 4) °C	yes

Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
45	±	5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Agilent 53132A
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	Start/Stop trigger error uncertainties – 0,05ns; Time resolution – 0,3ns; Trigger level timing error – 0,046ns

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22,52	±	0,68	ns
"dn3"	249,92	±	0,68	ns
"dn7"	1508,86	±	0,68	ns
"dn126"	12039,32	±	0,70	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs Clock		
1 pps (yes / no)	yes		
Frequency	1Hz	≤ 200 Hz	Yes
Low level	0V	0 V	Yes
High level (at 50 Ω)	≥ 2,4V	(1,75 ÷ 2,25) V	No
Rise time (20% to 80 %)	< 5ns	< 10 ns	Yes
Duty cycle	≤ 50 %	≤ 50 %	yes
Pulse width	20us	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 20	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 20	Inλ 20 or Inλ 100	yes
Ambient temperature during measurements	**Unit of measure**	Required reference conditions	Meet requirements? yes / no

23	±	2	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
45	±	5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Agilent 53132A
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	Start/Stop trigger error uncertainties – 0,05ns; Time resolution – 0,3ns; Trigger level timing error – 0,046ns

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24,23	±	0,65	ns	23	±	2	°C
Inλ 100	104,47	±	0,67	ns	23	±	2	°C
Inλ 300	307,26	±	0,68	ns	23	±	2	°C

Juraj Slučiak
SMU

Annex 7. Minimum contents for the measurement report

Identification of the participating laboratory

Acronym of institute: SMU

Country: Slovakia

Description of calibration method

Direct connection of measured devices to frequency counter HP53132A with direct synchronization (external 10MHz input) to national standard which consists of cesium clock HP5071A. Used coax cables had a length of 20cm each.

Description of the calibration set-up and equipment

Equipment: Frequency Counter HP53132A

Cesium clock: HP5071A

A pair of coax cables (20cm).

Traceability chart

Traced to Slovak National Standard of time and frequency (HP5071A).

Used relationship/ equation for obtaining estimates of results and uncertainty budget

Model equation that follows from the measurement setup:

$$TI = (T_2 - T_1) \pm (T_s + T_{sp} + T_{res} + T_L)$$

Description of the quantities in the model equation:

Quantity X_i	Description
T_2	start of measurement (trigger)
T_1	stop of measurement (trigger)
T_s	Start trigger error (uncertainty) (manual HP53132A)
T_{sp}	Stop trigger error (uncertainty) (manual HP53132A)
T_{res}	Time resolution of time interval counter (manual HP53132A)
T_L	Trigger level timing error (uncertainty) (manual HP53132A)

Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects

Uncertainty budget table

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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_2-T_1 (dn0)	22,52	0,14	Normal	A	1	0,14	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_2-T_1 (dn3)	249,92	0,14	Normal	A	1	0,14	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_2-T_1 (dn7)	1508,86	0,13	Normal	A	1	0,13	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (dn126)	12039,32	0,15	Normal	A	1	0,15	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,35
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,70

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (20ns)	24,234	0,085	Normal	A	1	0,085	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,32
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,65

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (100ns)	104,47	0,13	Normal	A	1	0,13	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,67

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (300ns)	307,26	0,14	Normal	A	1	0,14	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

Identification and description of the source 10 MHz reference frequency for TIGen standard

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	Cs clock	10 MHz ± 1 Hz	Yes
Amplitude (at 50 Ω)	2 V_{p-p}	within (0,5 ÷ 2) V_{p-p}	Yes

Description of the used input pulse signals for InLambda standards (low level, high level (amplitude), frequency, pulse width, rise time (20% to 80 %), duty cycle)

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs Clock		
1 pps (yes / no)	yes		
Frequency	1Hz	≤ 200 Hz	Yes
Low level	0V	0 V	Yes
High level (at 50 Ω)	≥ 2,4V	(1,75 ÷ 2,25) V	No

Rise time (20% to 80 %)	< 5ns	< 10 ns	Yes
Duty cycle	≤ 50 %	≤ 50 %	yes
Pulse width	20us	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes

Ambient conditions of measurements (the temperature and the relative humidity) – the temperature for every InLambda standard separately

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	2	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
45	±	5	%	within (50 ± 30) %	yes

Average date of performing measurements

20.8. – 24.8.2020

Date: 21.03.2022

Juraj Slučiak

SMU

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: SMU Country: Slovakia

Average date of measurements: 20.8. – 24.8.2020

Remarks:

Model equation that follows from the measurement setup:

$$TI = (T_2 - T_1) \pm (T_s + T_{sp} + T_{res} + T_L)$$

Description of the quantities in the model equation:

Quantity X_i	Description
T_2	start of measurement (trigger)
T_1	stop of measurement (trigger)
T_s	Start trigger error (uncertainty) (manual HP53132A)
T_{sp}	Stop trigger error (uncertainty) (manual HP53132A)
T_{res}	Time resolution of time interval counter (manual HP53132A)
T_L	Trigger level timing error (uncertainty) (manual HP53132A)

Uncertainty budget table

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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_2-T_1 (dn0)	22,52	0,14	Normal	A	1	0,14	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_2-T_1 (dn3)	249,92	0,14	Normal	A	1	0,14	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_2-T_1 (dn7)	1508,86	0,13	Normal	A	1	0,13	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (dn126)	12039,32	0,15	Normal	A	1	0,15	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,35
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,70

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (20ns)	24,234	0,085	Normal	A	1	0,085	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,32
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,65

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (100ns)	104,47	0,13	Normal	A	1	0,13	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,67

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 $c_i \cdot u(x_i)$ [ns]	Degrees of freedom ν_i
T_2-T_1 (300ns)	307,26	0,14	Normal	A	1	0,14	80
T_s	0	0,05	Normal	B	1	0,05	∞
T_{sp}	0	0,05	Normal	B	1	0,05	∞
T_{res}	0	0,3	Normal	B	1	0,3	∞
T_L	0	0,046	Normal	B	1	0,046	∞

Combined standard uncertainty	u_c	0,34
Effective degrees of freedom	ν_{eff}	>50 (k=2)
Expanded uncertainty ($p \approx 95\%$)	U	0,68

Juraj Slučiak
SMU

Appendix L

NIM report

Acronym of institute: **NIMB** Country: **Romania**
Average date of measurements: 09.09.2020-10.09.2020
Remarks: Contact person: **Violeta Ciociea**

Model equation that follows from the measurement setup:

$$T_x = (T_A - T_B) + \delta T$$

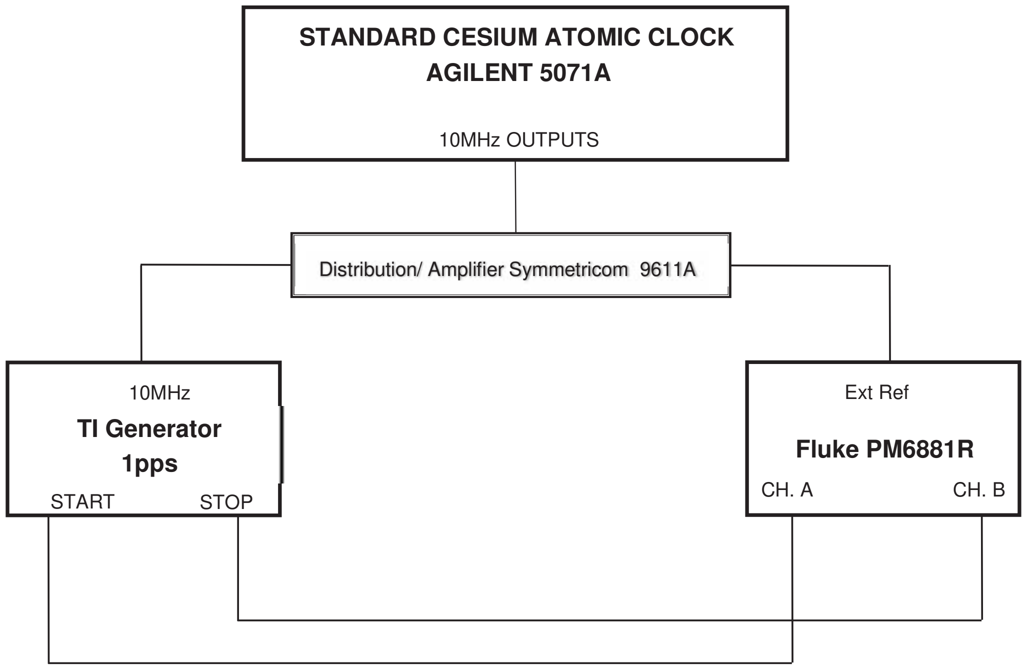
Where δT is:

$$\delta T = \delta T_R + \delta T_{TB} + \delta T_{trigger} + \delta T_{CD} + \delta T_{RV}$$

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock)		Cs clock 5071A		10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)				within (0,5 ÷ 2) V_{p-p}	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,5	±	0,5	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
42,5	±	2,5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	TIC Fluke type PM6681R
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	It is included in the time interval deviation due to random values of TIC



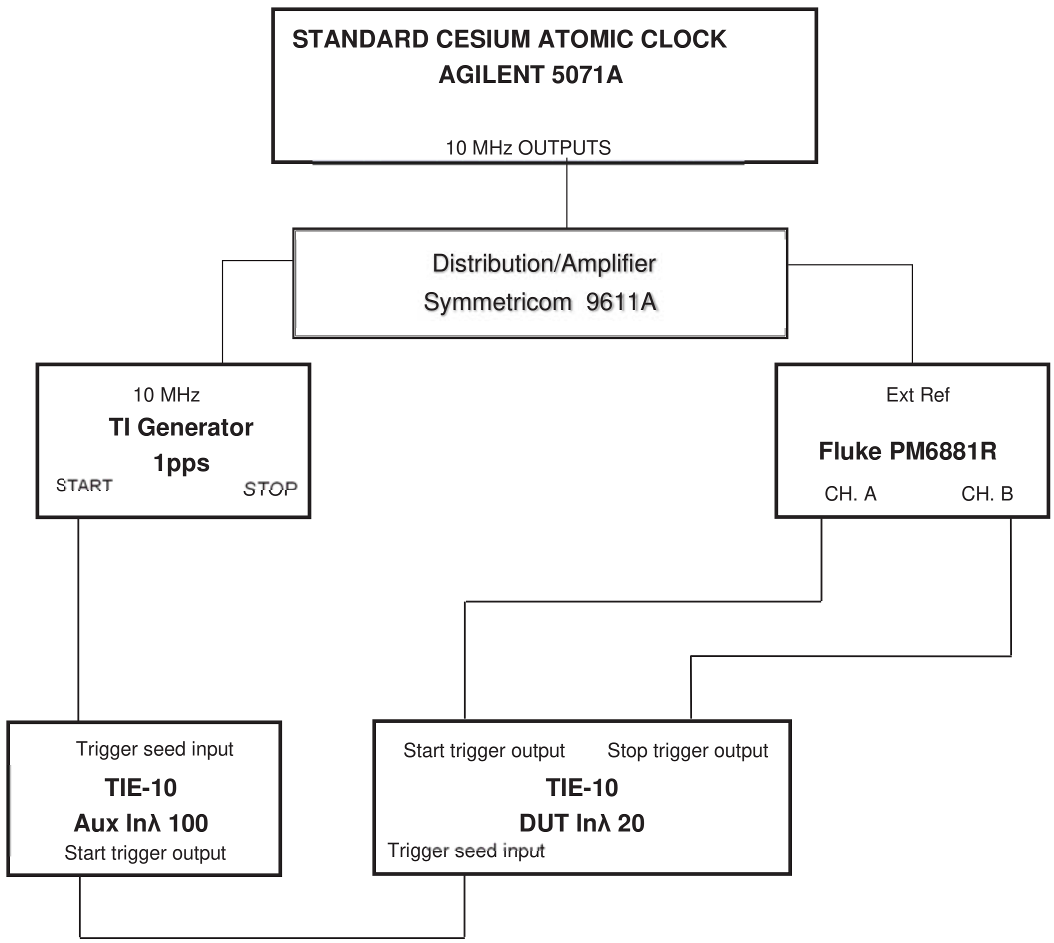
A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22,55	±	0,13	ns
"dn3"	249,94	±	0,13	ns
"dn7"	1508,93	±	0,13	ns
"dn126"	12039,37	±	0,13	ns

B1. InLambda standards – conditions met during measurements

1.DUT Inλ **20**

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2,25 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	< 0,5 ns	< 10 ns	yes
Duty cycle	0,0003 %	≤ 50 %	yes
Pulse width	3,3 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	yes


STANDARD CESIUM ATOMIC CLOCK
AGILENT 5071A
10 MHz OUTPUTS
Distribution/Amplifier
Symmetricom 9611A
10 MHz
TI Generator
1pps
START
STOP
Ext Ref
Fluke PM6881R
CH. A
CH. B
Trigger seed input
TIE-10
Aux Inλ 100
Start trigger output
Start trigger output
Stop trigger output
TIE-10
DUT Inλ 20
Trigger seed input

Description of the quantities in the model equation:

Quantity X_i	Description
δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC

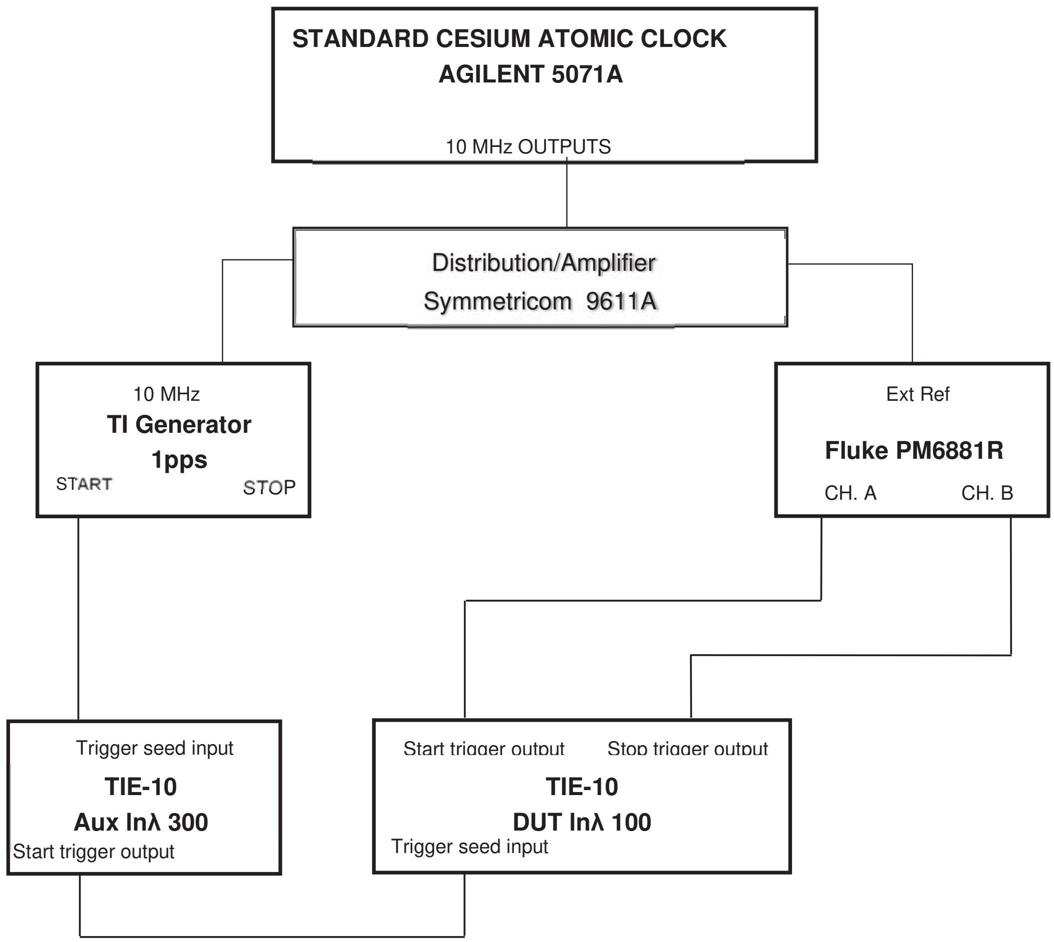
Uncertainty budget table

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 $c_i \cdot u(x_i)$ (ns)	Degrees of freedom ν_i
$T_A - T_B$	24.06	0.016	normal	A	1.0	0.016	9
δT_R	0	0.003	rectangular	B	1.0	0.003	∞
δT_{TB}	0	5×10^{-9}	rectangular	B	1.0	5×10^{-9}	∞
$\delta T_{trigger}$	0	0.016	rectangular	B	1.0	0.016	∞
δT_{CD}	0	0.006	rectangular	B	1.0	0.006	∞
δT_{RV}	0	0.060	rectangular	B	1.0	0.060	∞
		Combined standard uncertainty			u_c	0.064	
		Effective degrees of freedom			ν_{eff}	$> 10^6$	
T=	**24.06 ns**	**Expanded uncertainty ($p \approx 95\%$)**			***U***	**0.13 ns**	

B1. InLambda standards – conditions met during measurements

2.DUT Inλ 100

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2,25 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	< 0,5 ns	< 10 ns	yes
Duty cycle	0,0003 %	≤ 50 %	yes
Pulse width	3,3 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 100	Inλ 300	Inλ 20 or Inλ 300	yes


STANDARD CESIUM ATOMIC CLOCK
AGILENT 5071A
10 MHz OUTPUTS
Distribution/Amplifier
Symmetricom 9611A
10 MHz
TI Generator
1pps
START
STOP
Ext Ref
Fluke PM6881R
CH. A
CH. B
Trigger seed input
TIE-10
Aux Inλ 300
Start trigger output
Start trigger output
Stop trigger output
TIE-10
DUT Inλ 100
Trigger seed input

Description of the quantities in the model equation:

Quantity X_i	Description
δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC

Uncertainty budget table

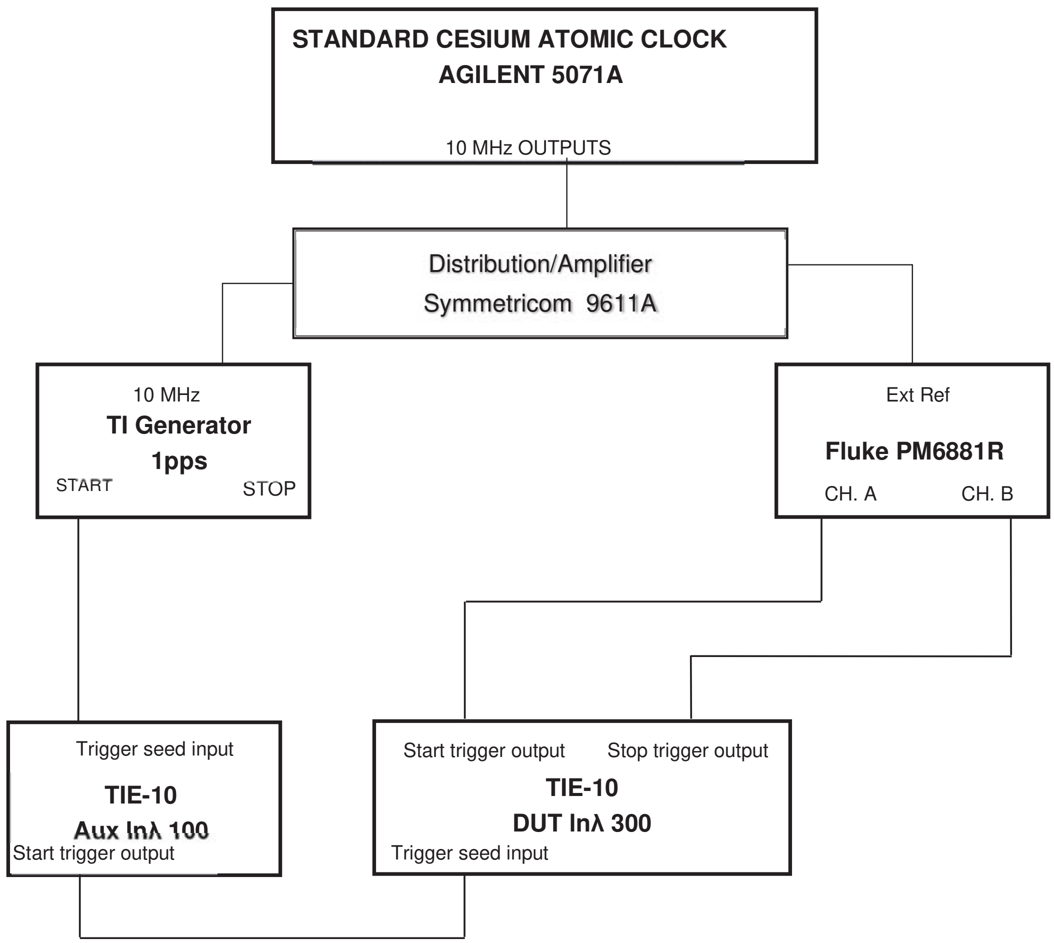
Quantity X_i	Estimate x_i (ns)	Standard uncertainty $u(x_i)$ (ns)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ns)	Degrees of freedom ν_i
$T_A - T_B$	104.44	0.014	normal	A	1.0	0.014	9
δT_R	0	0.003	rectangular	B	1.0	0.003	∞
δT_{TB}	0	2.5×10^{-8}	rectangular	B	1.0	2.5×10^{-8}	∞
$\delta T_{trigger}$	0	0.016	rectangular	B	1.0	0.016	∞
δT_{CD}	0	0.006	rectangular	B	1.0	0.006	∞
δT_{RV}	0	0.060	rectangular	B	1.0	0.060	∞

	Combined standard uncertainty	u_c	0.064
	Effective degrees of freedom	ν_{eff}	$> 10^6$
T= 104.44 ns	**Expanded uncertainty ($p \approx 95\%$)**	$\boldsymbol{U}$	**0.13 ns**

B1. InLambda standards – conditions met during measurements

3.DUT Inλ 300

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0V	0 V	yes
High level (at 50 Ω)	2,25 V	(1,75 ÷ 2,25) V	yes
Rise time (20 % to 80 %)	< 0,5 ns	< 10 ns	yes
Duty cycle	0,0003 %	≤ 50 %	yes
Pulse width	3,3 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	yes


STANDARD CESIUM ATOMIC CLOCK
AGILENT 5071A
10 MHz OUTPUTS
Distribution/Amplifier
Symmetricom 9611A
10 MHz
TI Generator
1pps
START
STOP
Ext Ref
Fluke PM6881R
CH. A
CH. B
Trigger seed input
TIE-10
Aux Inλ 100
Start trigger output
Start trigger output
Stop trigger output
TIE-10
DUT Inλ 300
Trigger seed input

Description of the quantities in the model equation:

Quantity X_i	Description
δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC

Uncertainty budget table

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 $c_i \cdot u(x_i)$ (ns)	Degrees of freedom ν_i
$T_A - T_B$	307.28	0.015	normal	A	1.0	0.015	9
δT_R	0	0.003	rectangular	B	1.0	0.003	∞
δT_{TB}	0	7.5×10^{-8}	rectangular	B	1.0	7.5×10^{-8}	∞
$\delta T_{trigger}$	0	0.016	rectangular	B	1.0	0.016	∞
δT_{CD}	0	0.006	rectangular	B	1.0	0.006	∞
δT_{RV}	0	0.060	rectangular	B	1.0	0.060	∞
		Combined standard uncertainty			u_c	0.064	
		Effective degrees of freedom			ν_{eff}	$> 10^6$	
T=	**307.28 ns**	**Expanded uncertainty ($p \approx 95\%$)**			***U***	**0.13 ns**	

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.5	±	0.5	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
42.5	±	2.5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	TIC Fluke type PM6681R
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	It is included in the time interval deviation due to random values of TIC

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	**24.06**	±	**0.13**	ns	22.5	±	0.5	°C
Inλ 100	**104.44**	±	**0.13**	ns	22.5	±	0.5	°C
Inλ 300	**307.28**	±	**0.13**	ns	22.5	±	0.5	°C

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Violeta Ciociea

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14.09.2020

Annex 7. Minimum contents for the measurement report

- Identification of the participating laboratory: NIMB
- Description of the calibration method: Direct method
- Description of the calibration set-up and equipment: Cs clock 5071A, Fluke type PM6681R, DUT, Distribution/Amplifier Symmetricom 9611A, Direct connection via BNC connectors (See the charts on pages 2,4 and 7)
- Traceability chart: Cs clock 5071A standard
- Used relationship/ equation for obtaining estimates of results and uncertainty budget,

$T_x = (T_A - T_B) + \delta T$, where $\delta T = \delta T_R + \delta T_{TB} + \delta T_{trigger} + \delta T_{CD} + \delta T_{RV}$

- Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects

Where δT is:

δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC

See charts on pages 5,8,11.

- Identification and description of the source: 10 MHz reference frequency for TIGen standard,

Source of 10 MHz reference frequency is Standard of Cs clock 5071A

- Description of the used input pulse signals for InLambda standards (low level, high level (amplitude), frequency, pulse width, rise time (20% to 80 %), duty cycle)

See charts on pages: 3,6,9

- Ambient conditions of measurements (the temperature and the relative humidity) – the temperature for every InLambda standard separately

For -DUT **Inλ 20** : temperature is: 22.5 °C

-DUT **Inλ 100 :** temperature is: 22.5 °C

-DUT **Inλ 300:** temperature is: 22.5 °C

- Average date of performing measurements

09- 10.09.2020(2 days)

- Date and signature.

Violeta Ciociea

Andrei Vladut 14.09.2020

Annex 7. Minimum contents for the measurement report

- Identification of the participating laboratory: NIMB

- Description of the calibration method: Direct method

- Description of the calibration set-up and equipment: Cs clock 5071A, Fluke type PM6681R, DUT, Distribution/Amplifier Symmetricom 9611A, Direct connection via BNC connectors (See the charts on pages 2,4 and 7)

- Traceability chart: Cs clock 5071A standard

- Used relationship/ equation for obtaining estimates of results and uncertainty budget,

$T_x = (T_A\text{-}T_B) + \delta T$, where $\delta T = \delta T_R + \delta T_{TB} + \delta T_{trigger} + \delta T_{CD} + \delta T_{RV}$

- Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects

Where δT is:

δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC

See charts on pages 5,8,11.

- Identification and description of the source: 10 MHz reference frequency for TIGen standard, Source of 10 MHz reference frequency is Standard of Cs clock 5071A

- Description of the used input pulse signals for InLambda standards (low level, high level (amplitude), frequency, pulse width, rise time (20% to 80 %), duty cycle)

See charts on pages: 3,6,9

- Ambient conditions of measurements (the temperature and the relative humidity) – the temperature for every InLambda standard separately

For -DUT Inλ 20 : temperature is: 22.5 °C

-DUT Inλ **100 :** temperature is: 22.5 °C

-DUT Inλ **300:** temperature is: 22.5 °C

- Average date of performing measurements

09- 10.09.2020(2 days)

- Date and signature.

Violeta Ciociea

Andrei Vladut 14.09.2020

Appendix L

NIM report - updated

Acronym of institute: **NIMB** Country: **Romania**
Average date of measurements: 09.09.2020-10.09.2020
Remarks: Contact person: **Violeta Ciociea**

Model equation that follows from the measurement setup:

$$T_x = (T_A - T_B) + \delta T$$

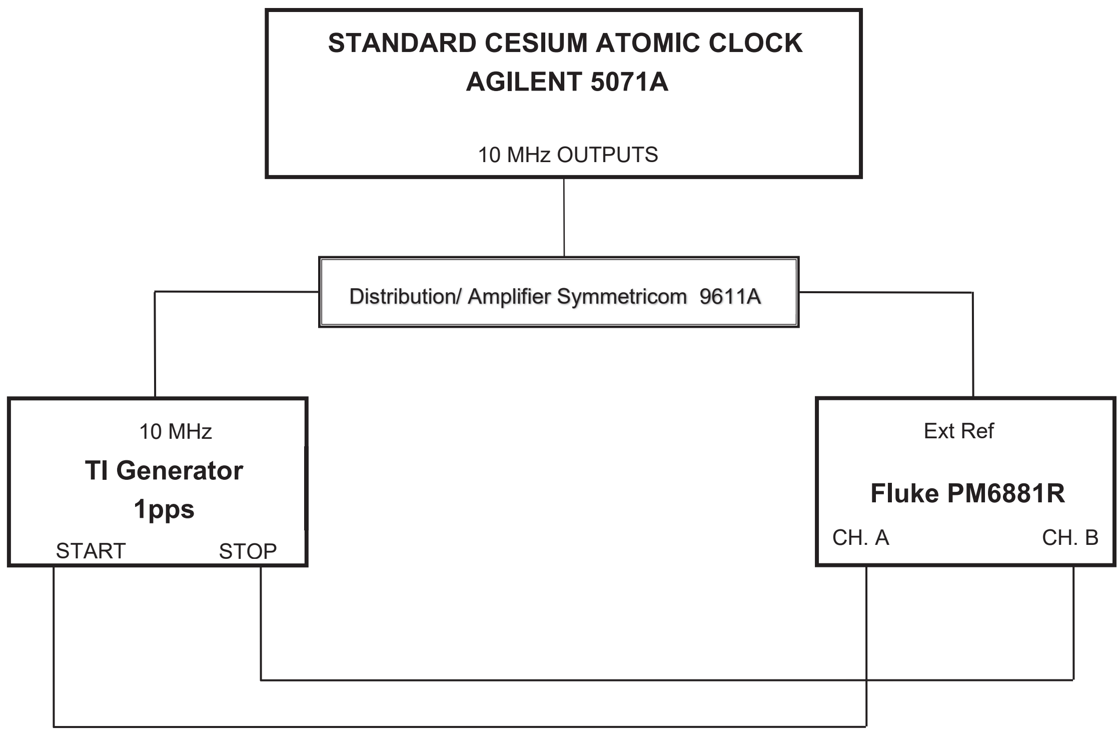
Where δT is:

$$\delta T = \delta T_R + \delta T_{TB} + \delta T_{trigger} + \delta T_{CD} + \delta T_{RV} + \delta T_{CA}$$

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock)		Cs clock 5071A		10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)				within (0,5 ÷ 2) V_{p-p}	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,5	±	0,5	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
42,5	±	2,5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	TIC Fluke type PM6681R
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	It is included in the time interval deviation due to random values of TIC



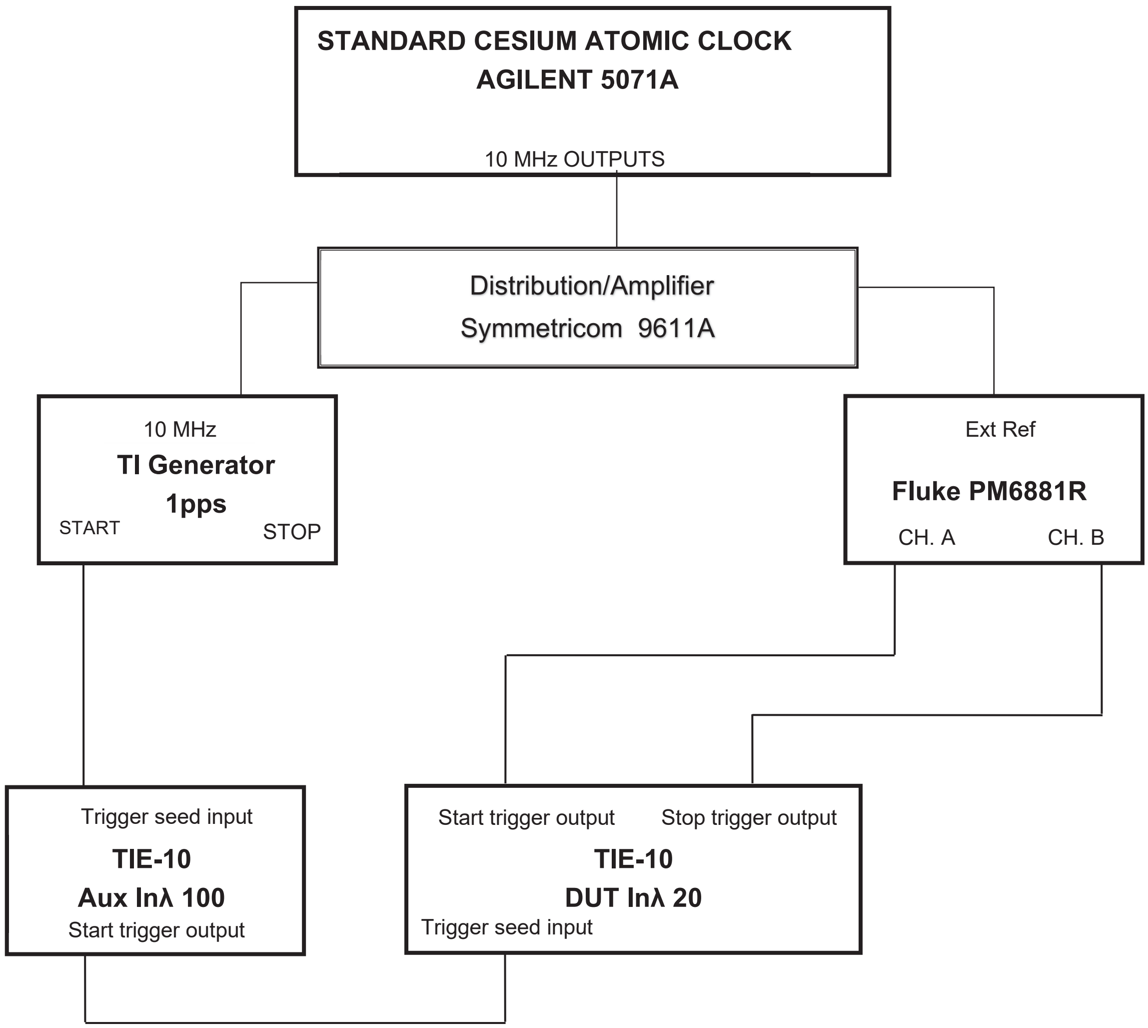
A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”	22,55	±	0,61	ns
“dn3”	249,94	±	0,61	ns
“dn7”	1508,93	±	0,61	ns
“dn126”	12039,37	±	0,61	ns

B1. InLambda standards – conditions met during measurements

1.DUT Inλ **20**

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2,25 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	< 0,5 ns	< 10 ns	yes
Duty cycle	0,0003 %	≤ 50 %	yes
Pulse width	3,3 μs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	yes


STANDARD CESIUM ATOMIC CLOCK
AGILENT 5071A
10 MHz OUTPUTS
Distribution/Amplifier
Symmetricom 9611A
10 MHz
TI Generator
1pps
START
STOP
Ext Ref
Fluke PM6881R
CH. A
CH. B
Trigger seed input
TIE-10
Aux Inλ 100
Start trigger output
Start trigger output
Stop trigger output
TIE-10
DUT Inλ 20
Trigger seed input

Description of the quantities in the model equation:

Quantity X_i	Description
δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC
δT_{CA}	Contribution due of the inter-channel asymmetry (as stated by the instrument manufacturer in the Operators Manual)

Uncertainty budget table

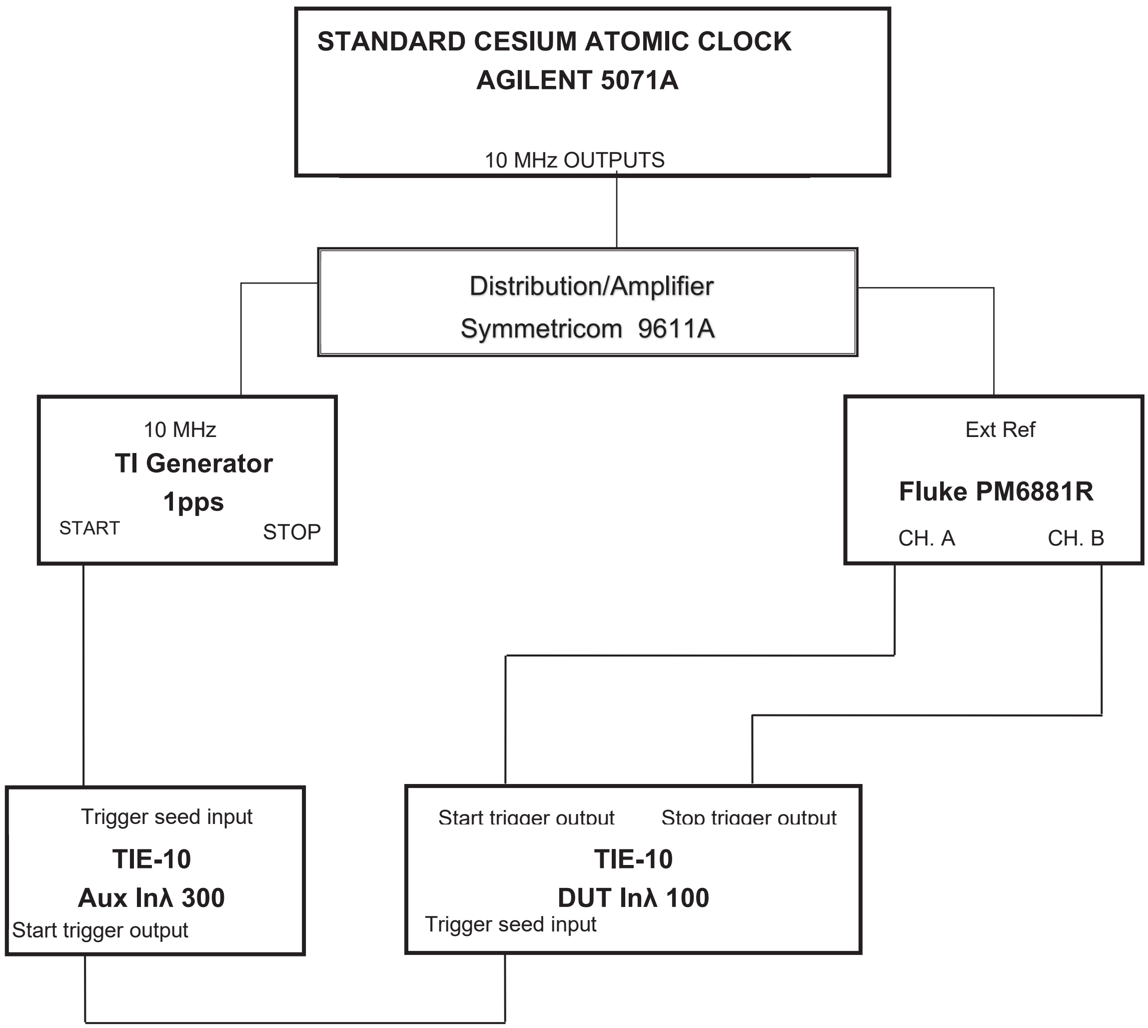
Quantity X_i	Estimate x_i (ns)	Standard uncertainty $u(x_i)$ (ns)	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$ (ns)	Degrees of freedom ν_i
$T_A - T_B$	24.06	0.016	normal	A	1.0	0.016	9
δT_R	0	0.003	rectangular	B	1.0	0.003	∞
δT_{TB}	0	5×10^{-9}	rectangular	B	1.0	5×10^{-9}	∞
$\delta T_{trigger}$	0	0.016	rectangular	B	1.0	0.016	∞
δT_{CD}	0	0.006	rectangular	B	1.0	0.006	∞
δT_{RV}	0	0.060	rectangular	B	1.0	0.060	∞
δT_{CA}	0	0.300	rectangular	B	1.0	0.300	∞

	Combined standard uncertainty	u_c	0.306
	Effective degrees of freedom	ν_{eff}	$> 10^6$
T= 24.06 ns	**Expanded uncertainty ($p \approx 95\%$)**	***U***	**0.61 ns**

B1. InLambda standards – conditions met during measurements

2.DUT Inλ **100**

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2,25 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	< 0,5 ns	< 10 ns	yes
Duty cycle	0,0003 %	≤ 50 %	yes
Pulse width	3,3 μs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 100	Inλ 300	Inλ 20 or Inλ 300	yes


STANDARD CESIUM ATOMIC CLOCK
AGILENT 5071A
10 MHz OUTPUTS
Distribution/Amplifier
Symmetricom 9611A
10 MHz
TI Generator
1pps
START
STOP
Ext Ref
Fluke PM6881R
CH. A
CH. B
Trigger seed input
TIE-10
Aux Inλ 300
Start trigger output
Start trigger output
Stop trigger output
TIE-10
DUT Inλ 100
Trigger seed input

Description of the quantities in the model equation:

Quantity X_i	Description
δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC
δT_{CA}	Contribution due of the inter-channel asymmetry (as stated by the instrument manufacturer in the Operators Manual)

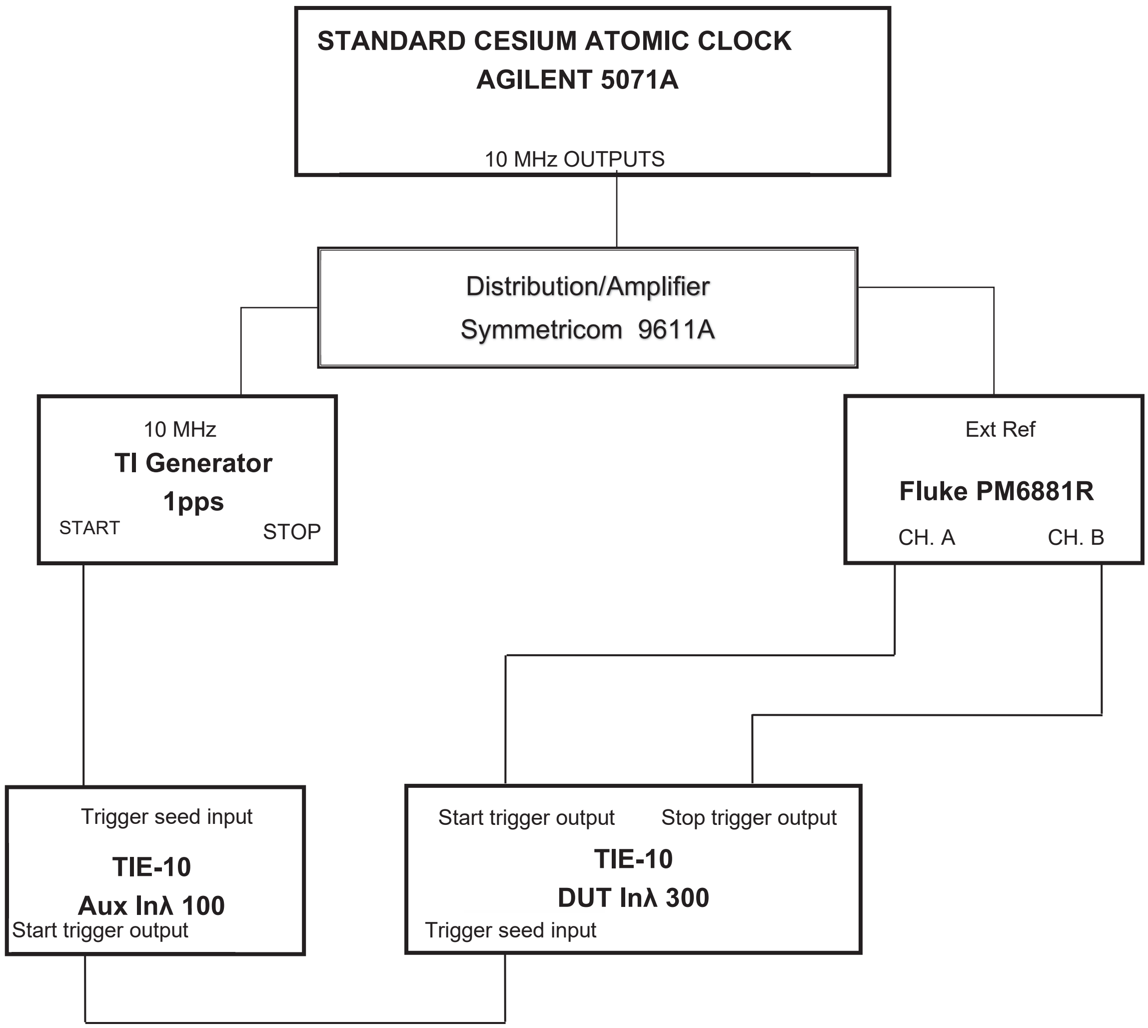
Uncertainty budget table

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 $c_i \cdot u(x_i)$ (ns)	Degrees of freedom ν_i
$T_A - T_B$	104.44	0.014	normal	A	1.0	0.014	9
δT_R	0	0.003	rectangular	B	1.0	0.003	∞
δT_{TB}	0	2.5×10^{-8}	rectangular	B	1.0	2.5×10^{-8}	∞
$\delta T_{trigger}$	0	0.016	rectangular	B	1.0	0.016	∞
δT_{CD}	0	0.006	rectangular	B	1.0	0.006	∞
δT_{RV}	0	0.060	rectangular	B	1.0	0.060	∞
δT_{CA}	0	0.300	rectangular	B	1.0	0.300	∞
		Combined standard uncertainty			u_c	0.307	
		Effective degrees of freedom			ν_{eff}	$> 10^6$	
T= 104.44 ns		**Expanded uncertainty ($p \approx 95\%$)**			***U***	**0.61 ns**	

B1. InLambda standards – conditions met during measurements

3.DUT Inλ **300**

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0V	0 V	yes
High level (at 50 Ω)	2,25 V	(1,75 ÷ 2,25) V	yes
Rise time (20 % to 80 %)	< 0,5 ns	< 10 ns	yes
Duty cycle	0,0003 %	≤ 50 %	yes
Pulse width	3,3 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	yes


STANDARD CESIUM ATOMIC CLOCK
AGILENT 5071A
10 MHz OUTPUTS
Distribution/Amplifier
Symmetricom 9611A
10 MHz
TI Generator
1pps
START
STOP
Ext Ref
Fluke PM6881R
CH. A
CH. B
Trigger seed input
TIE-10
Aux Inλ 100
Start trigger output
Start trigger output
Stop trigger output
TIE-10
DUT Inλ 300
Trigger seed input

Description of the quantities in the model equation:

Quantity X_i	Description
δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC
δT_{CA}	Contribution due of the inter-channel asymmetry (as stated by the instrument manufacturer in the Operators Manual)

Uncertainty budget table

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 $c_i \cdot u(x_i)$ (ns)	Degrees of freedom ν_i
$T_A - T_B$	307.28	0.015	normal	A	1.0	0.015	9
δT_R	0	0.003	rectangular	B	1.0	0.003	∞
δT_{TB}	0	7.5×10^{-8}	rectangular	B	1.0	7.5×10^{-8}	∞
$\delta T_{trigger}$	0	0.016	rectangular	B	1.0	0.016	∞
δT_{CD}	0	0.006	rectangular	B	1.0	0.006	∞
δT_{RV}	0	0.060	rectangular	B	1.0	0.060	∞
δT_{CA}	0	0.300	rectangular	B	1.0	0.300	∞
		Combined standard uncertainty			u_c	0.307	
		Effective degrees of freedom			ν_{eff}	$> 10^6$	
T= 307.28 ns		**Expanded uncertainty ($p \approx 95\%$)**			***U***	**0.61 ns**	

Ambient temperature during measurements			Unit of measure	Required reference conditions	Meet requirements? yes / no
22.5	±	0.5	°C	within (22 ± 4) °C	yes

Ambient humidity during measurements			Unit of measure	Required reference conditions	Meet requirements? yes / no
42.5	±	2.5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	TIC Fluke type PM6681R
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	It is included in the time interval deviation due to random values of TIC

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	**24.06**	±	**0.61**	ns	22.5	±	0.5	°C
Inλ 100	**104.44**	±	**0.61**	ns	22.5	±	0.5	°C
Inλ 300	**307.28**	±	**0.61**	ns	22.5	±	0.5	°C

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Violeta Ciociea

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01.10.2024

Annex 7. Minimum contents for the measurement report

- Identification of the participating laboratory: NIMB
- Description of the calibration method: Direct method
- Description of the calibration set-up and equipment: Cs clock 5071A, Fluke type PM6681R, DUT, Distribution/Amplifier Symmetricom 9611A, Direct connection via BNC connectors (See the charts on pages 2,4 and 7)
- Traceability chart: Cs clock 5071A standard
- Used relationship/ equation for obtaining estimates of results and uncertainty budget,

$T_x = (T_A - T_B) + \delta T$, where $\delta T = \delta T_R + \delta T_{TB} + \delta T_{trigger} + \delta T_{CD} + \delta T_{RV} + \delta T_{CA}$

- Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects

Where δT is:

δT_R	Time interval deviation due to resolution of TIC
δT_{TB}	Time interval deviation due to the time base error
$\delta T_{trigger}$	Time interval deviation due to the trigger level error
δT_{CD}	Time interval deviation due to the cable delays between A and B
δT_{RV}	Time interval deviation due to random values of TIC
δT_{CA}	Contribution due of the inter-channel asymmetry (as stated by the instrument manufacturer in the Operators Manual)

See charts on pages 5,8,11.

- Identification and description of the source: 10 MHz reference frequency for TIGen standard, Source of 10 MHz reference frequency is Standard of Cs clock 5071A

- Description of the used input pulse signals for InLambda standards (low level, high level (amplitude), frequency, pulse width, rise time (20% to 80 %), duty cycle)

See charts on pages: 3,6,9

- Ambient conditions of measurements (the temperature and the relative humidity) – the temperature for every InLambda standard separately

For -DUT **Inλ 20** : temperature is: 22.5 °C

-DUT **Inλ 100 :** temperature is: 22.5 °C

-DUT **Inλ 300:** temperature is: 22.5 °C

- Average date of performing measurements

09- 10.09.2020(2 days)

- Date and signature.

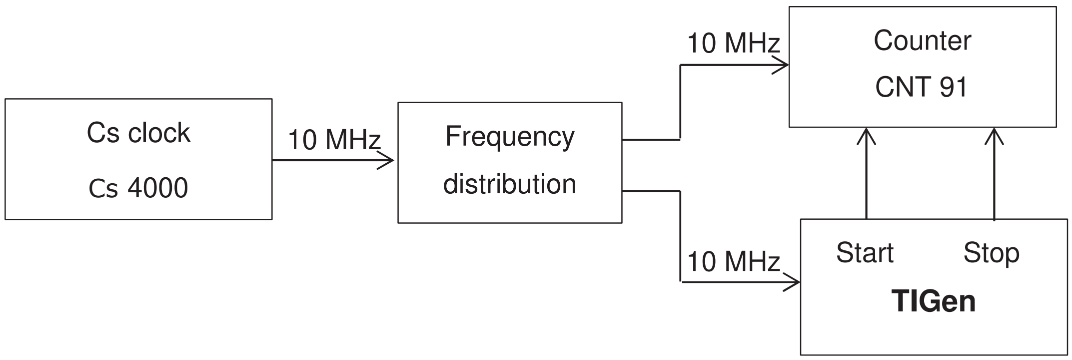
Violeta Ciociea

Andrei Vladut 01.10.2024

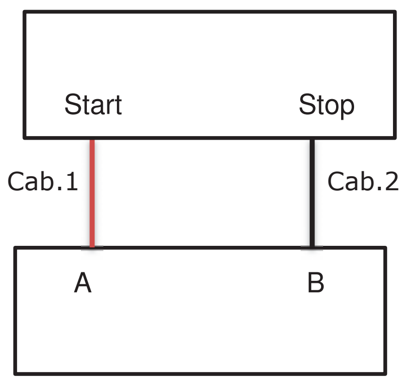
Appendix M

BIM report

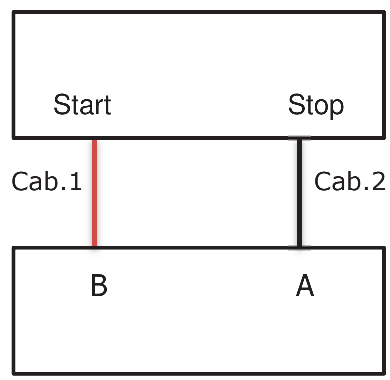
TIGen



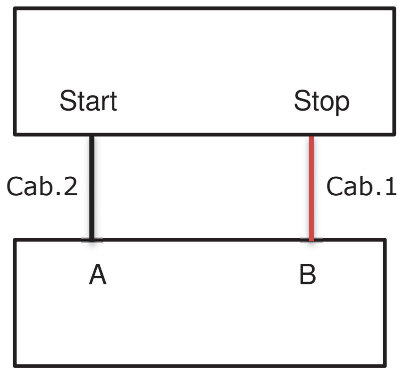
Four different measurements used to reduce differential delays of the used connecting cables between Time interval generators and the Time Interval Counter(CNT91):



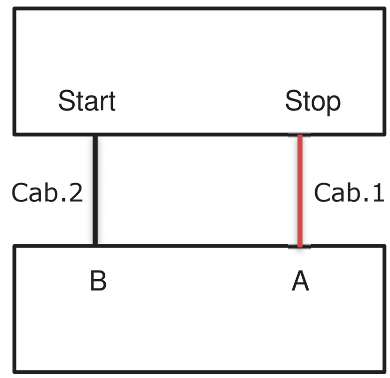
T1 measurement from channel **A** to **B**



T2 measurement from channel **B** to **A**



T3 measurement from channel **A** to **B**



T4 measurement from channel **B** to **A**

Model equation that follows from the measurement setup:

$$TI = \frac{T1+T2+T3+T4}{4} + \delta T_{rez} + \delta T_{Cs}$$

Description of the quantities in the model equation:

Quantity X_i	Description
T1, T2, T3, T4	time interval from 4 different measurements
TI	mean value of the different measurement time interval between start and stop signal
δT_{rez}	contains all internal residual time delays and quantisation errors of the TIC
δT_{Cs}	correction due to Time base short term stability (Cs Clock)

Uncertainty budget table INLambda 20 ns

Quantity, X_i	**Estimate,** x_i	**Standard uncertainty** $u_i(x_i)$	**Probability distribution**	**Method of evaluation**	**Sensitivity coefficient,** c_i	**Uncertainty contribution** $c_i \cdot u(x_i)$	**Degrees of freedom** ν_i
TI	24,23	0,004	normal	A	1	0,004	80
δT_{Cs}	0,00	0,012	normal	B	1	0,012	
δT_{rez}	0,00	0,10	normal	B	1	0,10	
	Combined standard uncertainty, u_c:					0,10	
	Effective degrees of freedom ν_{eff}:					28501344	
	Множител на покритие **k**:					2,00	
	Expanded uncertainty (p ≈ 95%):					0,20	

Uncertainty budget table INLambda 100 ns

Quantity, X_i	Estimate, x_i	Standard uncertainty $u_i(x_i)$	Probability distribution	Method of evaluation	Sensitivity coefficient, Ci	Uncertainty contribution $ci \cdot u(xi)$	Degrees of freedom νi
TI	104,54	0,005	normal	A	1	0,005	80
δT_{Cs}	0,00	0,012	normal	B	1	0,012	
δT_{rez}	0,00	0,10	normal	B	1	0,10	
					Combined standard uncertainty, u_c:	0,10	
					Effective degrees of freedom ν_{eff}:	14686068	
					Множител на покритие **k**:	2,00	
					Expanded uncertainty ($p \approx 95\%$):	0,20	

Uncertainty budget table INLambda 300 ns

Quantity, X_i	Estimate, x_i	Standard uncertainty $u_i(x_i)$	Probability distribution	Method of evaluation	Sensitivity coefficient, Ci	Uncertainty contribution $ci \cdot u(xi)$	Degrees of freedom νi
TI	307,34	0,006	normal	A	1	0,006	80
δT_{Cs}	0,00	0,012	normal	B	1	0,012	
δT_{rez}	0,00	0,10	normal	B	1	0,10	
					Combined standard uncertainty, u_c:	0,10	
					Effective degrees of freedom ν_{eff}:	8666135	
					Множител на покритие **k**:	2,00	
					Expanded uncertainty ($p \approx 95\%$):	0,20	

Uncertainty budget table TIGen dn0

Quantity, X_i	Estimate, x_i	Standard uncertainty $u_i(x_i)$	Probability distribution	Method of evaluation	Sensitivity coefficient, Ci	Uncertainty contribution $ci \cdot u(xi)$	Degrees of freedom νi
TI	22,66	0,004	normal	A	1	0,004	80
δT_{Cs}	0,00	0,012	normal	B	1	0,012	
δT_{rez}	0,00	0,10	normal	B	1	0,10	
					Combined standard uncertainty, u_c:	0,10	
					Effective degrees of freedom ν_{eff}:	27912931	
					Множител на покритие **k**:	2,00	
					Expanded uncertainty ($p \approx 95\%$):	0,20	

Uncertainty budget table TIGen dn3

Quantity, X_i	Estimate, x_i	Standard uncertainty $u_i(x_i)$	Probability distribution	Method of evaluation	Sensitivity coefficient, Ci	Uncertainty contribution ci · u(xi)	Degrees of freedom νi
TI	249,99	0,007	normal	A	1	0,007	80
δT_{Cs}	0,00	0,012	normal	B	1	0,012	
δT_{rez}	0,00	0,10	normal	B	1	0,10	
	Combined standard uncertainty, u_c:					0,10	
	Effective degrees of freedom ν_{eff}:					2785115	
	Множител на покритие **k**:					2,00	
	Expanded uncertainty (p ≈ 95%):					0,20	

Uncertainty budget table TIGen dn7

Quantity, X_i	Estimate, x_i	Standard uncertainty $u_i(x_i)$	Probability distribution	Method of evaluation	Sensitivity coefficient, Ci	Uncertainty contribution ci · u(xi)	Degrees of freedom νi
TI	1508,97	0,004	normal	A	1	0,004	80
δT_{Cs}	0,00	0,012	normal	B	1	0,012	
δT_{rez}	0,00	0,10	normal	B	1	0,10	
	Combined standard uncertainty, u_c:					0,10	
	Effective degrees of freedom ν_{eff}:					29842850	
	Множител на покритие **k**:					2,00	
	Expanded uncertainty (p ≈ 95%):					0,20	

Uncertainty budget table TIGen dn126

Quantity, X_i	Estimate, x_i	Standard uncertainty $u_i(x_i)$	Probability distribution	Method of evaluation	Sensitivity coefficient, Ci	Uncertainty contribution ci · u(xi)	Degrees of freedom νi
TI	12039,50	0,006	normal	A	1	0,006	80
δT_{Cs}	0,00	0,012	normal	B	1	0,012	
δT_{rez}	0,00	0,10	normal	B	1	0,10	
	Combined standard uncertainty, u_c:					0,10	
	Effective degrees of freedom ν_{eff}:					8633615	
	Множител на покритие **k**:					2,00	
	Expanded uncertainty (p ≈ 95%):					0,20	

Natasha Tosheva 11.06.2021

(Name) (Date)

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: BIM Country: Bulgaria

Average date of measurements: 25.09.2020

Remarks:

….

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)		Cs 4000		10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)		2		within (0,5 ÷ 2) V_{p-p}	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.93	±	0.24	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
48.43	±	1.6	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	CNT 91
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	<5E-10

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty ($p \approx 95$ %) (in ns)			Unit of measure
"dn0"	22.66	±	0.20	ns
"dn3"	249.99	±	0.20	ns
"dn7"	1508.97	±	0.20	ns
"dn126"	12039.50	±	0.20	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	frequency generator PM5193		
1 pps (yes / no)			
Frequency	10 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2.09	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	<4.5 ns	< 10 ns	yes
Duty cycle	50 %	≤ 50 %	yes
Pulse width	50	to avoid the pulse widths close (**<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 300	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 20	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.93	±	0.24	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
48.43	±	1.6	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	CNT 91
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	<5E-10

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.23	±	0.20	ns	22.93	±	0.24	°C
Inλ 100	104.54	±	0.20	ns	22.93	±	0.24	°C
Inλ 300	307.34	±	0.20	ns	22.93	±	0.24	°C

Natasha Tosheva — 11.06.2021

(Name) — (Date)

Appendix N

EIM report

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM
e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: EIM Country: Greece

Average date of measurements: 09/10/2020

Remarks:

….

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	Cs clock	10 MHz ± 1 Hz	Yes
Amplitude (at 50 Ω)	1.46 V_{p-p}	within (0,5 ÷ 2) V_{p-p}	Yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23,4	±	0,5	°C	within (22 ± 4) °C	Yes

Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
66	±	18	%	within (50 ± 30) %	No

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Fluke PM6681R universal counter
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	300 ps

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22,590	±	0,70	ns
"dn3"	249,998	±	0,70	ns
"dn7"	1,508993	±	0,70	ns
"dn126"	12,039426	±	0,70	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Frequency generator Agilent Tech. 33250A		
1 pps (yes / no)	no		
Frequency	100 Hz	≤ 200 Hz	Yes
Low level	0 V	0 V	Yes
High level (at 50 Ω)	2 V	(1,75 ÷ 2,25) V	Yes
Rise time (20% to 80 %)	5 ns	< 10 ns	Yes
Duty cycle	<50%	≤ 50 %	
Pulse width	200 ns	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	Yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	Yes
Inλ 100	Inλ 20	Inλ 20 or Inλ 300	Yes
Inλ 300	Inλ 20	Inλ 20 or Inλ 100	Yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23,4	±	0,5	°C	within (22 ± 4) °C	Yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
66	±	18	%	within (50 ± 30) %	No

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Fluke PM6681R universal counter
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	300 ps

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24,142	±	0,70	ns	23,4	±	0,5	°C
Inλ 100	104,482	±	0,70	ns	23,4	±	0,5	°C
Inλ 300	307,329	±	0,70	ns	23,4	±	0,5	°C

George Krikelas
(Name)

07/01/2022
(Date)

REPORT ON COMPARISON RESULTS ON TIME INTERVAL MEASUREMENTS

EIM/NQIS

1st of January 2022

CONTENTS

1. Introduction: goal of inter-comparison 3
2. Travelling Standards 3
3. Details of Participating Laboratory 6
4. Measurement period and conditions 6
5. Measurement system used 7
6. Traceability 7
7. Results 7

1. Introduction: goal of inter-comparison

The purpose of this Supplementary Comparison (SC) was to support CMC claims to support CMC claims in time interval measurements. It was proceeded by the experience with a cable delay measurement within #828 EURAMET Project, that showed that a cable delay is not well-defined measured quantity and its value is significantly dependent on the shape of signals used for cable delay measurements.

The measurements carried out concerned Time Intervals generated by (a) TI Generator (TIGen) based on PLL loops and programmable logic and counters and (b) 3 Delay standards (InLambda standards) based on stabilised fiber delays of c. 20 ns, c. 100 ns and c. 300 ns respectively.

2. Travelling Standards

For this comparison, two types of travelling standards have been selected: One (1) TIGen standard and three (3) InLambda standards.

A. TIGen is an electronic based time interval generator developed by AGH University of Science and Technology and GUM (Poland). TIGen is property of GUM. It requires external 10 MHz input frequency and generates 127 different time intervals between 1 pps outputs. The set of generated time intervals is determined by the applied PLL lines and the programmable logic and counters. All signal inputs/outputs are terminated with SMA-female connectors. TIGen is equipped with DC power supply that has to be connected to the input terminal in the rear panel. Three auxiliary SMA-male-BNC-female adapters are attached.

B. InLambda delay standards were developed by InLambda company (Instrumentation Technologies) in cooperation with SIQ (Slovenia) and are based on temperature stabilised fiber delays of approximately 20 ns, 100 ns and 300 ns respectively. InLambda standards are purchased and owned by SIQ. InLambda standards require external input pulses and should be used in pairs (in double configuration.

(a)

(b)

(c)

(d)

(e)

Figure 1: TIGen: a) the base unit, b) DC power supplier, c) front panel of the base unit, d) rear panel of the base unit, e) three auxiliary SMA-male-BNC-female adapters

(a)

(b)

(c)

Figure 2: InLambda standards: a) front panel (1 – nominal value of delay: 20 ns, 100 ns or 300 ns, 2 – status diodes, 3 – input for external pulses, 4 – output of START pulses, 5 – output of STOP pulses), b) rear panel, c) required double configuration for measurements

3. Details of Participating Laboratory

The contact details of the participating laboratory (NQIS/EIM) are given below:

Country	Institute	Acronym	Shipping Address	Contact Person*
GREECE	National Quality Infrastructure System / Hellenic Institute of Metrology	NQIS/EIM	National Quality Infrastructure System (NQIS/EIM) Industrial area of Thessaloniki, Block 45, GR-57022 Sindos GREECE	George KRIKELAS & Myrto Holiastou gkrik@eim.gr & holiastou@eim.gr Tel: +30 2310 569 970

*Because Dr. George Krikelas is no longer a member of EIM's staff, communications should also be addressed to Dr. Myrto Holiastou

4. Measurement period and conditions

The measurements were performed during 06/10/2020 and 14/10/2020.

Environmental conditions during the measurements

Temperature: (23,4 ± 0,5) °C

rH: (66 ± 18) %

5. Measurement set-up and calibration method

The calibration method used was similar for both types of travelling standards, with some differences for each standard. In both situations, a Fluke PM 6681R Rubidium Universal Counter served as a time interval counter, with a 10MHz external reference, taken from the Primary Time & Frequency Standard of the lab.

A) For the case of the TIGen, an external 10MHz frequency signal was supplied to the device. The pulse signals from the START and STOP outputs of the TIGen were applied at a counter's Channel A and Channel B respectively. For each selected time interval (dn0, dn3, dn7 and dn126-with approximate nominal values of 20 ns, 250 ns 1,5 μs and 12 μs) measurements of the time interval (Time A-B function of the counter) have been performed.

B) For the case of the InLambda standards, a similar setup has been used, adapted to the specific connection requirements of the standards. More specific, for each measurement two InLambda standards have been used, one serving as the auxiliary device, in the required "double configuration" for the measurement (see Fig. 2.c). The signal from the source has been fed into the "trigger seed" input of the auxiliary device and afterwards the "start trigger" output from the auxiliary device was driver into the "trigger seed" input of the DUT. Then measurements of the time interval (Time A-B function of the counter) have been performed, using the "start trigger" and "stop trigger" outputs of the.

The software used for the measurements was TimeView 2.1.14 from Pendulum.

6. Traceability

Traceability to UTC through the laboratory's Primary Time & Frequency Standard (participating in the on-going …. Intercomparison".

7. Results

The measurement results, measuring conditions and various measurement parameters are summarized to the provided completed document "Annex 4: Summary of results".

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: EIM Country: Greece

Average date of measurements:

Remarks:

Model equation that follows from the measurement setup:

$$TI = \mathrm{TI}_{meas} + \delta_{rnd(TI)} + \delta_{random\_eff} + \delta_{syst\_eff} + \delta_{round,LSD}$$

Description of the quantities in the model equation:

Quantity X_i	Description
TI_{meas}	Measured time interval
$\delta_{rnd(TI)}$	Correction due to repeatability of the measurement
δ_{random_eff}	Correction due to (total) random uncertainty of TI (including quantization errors & trigger errors due to noise)
δ_{syst_eff}	Correction due to systematic effect (including: trigger level timing errors, channel mismatch error & timebase error)
$\delta_{round,LSD}$	Correction due to least significant digit displayed

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
TI_{meas}	22,590 ns						
$\delta_{rnd(TI)}$	0 ns	0,025 ns	Normal	A	1	0,025 ns	8
δ_{random_eff}	0 ns	0,179 ns	Normal	B	1	0,179 ns	∞
δ_{syst_eff}	0 ns	0,300 ns	Normal	B	1	0,300 ns	∞
$\delta_{round,LSD}$	0 ns	0,001 ns	Normal	B	1	0,001 ns	∞

Combined standard uncertainty	u_c	0,35 ns
Effective degrees of freedom	ν_{eff}	∞
Expanded uncertainty ($p \approx 95\%$)	U	0,70 ns

George I Krikelas 13/01/2022
(Name) (Date)

Appendix O

BEV report

Bundesamt
für Eich- und
Vermessungswesen

EURAMET.TF-S1 Supplementary Comparison ”Comparison of time interval measurements”

Measurement Report

Description of the calibration method

Measurement of time interval with a time interval/frequency counter.

Description of the calibration set-up and equipment

The time interval measurements were carried out with a SR620 counter. For all measurements cables with different length were connected from the transfer standard to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Traceability chart

The frequency reference input of SR620 counter was connected to a 10 MHz signal from our Caesium master clock which represents UTC(BEV).

Measurement results and uncertainty budget

For every measured time interval the measurement result and uncertainty budget is attached in a separate document:

- EURAMET_TF_S1_DN0.pdf
- EURAMET_TF_S1_DN3.pdf
- EURAMET_TF_S1_DN7.pdf
- EURAMET_TF_S1_DN126.pdf
- EURAMET_TF_S1_InLambda20.pdf
- EURAMET_TF_S1_InLambda100.pdf
- EURAMET_TF_S1_InLambda300.pdf

A summarized report of measurements is written in document EURAMET_TF_S1_Results_BEV.pdf. The scheme of uncertainty budget with the example for DN0 generated by TIGen is also listed in document EURAMET_TF_S1_Uncertainty Budget_BEV.pdf.

Description of 10 MHz and 1 PPS source

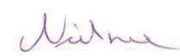
All details are listed in attached document EURAMET_TF_S1_Results_BEV.pdf.

Ambient conditions of measurements

All details are listed in attached document EURAMET_TF_S1_Results_BEV.pdf.

Average date of measurements

23.10.2020



Anton Niessner
30.11.2020

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: BEV Country: Austria

Average date of measurements: 23.10.2020

Remarks:

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)			Cs clock	10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)			1,15 V	within (0,5 ÷ 2) V	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,8	±	1	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
41	±	5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0,118 ns

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty ($p \approx 95$ %) (in ns)			Unit of measure
“dn0”	22,60	±	0,24	ns
“dn3”	249,95	±	0,24	ns
“dn7”	1508,96	±	0,24	ns
“dn126”	12039,44	±	0,24	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2,8 V	(1,75 ÷ 2,25) V	no
Rise time (20% to 80 %)	2 ns	< 10 ns	yes
Duty cycle	0,002 %	≤ 50 %	yes
Pulse width	20 µs	to avoid the pulse widths close **(<± 10 ns)** to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 300	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,8	±	1	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
41	±	5	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0,118 ns

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24,14	±	0,24	ns	22,8	±	1	°C
Inλ 100	104,44	±	0,24	ns	22,8	±	1	°C
Inλ 300	307,22	±	0,24	ns	22,8	±	1	°C

Anton Niessner 26.11.2020

(Name) (Date)

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM
e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: BEV Country: Austria

Average date of measurements: 23.10.2020

Remarks:

Model equation that follows from the measurement setup:

$$t_I = (t_1 + t_2)/2 + \delta_{StartStop} + \delta_{SR620}$$
$$t_1 = t_{1m} + \delta_{1LSD} + \delta_{1res} + \delta_{TriggerLevelStart} + \delta_{TriggerLevelStop}$$
$$t_2 = t_{2m} + \delta_{2LSD} + \delta_{2res} + \delta_{TriggerLevelStart} + \delta_{TriggerLevelStop}$$
$$\delta_{1res} = \delta_{Jitter} + t_{1m} \cdot \delta_{ref} + \delta_{TriggerJitterStart} + \delta_{TiggerJitterStop}$$
$$\delta_{2res} = \delta_{Jitter} + t_{2m} \cdot \delta_{ref} + \delta_{TriggerJitterStart} + \delta_{TiggerJitterStop}$$

Description of the quantities in the model equation:

Quantity X_i	Description
t_I	time interval of standard
t_1	time interval with shorter cable on START
t_2	time interval with shorter cable on STOP
$\delta_{StartStop}$	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	auxiliary quantity used to model further SR620 uncertainty
t_{1m}	measurement with shorter cable on START
δ_{1LSD}	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	auxiliary quantity used to model stop trigger level timing uncertainty
t_{2m}	measurement with shorter cable on STOP
δ_{2LSD}	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	auxiliary quantity used to model single-shot resolution of SR620
δ_{ref}	auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	auxiliary quantity used to model stop trigger timing jitter

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
$\delta_{StartStop}$	0 ns	0,0144 ns	rectangular	B	1	0,014 ns	infinity
δ_{SR620}	0 ns	0,118 ns	normal	B	1	0,12 ns	100
t_{1m}	25,147 ns	$600 \cdot 10^{-6}$ ns	normal	A	0,5	$300 \cdot 10^{-6}$ ns	99
δ_{1LSD}	0 ns	$2,31 \cdot 10^{-3}$ ns	rectangular	B	0,5	$1,2 \cdot 10^{-3}$ ns	infinity
$\delta_{TriggerLevelStart}$	0 ns	0,0101 ns	rectangular	B	1	0,010 ns	infinity
$\delta_{TriggerLevelStop}$	0 ns	0,0101 ns	rectangular	B	1	0,010 ns	infinity
t_{2m}	20,063 ns	$600 \cdot 10^{-6}$ ns	normal	A	0,5	$300 \cdot 10^{-6}$ ns	99
δ_{2LSD}	0 ns	$2,31 \cdot 10^{-3}$ ns	rectangular	B	0,5	$1,2 \cdot 10^{-3}$ ns	infinity
δ_{Jitter}	0 ns	$2,5 \cdot 10^{-3}$ ns	normal	A	1	$2,5 \cdot 10^{-3}$ ns	99
δ_{ref}	0	$1 \cdot 10^{-12}$	normal	A	23	$23 \cdot 10^{-12}$	99
$\delta_{TriggerJitterStart}$	0 ns	$50 \cdot 10^{-6}$ ns	normal	A	1	$50 \cdot 10^{-6}$ ns	99
$\delta_{TiggerJitterStop}$	0 ns	$50 \cdot 10^{-6}$ ns	normal	A	1	$50 \cdot 10^{-6}$ ns	99

Combined standard uncertainty	u_c	0,12 ns
Effective degrees of freedom	ν_{eff}	110
Expanded uncertainty ($p \approx 95\%$)	U	0,24 ns

Anton Niessner
(Name)

26.11.2020
(Date)

Time Interval Measurements

Author: Anton Niessner

Measurements of 7 time intervals of two different travelling standards (Time Interval Generator, InLambda Standards) for EURAMET Supplementary Comparison EURAMET.TF-S1.

The measurements were carried out with a SR620 counter. For all measurements cables with diffferent length were connected to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Measurement budget for dn0 channel of Time Interval Generator.

Time Interval Generator

Model Equation:

$t_I=(t_1+t_2)/2+\delta_{StartStop}+\delta_{SR620};$

$t_1=t_{1m}+\delta_{1LSD}+\delta_{1res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$

$t_2=t_{2m}+\delta_{2LSD}+\delta_{2res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$

$\delta_{1res}=\delta_{Jitter}+t_{1m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$

$\delta_{2res}=\delta_{Jitter}+t_{2m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$

List of Quantities:

Quantity	Unit	Definition
t_I	ns	time interval of standard
t_1	ns	time interval with shorter cable on START
t_2	ns	time interval with shorter cable on STOP
$\delta_{StartStop}$	ns	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	ns	auxiliary quantity used to model further SR620 uncertainty
t_{1m}	ns	measurement with shorter cable on START
δ_{1LSD}	ns	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	ns	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	ns	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	ns	auxiliary quantity used to model stop trigger level timing uncertainty

Quantity	Unit	Definition
t_{2m}	ns	measurement with shorter cable on STOP
δ_{2LSD}	ns	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	ns	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	ns	auxiliary quantity used to model single-shot resolution of SR620
δ_{ref}		auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	ns	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	ns	auxiliary quantity used to model stop trigger timing jitter

$\delta_{StartStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.025 ns

δ_{SR620}: Type B normal distribution
Value: 0 ns
Expanded Uncertainty: 0.236
Coverage Factor: 2

t_{1m}: Type A summarized
Mean: 25.147 ns
Experimental Standard Deviation: 0.006 ns
Number of observations: 100

δ_{1LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

$\delta_{TriggerLevelStart}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

$\delta_{TriggerLevelStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

t_{2m}: Type A summarized
Mean: 20.063 ns
Experimental Standard Deviation: 0.006 ns
Number of observations: 100

δ_{2LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

δ_{Jitter}: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.025 ns
Number of observations: 100

δ_{ref}: Type A summarized
Mean: 0
Experimental Standard Deviation: $1 \cdot 10^{-11}$
Number of observations: 100

$\delta_{TriggerJitterStart}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

$\delta_{TiggerJitterStop}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

Interim Results:

Quantity	Value	Standard Uncertainty	Degrees of Freedom
t_1	25.1470 ns	0.0147 ns	infinity
t_2	20.0630 ns	0.0147 ns	infinity
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99

Uncertainty Budgets:

t_I: time interval of standard

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_1	25.1470 ns	0.0147 ns	infinity				
t_2	20.0630 ns	0.0147 ns	infinity				
$\delta_{StartStop}$	0.0 ns	0.0144 ns	infinity	rectangular	1.0	0.014 ns	1.5 %
δ_{SR620}	0.0 ns	0.118 ns	100	normal	1.0	0.12 ns	97.1 %
t_{1m}	25.147000 ns	$600 \cdot 10^{-6}$ ns	99	normal	0.50	$300 \cdot 10^{-6}$ ns	0.0 %
δ_{1LSD}	0.0 ns	$2.31 \cdot 10^{-3}$ ns	infinity	rectangular	0.50	$1.2 \cdot 10^{-3}$ ns	0.0 %
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99				
$\delta_{TriggerLevelStart}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
$\delta_{TriggerLevelStop}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
t_{2m}	20.063000 ns	$600 \cdot 10^{-6}$ ns	99	normal	0.50	$300 \cdot 10^{-6}$ ns	0.0 %
δ_{2LSD}	0.0 ns	$2.31 \cdot 10^{-3}$ ns	infinity	rectangular	0.50	$1.2 \cdot 10^{-3}$ ns	0.0 %
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99				
δ_{Jitter}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99	normal	1.0	$2.5 \cdot 10^{-3}$ ns	0.0 %
δ_{ref}	0.0	$1.00 \cdot 10^{-12}$	99	normal	23	$23 \cdot 10^{-12}$ ns	0.0 %
$\delta_{TriggerJitterStart}$	0.0 ns	$50.0 \cdot 10^{-6}$ ns	99	normal	1.0	$50 \cdot 10^{-6}$ ns	0.0 %
$\delta_{TiggerJitterStop}$	0.0 ns	$50.0 \cdot 10^{-6}$ ns	99	normal	1.0	$50 \cdot 10^{-6}$ ns	0.0 %
t_I	22.605 ns	0.120 ns	110				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
t_I	22.60 ns	0.24 ns	2.00	95% (normal)

Time Interval Measurements

Author: Anton Niessner

Measurements of 7 time intervals of two different travelling standards (Time Interval Generator, InLambda Standards) for EURAMET Supplementary Comparison EURAMET.TF-S1.

The measurements were carried out with a SR620 counter. For all measurements cables with diffferent length were connected to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Measurement budget for dn3 channel of Time Interval Generator.

Time Interval Generator

Model Equation:

$t_I=(t_1+t_2)/2+\delta_{StartStop}+\delta_{SR620}$;

$t_1=t_{1m}+\delta_{1LSD}+\delta_{1res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop}$;

$t_2=t_{2m}+\delta_{2LSD}+\delta_{2res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop}$;

$\delta_{1res}=\delta_{Jitter}+t_{1m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop}$;

$\delta_{2res}=\delta_{Jitter}+t_{2m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop}$;

List of Quantities:

Quantity	Unit	Definition
t_I	ns	time interval of standard
t_1	ns	time interval with shorter cable on START
t_2	ns	time interval with shorter cable on STOP
$\delta_{StartStop}$	ns	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	ns	auxiliary quantity used to model further SR620 uncertainty
t_{1m}	ns	measurement with shorter cable on START
δ_{1LSD}	ns	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	ns	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	ns	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	ns	auxiliary quantity used to model stop trigger level timing uncertainty

Quantity	Unit	Definition
t_{2m}	ns	measurement with shorter cable on STOP
δ_{2LSD}	ns	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	ns	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	ns	auxiliary quantity used to model single-shot resolution of SR620
δ_{ref}		auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	ns	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	ns	auxiliary quantity used to model stop trigger timing jitter

$\delta_{StartStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.001 ns

δ_{SR620}: Type B normal distribution
Value: 0 ns
Expanded Uncertainty: 0.236
Coverage Factor: 2

t_{1m}: Type A summarized
Mean: 252.527 ns
Experimental Standard Deviation: 0.007 ns
Number of observations: 100

δ_{1LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

$\delta_{TriggerLevelStart}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

$\delta_{TriggerLevelStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

t_{2m}: Type A summarized
Mean: 247.372 ns
Experimental Standard Deviation: 0.005 ns
Number of observations: 100

δ_{2LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

δ_{Jitter}: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.025 ns
Number of observations: 100

δ_{ref}: Type A summarized
Mean: 0
Experimental Standard Deviation: $1 \cdot 10^{-11}$
Number of observations: 100

$\delta_{TriggerJitterStart}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

$\delta_{TiggerJitterStop}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

Interim Results:

Quantity	Value	Standard Uncertainty	Degrees of Freedom
t_1	252.5270 ns	0.0147 ns	infinity
t_2	247.3720 ns	0.0147 ns	infinity
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99

Uncertainty Budgets:

t_I: **time interval of standard**

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_1	252.5270 ns	0.0147 ns	infinity				
t_2	247.3720 ns	0.0147 ns	infinity				
$\delta_{StartStop}$	0.0 ns	$577\cdot10^{-6}$ ns	infinity	rectangular	1.0	$580\cdot10^{-6}$ ns	0.0 %
δ_{SR620}	0.0 ns	0.118 ns	100	normal	1.0	0.12 ns	98.5 %
t_{1m}	252.527000 ns	$700\cdot10^{-6}$ ns	99	normal	0.50	$350\cdot10^{-6}$ ns	0.0 %
δ_{1LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{1res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
$\delta_{TriggerLevelStart}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
$\delta_{TriggerLevelStop}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
t_{2m}	247.372000 ns	$500\cdot10^{-6}$ ns	99	normal	0.50	$250\cdot10^{-6}$ ns	0.0 %
δ_{2LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{2res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
δ_{Jitter}	0.0 ns	$2.50\cdot10^{-3}$ ns	99	normal	1.0	$2.5\cdot10^{-3}$ ns	0.0 %
δ_{ref}	0.0	$1.00\cdot10^{-12}$	99	normal	250	$250\cdot10^{-12}$ ns	0.0 %
$\delta_{TriggerJitterStart}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
$\delta_{TiggerJitterStop}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
t_I	249.950 ns	0.119 ns	100				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
t_I	249.95 ns	0.24 ns	2.00	95% (normal)

Time Interval Measurements

Author: Anton Niessner

Measurements of 7 time intervals of two different travelling standards (Time Interval Generator, InLambda Standards) for EURAMET Supplementary Comparison EURAMET.TF-S1.

The measurements were carried out with a SR620 counter. For all measurements cables with diffferent length were connected to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Measurement budget for dn7 channel of Time Interval Generator.

Time Interval Generator

Model Equation:

$$t_I=(t_1+t_2)/2+\delta_{StartStop}+\delta_{SR620};$$

$$t_1=t_{1m}+\delta_{1LSD}+\delta_{1res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$$

$$t_2=t_{2m}+\delta_{2LSD}+\delta_{2res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$$

$$\delta_{1res}=\delta_{Jitter}+t_{1m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$$

$$\delta_{2res}=\delta_{Jitter}+t_{2m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$$

List of Quantities:

Quantity	Unit	Definition
t_I	ns	time interval of standard
t_1	ns	time interval with shorter cable on START
t_2	ns	time interval with shorter cable on STOP
$\delta_{StartStop}$	ns	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	ns	auxiliary quantity used to model further S620 uncertainty
t_{1m}	ns	measurement with shorter cable on START
δ_{1LSD}	ns	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	ns	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	ns	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	ns	auxiliary quantity used to model stop trigger level timing uncertainty

Quantity	Unit	Definition
t_{2m}	ns	measurement with shorter cable on STOP
δ_{2LSD}	ns	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	ns	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	ns	auxiliary quantity used to model single-shot resolution of SR620
δ_{ref}		auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	ns	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	ns	auxiliary quantity used to model stop trigger timing jitter

$\delta_{StartStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.05 ns

δ_{SR620}: Type B normal distribution
Value: 0 ns
Expanded Uncertainty: 0.236
Coverage Factor: 2

t_{1m}: Type A summarized
Mean: 1511.514 ns
Experimental Standard Deviation: 0.006 ns
Number of observations: 100

δ_{1LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

$\delta_{TriggerLevelStart}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

$\delta_{TriggerLevelStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

t_{2m}: Type A summarized
Mean: 1506.403 ns
Experimental Standard Deviation: 0.006 ns
Number of observations: 100

δ_{2LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

δ_{Jitter}: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.025 ns
Number of observations: 100

δ_{ref}:

Type A summarized
Mean: 0
Experimental Standard Deviation: $1 \cdot 10^{-11}$
Number of observations: 100

$\delta_{TriggerJitterStart}$:

Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

$\delta_{TiggerJitterStop}$:

Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

Interim Results:

Quantity	Value	Standard Uncertainty	Degrees of Freedom
t_1	1511.5140 ns	0.0147 ns	infinity
t_2	1506.4030 ns	0.0147 ns	infinity
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99

Uncertainty Budgets:

t_I: time interval of standard

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_1	1511.5140 ns	0.0147 ns	infinity				
t_2	1506.4030 ns	0.0147 ns	infinity				
$\delta_{StartStop}$	0.0 ns	0.0289 ns	infinity	rectangular	1.0	0.029 ns	5.6 %
δ_{SR620}	0.0 ns	0.118 ns	100	normal	1.0	0.12 ns	93.0 %
t_{1m}	1511.514000 ns	$600\cdot10^{-6}$ ns	99	normal	0.50	$300\cdot10^{-6}$ ns	0.0 %
δ_{1LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{1res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
$\delta_{TriggerLevelStart}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
$\delta_{TriggerLevelStop}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
t_{2m}	1506.403000 ns	$600\cdot10^{-6}$ ns	99	normal	0.50	$300\cdot10^{-6}$ ns	0.0 %
δ_{2LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{2res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
δ_{Jitter}	0.0 ns	$2.50\cdot10^{-3}$ ns	99	normal	1.0	$2.5\cdot10^{-3}$ ns	0.0 %
δ_{ref}	0.0	$1.00\cdot10^{-12}$	99	normal	1500	$1.5\cdot10^{-9}$ ns	0.0 %
$\delta_{TriggerJitterStart}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
$\delta_{TiggerJitterStop}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
t_I	1508.958 ns	0.122 ns	120				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
t_I	1508.96 ns	0.24 ns	2.00	95% (normal)

Time Interval Measurements

Author: Anton Niessner

Measurements of 7 time intervals of two different travelling standards (Time Interval Generator, InLambda Standards) for EURAMET Supplementary Comparison EURAMET.TF-S1.

The measurements were carried out with a SR620 counter. For all measurements cables with diffferent length were connected to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Measurement budget for dn126 channel of Time Interval Generator.

Time Interval Generator

Model Equation:

$t_I=(t_1+t_2)/2+\delta_{StartStop}+\delta_{SR620}$;

$t_1=t_{1m}+\delta_{1LSD}+\delta_{1res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop}$;

$t_2=t_{2m}+\delta_{2LSD}+\delta_{2res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop}$;

$\delta_{1res}=\delta_{Jitter}+t_{1m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop}$;

$\delta_{2res}=\delta_{Jitter}+t_{2m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop}$;

List of Quantities:

Quantity	Unit	Definition
t_I	ns	time interval of standard
t_1	ns	time interval with shorter cable on START
t_2	ns	time interval with shorter cable on STOP
$\delta_{StartStop}$	ns	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	ns	auxiliary quantity used to model further SR620 uncertainty
t_{1m}	ns	measurement with shorter cable on START
δ_{1LSD}	ns	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	ns	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	ns	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	ns	auxiliary quantity used to model stop trigger level timing uncertainty

Quantity	Unit	Definition
t_{2m}	ns	measurement with shorter cable on STOP
δ_{2LSD}	ns	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	ns	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	ns	auxiliary quantity used to model single-shot resolution of SR620
δ_{ref}		auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	ns	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	ns	auxiliary quantity used to model stop trigger timing jitter

$\delta_{StartStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.02 ns

δ_{SR620}: Type B normal distribution
Value: 0 ns
Expanded Uncertainty: 0.236
Coverage Factor: 2

t_{1m}: Type A summarized
Mean: 12042.022 ns
Experimental Standard Deviation: 0.006 ns
Number of observations: 100

δ_{1LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

$\delta_{TriggerLevelStart}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

$\delta_{TriggerLevelStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

t_{2m}: Type A summarized
Mean: 12036.850 ns
Experimental Standard Deviation: 0.006 ns
Number of observations: 100

δ_{2LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

δ_{Jitter}: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.025 ns
Number of observations: 100

δ_{ref}: Type A summarized
Mean: 0
Experimental Standard Deviation: $1 \cdot 10^{-11}$
Number of observations: 100

$\delta_{TriggerJitterStart}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

$\delta_{TiggerJitterStop}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

Interim Results:

Quantity	**Value**	**Standard Uncertainty**	**Degrees of Freedom**
t_1	12042.0220 ns	0.0147 ns	infinity
t_2	12036.8500 ns	0.0147 ns	infinity
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99

Uncertainty Budgets:

t_I: time interval of standard

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_1	12042.0220 ns	0.0147 ns	infinity				
t_2	12036.8500 ns	0.0147 ns	infinity				
$\delta_{StartStop}$	0.0 ns	0.0115 ns	infinity	rectangular	1.0	0.012 ns	0.9 %
δ_{SR620}	0.0 ns	0.118 ns	100	normal	1.0	0.12 ns	97.6 %
t_{1m}	12042.022000 ns	$600\cdot10^{-6}$ ns	99	normal	0.50	$300\cdot10^{-6}$ ns	0.0 %
δ_{1LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{1res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
$\delta_{TriggerLevelStart}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
$\delta_{TriggerLevelStop}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
t_{2m}	12036.850000 ns	$600\cdot10^{-6}$ ns	99	normal	0.50	$300\cdot10^{-6}$ ns	0.0 %
δ_{2LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{2res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
δ_{Jitter}	0.0 ns	$2.50\cdot10^{-3}$ ns	99	normal	1.0	$2.5\cdot10^{-3}$ ns	0.0 %
δ_{ref}	0.0	$1.00\cdot10^{-12}$	99	normal	12000	$12\cdot10^{-9}$ ns	0.0 %
$\delta_{TriggerJitterStart}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
$\delta_{TiggerJitterStop}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
t_I	12039.436 ns	0.119 ns	110				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
t_I	12039.44 ns	0.24 ns	2.00	95% (normal)

Time Interval Measurements

Author: Anton Niessner

Measurements of 7 time intervals of two different travelling standards (Time Interval Generator, InLambda Standards) for EURAMET Supplementary Comparison EURAMET.TF-S1.

The measurements were carried out with a SR620 counter. For all measurements cables with diffferent length were connected to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Measurement budget for InLambda 20 ns standard.

InLambda Standard

Model Equation:

$t_I=(t_1+t_2)/2+\delta_{StartStop}+\delta_{SR620};$

$t_1=t_{1m}+\delta_{1LSD}+\delta_{1res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$

$t_2=t_{2m}+\delta_{2LSD}+\delta_{2res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$

$\delta_{1res}=\delta_{Jitter}+t_{1m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$

$\delta_{2res}=\delta_{Jitter}+t_{2m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$

List of Quantities:

Quantity	Unit	Definition
t_I	ns	time interval of standard
t_1	ns	time interval with shorter cable on START
t_2	ns	time interval with shorter cable on STOP
$\delta_{StartStop}$	ns	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	ns	auxiliary quantity used to model further SR620 uncertainty
t_{1m}	ns	measurement with shorter cable on START
δ_{1LSD}	ns	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	ns	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	ns	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	ns	auxiliary quantity used to model stop trigger level timing uncertainty
t_{2m}	ns	measurement with shorter cable on STOP
δ_{2LSD}	ns	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	ns	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	ns	auxiliary quantity used to model single-shot resolution of SR620

Quantity	Unit	Definition
δ_{ref}		auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	ns	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	ns	auxiliary quantity used to model stop trigger timing jitter

$\delta_{StartStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.035 ns

δ_{SR620}: Type B normal distribution
Value: 0 ns
Expanded Uncertainty: 0.236
Coverage Factor: 2

t_{1m}: Type A summarized
Mean: 26.741 ns
Experimental Standard Deviation: 0.012 ns
Number of observations: 100

δ_{1LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

$\delta_{TriggerLevelStart}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

$\delta_{TriggerLevelStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

t_{2m}: Type A summarized
Mean: 21.538 ns
Experimental Standard Deviation: 0.009 ns
Number of observations: 100

δ_{2LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

δ_{Jitter}: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.025 ns
Number of observations: 100

δ_{ref}: Type A summarized
Mean: 0
Experimental Standard Deviation: $1 \cdot 10^{-11}$
Number of observations: 100

$\delta_{TriggerJitterStart}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

$\delta_{TiggerJitterStop}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

Interim Results:

Quantity	Value	Standard Uncertainty	Degrees of Freedom
t_1	26.7410 ns	0.0147 ns	infinity
t_2	21.5380 ns	0.0147 ns	infinity
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99

Uncertainty Budgets:

t_I: time interval of standard

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_1	26.7410 ns	0.0147 ns	infinity				
t_2	21.5380 ns	0.0147 ns	infinity				
$\delta_{StartStop}$	0.0 ns	0.0202 ns	infinity	rectangular	1.0	0.020 ns	2.8 %
δ_{SR620}	0.0 ns	0.118 ns	100	normal	1.0	0.12 ns	95.7 %
t_{1m}	26.74100 ns	$1.20 \cdot 10^{-3}$ ns	99	normal	0.50	$600 \cdot 10^{-6}$ ns	0.0 %
δ_{1LSD}	0.0 ns	$2.31 \cdot 10^{-3}$ ns	infinity	rectangular	0.50	$1.2 \cdot 10^{-3}$ ns	0.0 %
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99				
$\delta_{TriggerLevelStart}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
$\delta_{TriggerLevelStop}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
t_{2m}	21.538000 ns	$900 \cdot 10^{-6}$ ns	99	normal	0.50	$450 \cdot 10^{-6}$ ns	0.0 %
δ_{2LSD}	0.0 ns	$2.31 \cdot 10^{-3}$ ns	infinity	rectangular	0.50	$1.2 \cdot 10^{-3}$ ns	0.0 %
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99				
δ_{Jitter}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99	normal	1.0	$2.5 \cdot 10^{-3}$ ns	0.0 %
δ_{ref}	0.0	$1.00 \cdot 10^{-12}$	99	normal	24	$24 \cdot 10^{-12}$ ns	0.0 %
$\delta_{TriggerJitterStart}$	0.0 ns	$50.0 \cdot 10^{-6}$ ns	99	normal	1.0	$50 \cdot 10^{-6}$ ns	0.0 %
$\delta_{TiggerJitterStop}$	0.0 ns	$50.0 \cdot 10^{-6}$ ns	99	normal	1.0	$50 \cdot 10^{-6}$ ns	0.0 %
t_I	24.140 ns	0.121 ns	110				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
t_I	24.14 ns	0.24 ns	2.00	95% (normal)

Time Interval Measurements

Author: Anton Niessner

Measurements of 7 time intervals of two different travelling standards (Time Interval Generator, InLambda Standards) for EURAMET Supplementary Comparison EURAMET.TF-S1.

The measurements were carried out with a SR620 counter. For all measurements cables with diffferent length were connected to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Measurement budget for InLambda 100 ns standard.

InLambda Standard

Model Equation:

$t_I=(t_1+t_2)/2+\delta_{StartStop}+\delta_{SR620};$

$t_1=t_{1m}+\delta_{1LSD}+\delta_{1res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$

$t_2=t_{2m}+\delta_{2LSD}+\delta_{2res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop};$

$\delta_{1res}=\delta_{Jitter}+t_{1m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$

$\delta_{2res}=\delta_{Jitter}+t_{2m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop};$

List of Quantities:

Quantity	Unit	Definition
t_I	ns	time interval of standard
t_1	ns	time interval with shorter cable on START
t_2	ns	time interval with shorter cable on STOP
$\delta_{StartStop}$	ns	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	ns	auxiliary quantity used to model further SR620 uncertainty
t_{1m}	ns	measurement with shorter cable on START
δ_{1LSD}	ns	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	ns	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	ns	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	ns	auxiliary quantity used to model stop trigger level timing uncertainty
t_{2m}	ns	measurement with shorter cable on STOP
δ_{2LSD}	ns	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	ns	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	ns	auxiliary quantity used to model single-shot resolution of SR620

Quantity	Unit	Definition
δ_{ref}		auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	ns	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	ns	auxiliary quantity used to model stop trigger timing jitter

$\delta_{StartStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.015 ns

δ_{SR620}: Type B normal distribution
Value: 0 ns
Expanded Uncertainty: 0.236
Coverage Factor: 2

t_{1m}: Type A summarized
Mean: 107.064 ns
Experimental Standard Deviation: 0.011 ns
Number of observations: 100

δ_{1LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

$\delta_{TriggerLevelStart}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

$\delta_{TriggerLevelStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

t_{2m}: Type A summarized
Mean: 101.822 ns
Experimental Standard Deviation: 0.011 ns
Number of observations: 100

δ_{2LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

δ_{Jitter}: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.025 ns
Number of observations: 100

δ_{ref}: Type A summarized
Mean: 0
Experimental Standard Deviation: $1 \cdot 10^{-11}$
Number of observations: 100

$\delta_{TriggerJitterStart}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

$\delta_{TiggerJitterStop}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

Interim Results:

Quantity	Value	Standard Uncertainty	Degrees of Freedom
t_1	107.0640 ns	0.0147 ns	infinity
t_2	101.8220 ns	0.0147 ns	infinity
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99

Uncertainty Budgets:

t_I: time interval of standard

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_1	107.0640 ns	0.0147 ns	infinity				
t_2	101.8220 ns	0.0147 ns	infinity				
$\delta_{StartStop}$	0.0 ns	$8.66\cdot10^{-3}$ ns	infinity	rectangular	1.0	$8.7\cdot10^{-3}$ ns	0.5 %
δ_{SR620}	0.0 ns	0.118 ns	100	normal	1.0	0.12 ns	98.0 %
t_{1m}	107.06400 ns	$1.10\cdot10^{-3}$ ns	99	normal	0.50	$550\cdot10^{-6}$ ns	0.0 %
δ_{1LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{1res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
$\delta_{TriggerLevelStart}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
$\delta_{TriggerLevelStop}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
t_{2m}	101.82200 ns	$1.10\cdot10^{-3}$ ns	99	normal	0.50	$550\cdot10^{-6}$ ns	0.0 %
δ_{2LSD}	0.0 ns	$2.31\cdot10^{-3}$ ns	infinity	rectangular	0.50	$1.2\cdot10^{-3}$ ns	0.0 %
δ_{2res}	0.0 ns	$2.50\cdot10^{-3}$ ns	99				
δ_{Jitter}	0.0 ns	$2.50\cdot10^{-3}$ ns	99	normal	1.0	$2.5\cdot10^{-3}$ ns	0.0 %
δ_{ref}	0.0	$1.00\cdot10^{-12}$	99	normal	100	$100\cdot10^{-12}$ ns	0.0 %
$\delta_{TriggerJitterStart}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
$\delta_{TiggerJitterStop}$	0.0 ns	$50.0\cdot10^{-6}$ ns	99	normal	1.0	$50\cdot10^{-6}$ ns	0.0 %
t_I	104.443 ns	0.119 ns	100				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
t_I	104.44 ns	0.24 ns	2.00	95% (normal)

Time Interval Measurements

Author: Anton Niessner

Measurements of 7 time intervals of two different travelling standards (Time Interval Generator, InLambda Standards) for EURAMET Supplementary Comparison EURAMET.TF-S1.

The measurements were carried out with a SR620 counter. For all measurements cables with diffferent length were connected to START and STOP of the counter and two interchanged measurements were done to cancel out the cable delay influence.

Measurement budget for InLambda 300 ns standard.

InLambda Standard

Model Equation:

$t_I=(t_1+t_2)/2+\delta_{StartStop}+\delta_{SR620}$;

$t_1=t_{1m}+\delta_{1LSD}+\delta_{1res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop}$;

$t_2=t_{2m}+\delta_{2LSD}+\delta_{2res}+\delta_{TriggerLevelStart}+\delta_{TriggerLevelStop}$;

$\delta_{1res}=\delta_{Jitter}+t_{1m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop}$;

$\delta_{2res}=\delta_{Jitter}+t_{2m}*\delta_{ref}+\delta_{TriggerJitterStart}+\delta_{TiggerJitterStop}$;

List of Quantities:

Quantity	Unit	Definition
t_I	ns	time interval of standard
t_1	ns	time interval with shorter cable on START
t_2	ns	time interval with shorter cable on STOP
$\delta_{StartStop}$	ns	auxiliary quantity used to model difference of START/STOP change (short or long time interval)
δ_{SR620}	ns	auxiliary quantity used to model further SR620 uncertainty
t_{1m}	ns	measurement with shorter cable on START
δ_{1LSD}	ns	auxiliary quantity used to model least significant digit for t_1
δ_{1res}	ns	auxiliary quantity used to model measurement resolution of t_1
$\delta_{TriggerLevelStart}$	ns	auxiliary quantity used to model start trigger level timing uncertainty
$\delta_{TriggerLevelStop}$	ns	auxiliary quantity used to model stop trigger level timing uncertainty
t_{2m}	ns	measurement with shorter cable on STOP
δ_{2LSD}	ns	auxiliary quantity used to model least significant digit for t_2
δ_{2res}	ns	auxiliary quantity used to model measurement resolution of t_2
δ_{Jitter}	ns	auxiliary quantity used to model single-shot resolution of SR620

Quantity	Unit	Definition
δ_{ref}		auxiliary quantity used to model frequency stability
$\delta_{TriggerJitterStart}$	ns	auxiliary quantity used to model start trigger timing jitter
$\delta_{TiggerJitterStop}$	ns	auxiliary quantity used to model stop trigger timing jitter

$\delta_{StartStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.026 ns

δ_{SR620}: Type B normal distribution
Value: 0 ns
Expanded Uncertainty: 0.236
Coverage Factor: 2

t_{1m}: Type A summarized
Mean: 309.830 ns
Experimental Standard Deviation: 0.011 ns
Number of observations: 100

δ_{1LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

$\delta_{TriggerLevelStart}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

$\delta_{TriggerLevelStop}$: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.0175 ns

(15 mV + 0,005*$U_{Trigger}$)/Input Slew Rate

t_{2m}: Type A summarized
Mean: 304.613 ns
Experimental Standard Deviation: 0.011 ns
Number of observations: 100

δ_{2LSD}: Type B rectangular distribution
Value: 0 ns
Halfwidth of Limits: 0.004 ns

δ_{Jitter}: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.025 ns
Number of observations: 100

δ_{ref}: Type A summarized
Mean: 0
Experimental Standard Deviation: $1 \cdot 10^{-11}$
Number of observations: 100

$\delta_{TriggerJitterStart}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

$\delta_{TiggerJitterStop}$: Type A summarized
Mean: 0 ns
Experimental Standard Deviation: 0.0005 ns
Number of observations: 100

Signal Noise/Input Slew Rate

Interim Results:

Quantity	Value	Standard Uncertainty	Degrees of Freedom
t_1	309.8300 ns	0.0147 ns	infinity
t_2	304.6130 ns	0.0147 ns	infinity
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99

Uncertainty Budgets:

t_I: time interval of standard

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_1	309.8300 ns	0.0147 ns	infinity				
t_2	304.6130 ns	0.0147 ns	infinity				
$\delta_{StartStop}$	0.0 ns	0.0150 ns	infinity	rectangular	1.0	0.015 ns	1.6 %
δ_{SR620}	0.0 ns	0.118 ns	100	normal	1.0	0.12 ns	96.9 %
t_{1m}	309.83000 ns	$1.10 \cdot 10^{-3}$ ns	99	normal	0.50	$550 \cdot 10^{-6}$ ns	0.0 %
δ_{1LSD}	0.0 ns	$2.31 \cdot 10^{-3}$ ns	infinity	rectangular	0.50	$1.2 \cdot 10^{-3}$ ns	0.0 %
δ_{1res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99				
$\delta_{TriggerLevelStart}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
$\delta_{TriggerLevelStop}$	0.0 ns	0.0101 ns	infinity	rectangular	1.0	0.010 ns	0.7 %
t_{2m}	304.61300 ns	$1.10 \cdot 10^{-3}$ ns	99	normal	0.50	$550 \cdot 10^{-6}$ ns	0.0 %
δ_{2LSD}	0.0 ns	$2.31 \cdot 10^{-3}$ ns	infinity	rectangular	0.50	$1.2 \cdot 10^{-3}$ ns	0.0 %
δ_{2res}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99				
δ_{Jitter}	0.0 ns	$2.50 \cdot 10^{-3}$ ns	99	normal	1.0	$2.5 \cdot 10^{-3}$ ns	0.0 %
δ_{ref}	0.0	$1.00 \cdot 10^{-12}$	99	normal	310	$310 \cdot 10^{-12}$ ns	0.0 %
$\delta_{TriggerJitterStart}$	0.0 ns	$50.0 \cdot 10^{-6}$ ns	99	normal	1.0	$50 \cdot 10^{-6}$ ns	0.0 %
$\delta_{TiggerJitterStop}$	0.0 ns	$50.0 \cdot 10^{-6}$ ns	99	normal	1.0	$50 \cdot 10^{-6}$ ns	0.0 %
t_I	307.222 ns	0.120 ns	110				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
t_I	307.22 ns	0.24 ns	2.00	95% (normal)

Appendix P

ILNAS report

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Measurement report

Time-Frequency laboratory

Measurement Instrument

Designation : **Comparison EURAMET.TF-S1.**

This report includes 17 pages

Date of issue: **06/11/2020**

Signature :

Franck, Lionel, Marcel Calabraise

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1) Reference

- ISO/IEC 17025:2017: "General requirements for the competence of testing and calibration laboratories"
- JCGM 100:2008, "Evaluation of measurement data – Guide to the expression of uncertainty in measurement"
- Keysight Technologies, 53200A Series, RF/Universal Frequency, Counter/Timers Datasheet, 5990-6283EN, 2017
- G D Rovera, M Siccardi, S Römisch and M Abgrall
  Time delay measurement: estimation of the error budget, Metrologia 2019 56 035004

2) Calibration method

The time interval measurements were made using a time interval counter (TIC) driven by the reference UTC(LUX). In order to reduce differential channel delays of the TIC and differential delays of the used connecting cables between the delay generators and the TIC, each measurements was performed in two steps like in figure 1. The measurement is repeated 100 times to obtain T_1 and T_2.

The reference time intervals are defined between appearing rising slopes of the pulses at the outer ends of the dielectric of the SMA connectors (TIGen) / BNC connectors (for InLambda standards) at the start and stop outputs at the same trigger. The trigger levels are fixed at 0,5 V in each channel of the TIC.

Step 1: T_1

Step 2: T_2

Figure 1: Measurement method (DUT = device under test)

One T_x consists of 10 measurements of T_1 and T_2. T_x is calculated using the following formula:

$$T_{x_i} = \frac{T_1 - T_2}{2}$$

$$T_x = \frac{1}{10} \sum_{k=1}^{10} T_{x_i}$$

With:
T_x: The time interval of device under test.
T_1: First time interval measurement between start and stop signal (step 1).
T_2: Second time interval measurement between start and stop signal (step 2).

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All measurements were performed in an air-conditioned room and after the initial period for stabilizing the temperature of the different standards after transport.

3) DUT configuration

a. TIGen

For TIGen, we use the input signal 10 MHz from UTC(LUX) as described in §5.a. We add a 6 dB attenuator to respect the specification ((0,5 ÷ 2) V_{pp} / 50 Ω).

Figure 2: TIGen

b. InLambda

InLambda standards require external input pulses and must be used in pairs (in double configuration). The external pulse is the PPS from UTC(LUX). We add a 3 dB attenuator to respect the specification (high level – (1,75 ÷ 2,25) V_{pp} / 50 Ω).

Figure 3: InLambda in double configuration

4) Traceability

The traceability is given by participation in the “key comparison” CCTF-K001.UTC for the Time Frequency, published monthly by the BIPM in the KCDB in accordance with “WGMRA Guideline 9 - CCTF criteria for obtaining traceability in time and

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frequency". This comparison gives the traceability to the International System of units (SI) by the determination of UTC-UTC(k) and makes it possible to determine the frequency error of our clock.

UTC(LUX) is generated according to the procedure ILNAS-LAB-PT_T&F001.

The time interval counter used is a Keysight 53230A (internal identification: T&F00013) with the 10 MHz from UTC(LUX) as reference.

5) External Reference UTC(LUX)

UTC(LUX) is generated from equipment in the time / frequency lab room. ILNAS has a main channel to produce UTC(LUX) and a backup channel to ensure the robustness of the signal.

ILNAS has two Microsemi 5071A high performance atomic clocks. The 10 MHz signal of the main clock (T&F00001) is connected to the "High Resolution frequency and phase Offset Generator" (HROG) (T&F00008). It brings UTC(LUX) as close as possible to UTC, thanks to a correction applied to the frequency coming from the clock. A correction is applied after each publication of UTCr.

The reference point of UTC(LUX) is defined by the 1 PPS signal of the output 16 of the Timetech pulse distributor (T&F00010), at a trigger level of 1 V.

a. 10 MHz

The 10 MHz of UTC(LUX) has an amplitude of 2,8 V_{pp}. In order to respect the input specification of TIGen, we add a 6 dB attenuator. Therefore, the 10 MHz has an amplitude of 1,4 V_{pp}.

b. 1 PPS

The 1 PPS has a rise time of 350 ps and is given by the specification of the HROG (T&F00008). The low level is 0 V and the high level is 2,5 V at 50 Ω. To respect the input specification of the InLambda, we add a 3 dB attenuator. The High level with the attenuator is 1,9 V.

6) Measurement Model of uncertainty

$$T_x = \frac{1}{2}\left(T_1 + \partial_{Quant} + \partial_{Linearity} + \partial_{Syst} + \partial_{Trigger} + \partial_{Imp} + \partial_{Band} + \partial_{Cable} + \partial_{Timebase} + \partial_{Standard}\right) - \frac{1}{2}\left(T_2 + \partial_{Quant} + \partial_{Linearity} + \partial_{Syst} + \partial_{Trigger} + \partial_{Imp} + \partial_{Band} + \partial_{Cable} + \partial_{Timebase} + \partial_{Standard}\right)$$

With:
T_x: The time interval of device under test.
T_1: First time interval measurement between start and stop signal (step 1).
T_2: Second time interval measurement between start and stop signal (step 2).
∂_{Quant} : Correction due to the quantization error of the TIC.
$\partial_{Linearity}$: Correction due to the linearity error of the TIC.
∂_{Syst} : Correction due to the systematic error of the TIC.
$\partial_{Trigger}$: Correction due to trigger jitter and level timing trigger error.
∂_{Imp} : Correction due to impedance mismatch.
∂_{Band} : Correction due to bandwidth filter.
∂_{Cable} : Correction due to residual delay of cable.
$\partial_{Timebase}$: Correction due to the timebase error from UTC(LUX).
$\partial_{Standard}$: Correction due to the standard.

We do not apply any correction, but consider all these parameters in the uncertainty budget.
These parameters are assumed to be all uncorrelated.

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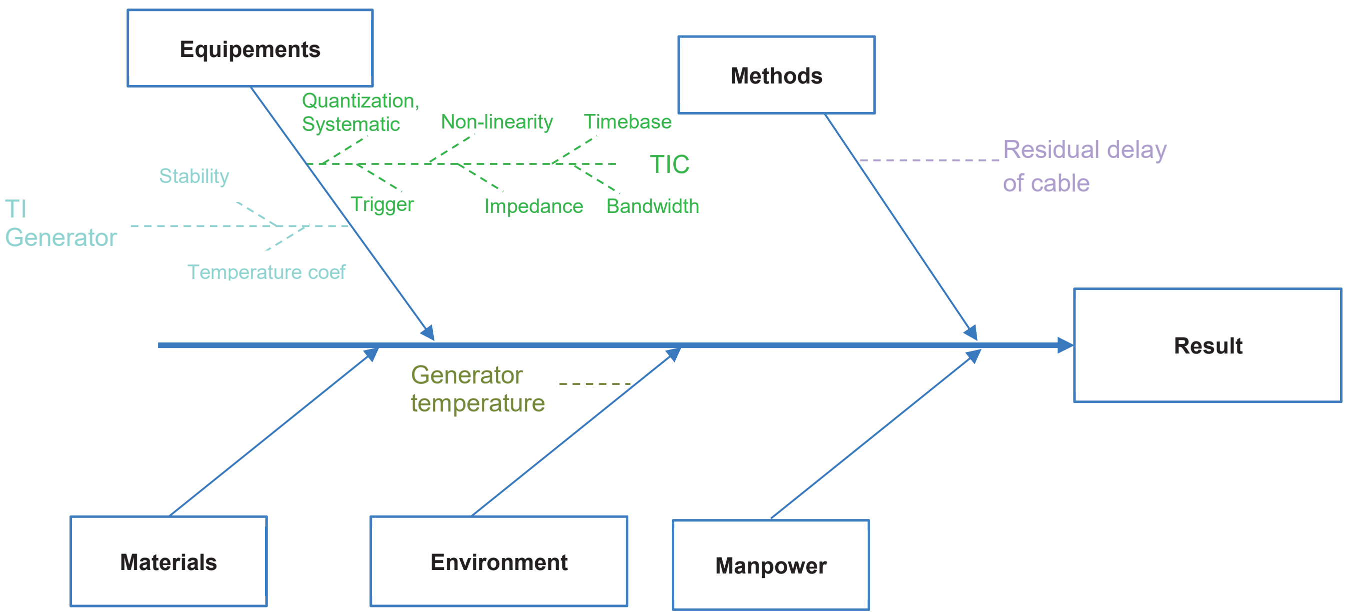
7) Analysis of the measurement process



8) Measurement uncertainty

For the time interval measurement from 1 ns to 1000 s, ILNAS provides an uncertainty of 2 ns.
In this comparison, we reduce the uncertainty of the measure because of the fact that the start and stop pulse have identical shapes and fast rise time.

$$u_{T_x}^2 = u_A^2 + u_B^2$$

With:

$$u_A = \sqrt{C_1^2 \times u_{repet_{T_1}}^2 + C_2^2 \times u_{repet_{T_2}}^2 + C_3^2 \times u_{repet_{T_x}}^2}$$

$$u_B = \sqrt{C^2 \times \left(u_{Quant}^2 + u_{Linearity}^2 + u_{Syst}^2 + u_{Trigger}^2 + u_{Imp}^2 + u_{Band}^2 + u_{Cable}^2 + u_{Timebase}^2 + u_{Standard}^2\right)}$$

where $C = 1$, $C_1 = 0{,}5$, $C_2 = -0{,}5$ and $C_3 = 1$.

All uncertainties are describes below.

a. Type B evaluation of the standard uncertainty

i. TIGen uncertainty

$$u_{Standard} = \sqrt{u_{reference}^2 + u_{temperature}^2 + u_{Stability\ TIGen}^2}$$

1. TIGen stability

In reference condition, the specification in the technical protocol gives an instability, repeatability of the generator of 3 ps. We consider this uncertainty like a type B with a normal distribution.

$$u_{Stability\ TIGen} = 3\ ps$$

The stability effects of the generator may be assumed to be reliable to 5 percent, and thus the degree of freedom, given by the following equation from GUM (this equation is used for each type B parameters), is estimated by:

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$$\upsilon_i \approx \frac{1}{2}\left[\frac{\Delta u(x_i)}{u(x_i)}\right]^{-2}$$

So for this parameter, we have a degree of freedom of 200.

2. Temperature effect on TIGen

In reference condition, the specification in the technical protocol says that no temperature influence was observed in 22 ± 5°C. We consider an uncertainty of 1 ps for this parameter.

$$u_{temperature} = 1\,ps$$

The temperature effects of the generator may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

3. Reference input effect

The generator uses the reference signal from UTC(LUX). We retain an uncertainty of 1 ps.

$$u_{reference} = 1\,ps$$

The input reference effects of the generator may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

ii. InLambda uncertainty

$$u_{Standard} = \sqrt{u_{reference}^2 + u_{temperature}^2 + u_{Stability\ InLambda}^2}$$

1. Stability uncertainty of InLambda

In reference condition, the specification in the technical protocol gives an instability, repeatability of the generator of 10 ps. We consider this uncertainty like a type B with a normal distribution.

$$u_{Stability\ InLambda} = 10\,ps$$

The stability effects of the generator may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

2. Temperature uncertainty

- Inλ20: in the specification sheet, we have a coefficient of (0,6 ± 0,2) ps / K
- Inλ100: in the specification sheet, we have a coefficient of (1,4 ± 0,2) ps / K
- Inλ300: in the specification sheet, we have a coefficient of (2,5 ± 0,2) ps / K

The lab is regulated at 23 ± 3 °C. We decided not to apply this correction on the measurement. Assuming a U-shaped distribution, we have respectively a temperature uncertainty of:

- **Inλ20:**

$$u_{temperature} = \frac{0{,}6\ \times 3}{\sqrt{2}} \approx 1\,ps$$

- **Inλ100:**

$$u_{temperature} = \frac{1{,}4\ \times 3}{\sqrt{2}} \approx 4\,ps$$

- **Inλ300:**

$$u_{temperature} = \frac{2{,}5\ \times 3}{\sqrt{2}} \approx 6\,ps$$

The stability effects of the generator may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

3. Reference input effect

The generator uses the reference signal from UTC(LUX). We retain an uncertainty of 1 ps.

$$u_{reference} = 1\,ps$$

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The input reference effects of the generator may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

iii. Quantization uncertainty

We estimate the quantization error experimentally by measuring a constant delay with noise. The quantization error effect can be seen in the graph below. The quantization levels are spaced by no more than 10 ps.

The uncertainty associated with the quantization is a type B uncertainty that in an ideal case can be estimated as $\partial t/2\sqrt{3}$, where ∂t is the quantization error. We retain a value of 3 ps.

$$u_{Quant} = \frac{10}{2 \times \sqrt{3}} \approx 3\ ps$$

The quantization effects of the generator may be assumed to be reliable to 10 percent, and thus the degree of freedom is 50.

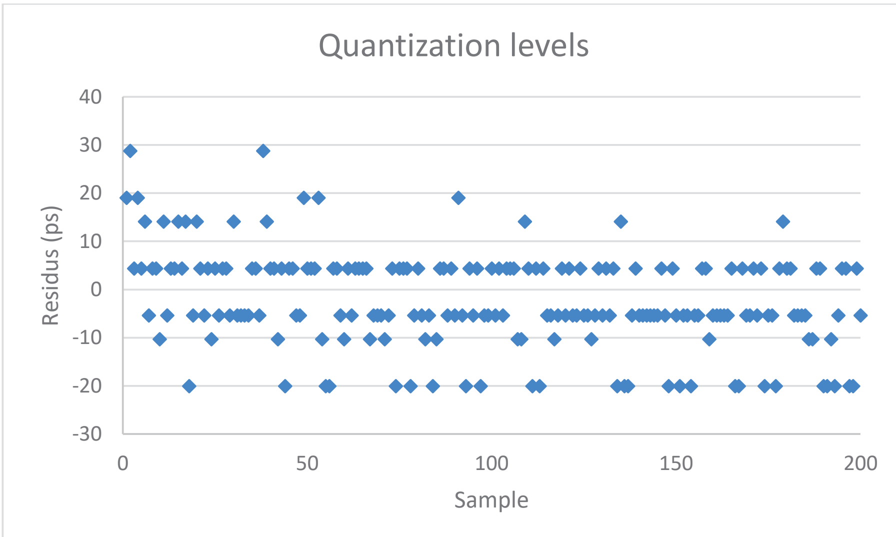

Figure 4: Measurement of a constant noisy delay

iv. Non-linearity uncertainty

This error is due to the interpolator in the TIC. The non-linearity of the interpolator is evaluated experimentally. We use an auxiliary offset generator that produces a series of pulses sent to the stop of the TIC with a known rate offset with respect to the time series going directly to the start input of the TIC. We make this for a short delay and long delay (in graphs below).

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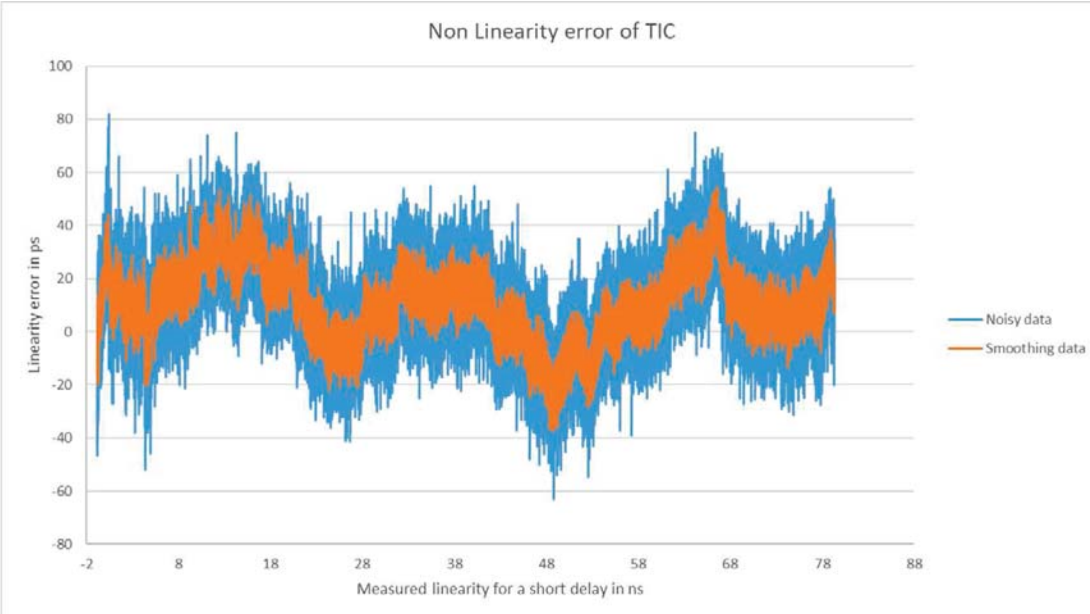

Figure 5: Non-linearity for a short delay like T_1

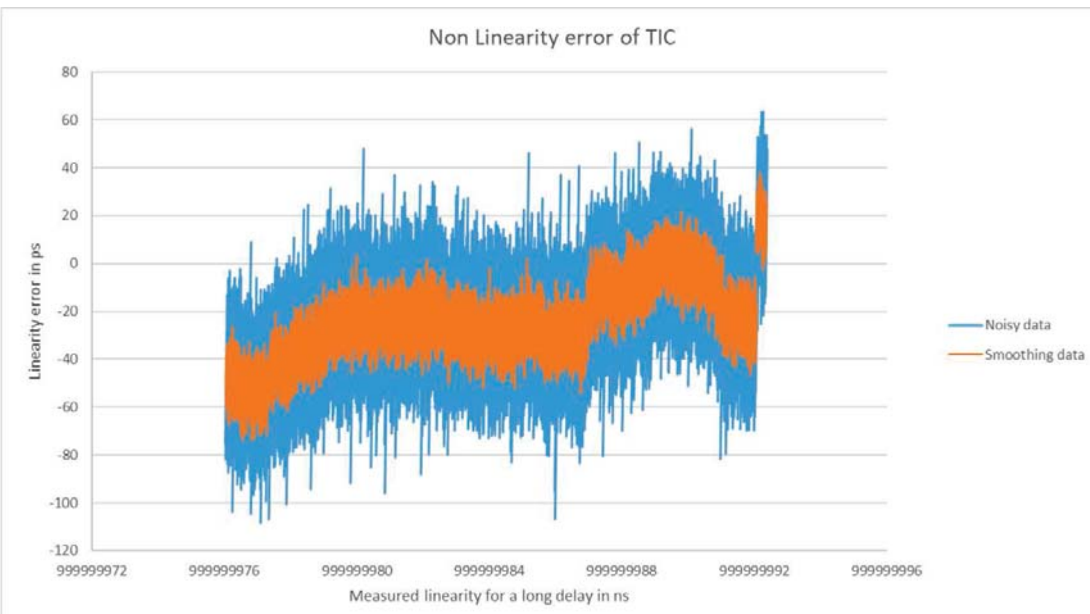

Figure 6: Non-linearity for a long delay like T_2

By smoothing out the noise with a moving average, we can deduce that the residual non-linearity is at most 80 ps. The standard systematic uncertainty is:

$$u_{Linearity} = \frac{80}{\sqrt{3}} \approx 46\ ps$$

The linearity effects of the TIC may be assumed to be reliable to 20 percent, and thus the degree of freedom is 12.

v. Trigger uncertainty

In the constructor specifications, we have a trigger level setting error of ± (0,2% of setting + 0,1% of range). In our application, we have the trigger level fixed at 0,5 V. We obtain an error of 6 mV. For TIGen, we know that we have a rise time (20-80%) < 0,5 ns for a signal of 2,25 V and for InLambda we have a the same rise time for a signal of 0 – 2 V. We consider a rectangular distribution for this uncertainty.

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We obtain for start trigger:

For TIGen :

$$u_{Trigger\ level_{start}} = \frac{\text{Trigger error}}{SR \times \sqrt{3}} = \frac{\text{Trigger error}}{\Delta_{V\,20-80}/_{t_{20-80}} \times \sqrt{3}} = \frac{0{,}006}{1{,}35/_{0{,}5}\sqrt{3}} \approx \frac{3}{\sqrt{3}}\ ps$$

For InLambda :

$$u_{Trigger\ level_{start}} = \frac{\text{Trigger error}}{SR \times \sqrt{3}} = \frac{\text{Trigger error}}{\Delta_{V\,20-80}/_{t_{20-80}} \times \sqrt{3}} = \frac{0{,}006}{1{,}2/_{0{,}5}\sqrt{3}} \approx \frac{3}{\sqrt{3}}\ ps$$

So we have an error due to the trigger of 3 ps for the start and of 3 ps for the stop trigger level.

$$u_{Trigger\ level} = \sqrt{2} \times \frac{3}{\sqrt{3}}\ ps$$

We have also an uncertainty due to the start and stop trigger jitter:

$$u_{Trigger\ jitter} = \sqrt{2} \times \frac{\sqrt{internal\ noise^2 + external\ noise\ signal^2}}{SR}$$

We assume that the trigger external noise is less than 30 mV.
For TIGen:

$$u_{Trigger\ jitter} = \sqrt{2} \times \frac{\sqrt{500\ \mu V^2 + 30\ mV^2}}{2{,}7 \times 10^9\ ^V/_{ns}}$$

For InLambda:

$$u_{Trigger\ jitter} = \sqrt{2} \times \frac{\sqrt{500\ \mu V^2 + 30\ mV^2}}{2{,}4 \times 10^9\ ^V/_{ns}}$$

The trigger uncertainty is:

$$u_{Trigger} = \sqrt{u^2_{Trigger\ jitter} + u^2_{Trigger\ level}}$$

For TIGen:

$$u_{Trigger} \approx 16\ ps$$

For InLambda:

$$u_{Trigger} \approx 18\ ps$$

The trigger level effects of the TIC may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

vi. Impedance mismatch uncertainty

For the measurement, the load impedance should to be at 50 Ω. The constructor specification indicates 50 Ω ± 1,5% in parallel with 25 pF. With the method used for the measurement, we consider only a residual uncertainty. We consider the value from the publication “Time delay measurements: estimation of the error budget, Metrologia 56 035004”. In section 4.5, we take the worst case for slow rising pulses because the rising pulse signal measured is between the two cases in the publication. This gives a delay of 70 ps. Due to the method we retain 5 % of this uncertainty.

$$u_{Imp} = 70\ \times 0{,}05 \approx 4\ ps$$

The impedance mismatch effects of the generator may be assumed to be reliable to 10 percent, and thus the degree of freedom is 50.

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vii. Input filter uncertainty

In the constructor specifications, we have a bandwidth of 350 MHz. This filter introduces a delay in time measurement and it reduces the slope of the signal. So it is increases the trigger error impact. We measured two PPS signals with a rise time of 350 ps specified by the constructor and made some measurements at different trigger levels. We obtain:

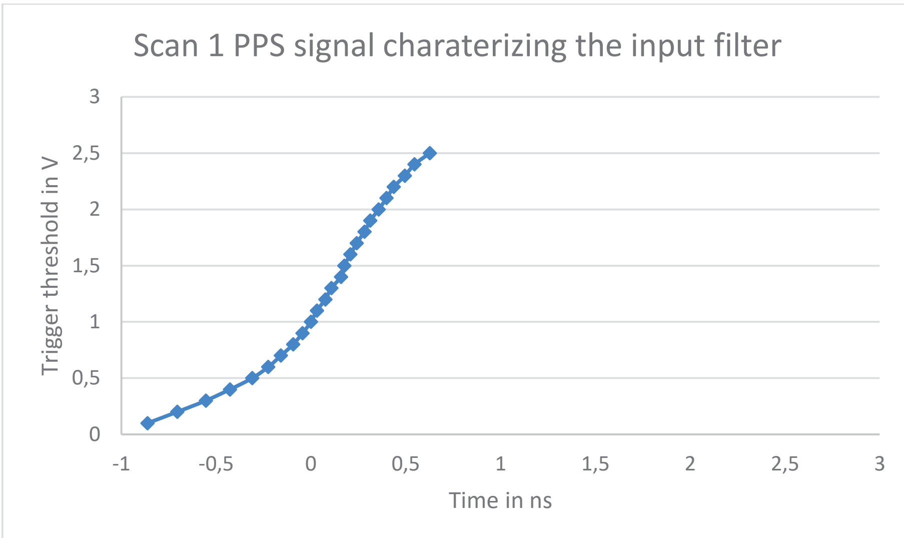

Figure 7: Scan of a fast 1 PPS signal

We consider the value from the publication "Time delay measurements: estimation of the error budget, Metrologia 56 035004". In section 4.6, we retain a systematic delay of 400 ps. Due to the measurement method we considering a residual uncertainty of 5% of this delay. We obtain:

$$u_{Band} = 400 \times 0{,}05 = 20\ ps$$

The input filter effects of the TIC may be assumed to be reliable to 20 percent, and thus the degree of freedom is 12.

viii. Cable delay uncertainty

With this measurement method (step 1 and step 2), we consider that the effect of the short coaxial cables are compensated. We retain 1 ps for the uncertainty calculus.

$$u_{Cable} = 1\ ps$$

The Cable delay effects may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

ix. TIC systematic uncertainty

In the constructor specifications, we have a systematic uncertainty between two point measurements. It is given by 100 ps with a confidence level of 95 % (k=2).

$$u_{Syst} = 50\ ps$$

The systematic uncertainty may be assumed to be reliable to 25 percent, and thus the degree of freedom is 8.

x. Timebase uncertainty

We started to participate in November 2018 and have the following history. Our history is too recent for the moment, so it is better to increase this error. For safety, we consider a maximal error of $5 \times 10^{-13}\ Hz/Hz$.

We consider a rectangular distribution so we have:

$$u_{Timebase} = \frac{5 \times 10^{-13}}{\sqrt{3}} \times T_x$$

With:
$T_x =$ time interval measured

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The timebase effects may be assumed to be reliable to 5 percent, and thus the degree of freedom is 200.

For the impact of the temperature on the reference, the measurements are made in a temperature-controlled room at 23 ± 3°C. On this same time, we have the data from CCTF-k001.UTC and the frequency error criterion of $5 \times 10^{-13}\ {}^{Hz}/_{Hz}$ is checked. The laboratory meets this criterion. Temperature is a factor that is controlled over this temperature range. This allows the lab to ignore the uncertainty due to temperature.

b. Type A evaluation of the standard uncertainty

The measurements of T_1 and T_2 are repeated 100 times. With these results, we obtain a standard deviation on each measurement. We consider a normal distribution. T_x is obtain by 10 repetitions. For T_1 and T_2 standard deviation, we take the maximum values over the 10 repetitions.

$$u_{repet_{T_1}} = \sigma_{T_1 max}$$

$$u_{repet_{T_2}} = \sigma_{T_2 max}$$

$$u_{repet_{T_x}} = \sigma_{T_x}$$

With:
$\sigma_{T_1 max}$ = Maximum standard deviation of the T_1.
$\sigma_{T_1 max}$ = Maximum standard deviation of the T_2.
σ_{T_x} = Standard deviation of the T_x.

We have for type A uncertainty:

$$u_A = \sqrt{C_1^2 \times u_{repet_{T_1}}^2 + C_2^2 \times u_{repet_{T_2}}^2 + C_3^2 \times u_{repet_{T_x}}^2}$$

$$u_A = \sqrt{0{,}5^2 \times u_{repet_{T_1}}^2 + (-0{,}5)^2 \times u_{repet_{T_2}}^2 + 1 \times u_{repet_{T_x}}^2}$$

We obtained the results from 100 repeated observations, thus the degree of freedom is 100-1=99 (GUM) for $u_{repet_{T_1}}$ and $u_{repet_{T_2}}$ and 9 for $u_{repet_{T_x}}$.

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c. Summary of uncertainties

i. Example for measurement TIGen Dn7

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 $u(x_i)$ (ns)	Uncertainty contribution $c_i \cdot u(x_i)$ (ns)	Degrees of freedom v_i
T_1		0,011	Normal=1	A	0,50	0,011	0,005	99
T_2		0,013	Normal=1	A	-0,50	0,013	-0,006	99
$\frac{T_1 - T_2}{2}$	1508,953	0,001	Normal=1	A	1,00	0,001	0,001	9
Quantification of the TIC		0,003	Rectangular	B	1	0,003	0,003	50
Non linearity effects		0,046	Rectangular	B	1	0,046	0,046	12
Uncertainty systematic (specification)		0,050	Normal=2	B	1	0,050	0,050	8
Trigger		0,016	Rectangular	B	1	0,016	0,016	200
Impedance mismatch effects		0,004	/	B	1	0,004	0,004	50
Bandwidth 350 MHz effects		0,020	/	B	1	0,020	0,020	12
Residual delay of cable		0,001	/	B	1	0,001	0,001	200
Timebase effects		0,001	/	B	1	0,001	0,001	200
Reference input standard effects		0,001	/	B	1	0,001	0,001	200
Temperature effects standard		0,001	U-Shaped	B	1	0,001	0,001	200
Standard stability		0,003	Normal =1	B	1	0,003	0,003	200

Combined standard uncertainty:	u_c	**0,073**
Effective degrees of freedom:	v_{eff}	**24**
Expanded uncertainty (p ≈ 95%): (k=2,09)	U_c	**0,16**
	T_x	**1508,95**

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ii. Example for measurement InLambda100

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 $u(x_i)$ (ns)	Uncertainty contribution $c_i \cdot u(x_i)$ (ns)	Degrees of freedom v_i
T_1		0,011	Normal=1	A	0,50	0,011	0,006	99
T_2		0,016	Normal=1	A	-0,50	0,016	-0,008	99
$\frac{T_1 - T_2}{2}$	104,479	0,001	Normal=1	A	1,00	0,001	0,001	9
Quantification of the TIC		0,003	Rectangular	B	1	0,003	0,003	50
Non linearity effects		0,046	Rectangular	B	1	0,046	0,046	12
Uncertainty systematic (specification)		0,050	Normal=2	B	1	0,050	0,050	8
Trigger		0,016	Rectangular	B	1	0,016	0,016	200
Impedance mismatch effects		0,004	/	B	1	0,004	0,004	50
Bandwidth 350 MHz effects		0,020	/	B	1	0,020	0,020	12
Residual delay of cable		0,001	/	B	1	0,001	0,001	200
Timebase effects		0,001	/	B	1	0,001	0,001	200
Reference input standard effects		0,001	/	B	1	0,001	0,001	200
Temperature effects standard		0,004	U-Shaped	B	1	0,004	0,004	200
Standard stability		0,010	Normal =1	B	1	0,010	0,010	200
			Combined standard uncertainty:		u_c	0,074		
			Effective degrees of freedom:		v_{eff}	25		
			Expanded uncertainty (p ≈ 95%): (k=2,06)		U_c	0,16		
					T_x	104,48		

9) Measurement results

Measurement location: 22 Avenue des Hauts-Fourneaux, L-4362 Esch-Sur-Alzette - Luxembourg.

Realized by: Franck Calabraise

Measurement Date: 02/11/2020 to 05/11/2020

InLambda 20 could not be measured.

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a. TIGen standard

i. Conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source	**Cs + µphasestepper**	10 MHz ± 1 Hz	**Yes**
Amplitude (at 50 Ω)	**1,4 V**	within (0,5 ÷ 2) V_{pp}	**Yes**

Ambient temperature during measurements			Unit of measure	Required reference conditions	Meet requirements? yes / no
23	±	**3**	°C	within (22 ± 4) °C	**Yes**

Ambient humidity during measurements			Unit of measure	Required reference conditions	Meet requirements? yes / no
50	±	**20**	%	within (50 ± 30) %	**Yes**

The base equipment used for time interval measurements	
The type / brand of time interval counter	**Keysight – 53230A T&F00013**
Applied trigger level (50 Ω) (Required: 0,5 V)	**0,5 V**
Standard uncertainty	**0,073 ns**

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ii. Measurement results with uncertainty

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p≈95 %) (in ns)			Unit of measure
"dn0"	22,64	±	0,16	ns
"dn3"	250,00	±	0,16	ns
"dn7"	1508,95	±	0,16	ns
"dn126"	12039,48	±	0,16	ns

b. InLambda standards

i. Conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, …)	**Cs + µphasestepper**		
1 pps (yes/no)	**Yes**		
Frequency	**1 Hz**	≤ 200 Hz	**Yes**
Low level	**0 V**	0 V	**Yes**
High level (at 50 Ω)	**1,9 V**	(1,75 ÷ 2,25) V	**Yes**
Rise time (20% to 80 %)	**350 ps**	< 10 ns	**Yes**
Duty cycle	**< 0,1 %**	≤ 50 %	**Yes**

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Pulse width	**25,6 µs**	to avoid the pulse widths close (<± 10 ns) to the measured time intervals	**Yes**

The base equipment used for time interval measurements	
The type / brand of time interval counter	**Keysight – 53230A T&F00013**
Applied trigger level (50 Ω) (Required: 0,5 V)	**0,5 V**
Standard uncertainty	**0,073 ns**

Application of a double configuration

DUT - Device Under Test	Auxiliary used device	Meet requirements? yes / no
InLambda 100	InLambda 300	Yes
InLambda 300	InLambda 100	Yes
X	X	X

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ii. Measurement results with uncertainty

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p≈95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately - including expanded uncertainty, 95 %)			Unit of measure
Inλ 20	X	±	X	ns	X	±	X	°C
Inλ 100	104,48	±	0,16	ns	23,0	±	0,6	°C
Inλ 300	307,28	±	0,16	ns	23,0	±	0,6	°C

End of report

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Appendix Q

NPL report

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: NPL Country: UK

Average date of measurements: 4-7 December 2020

Remarks: The InLambda 20 ns standard was found to be faulty and was not measured.

….

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	AHM	10 MHz ± 1 Hz	Yes
Amplitude (at 50 Ω)	2.0 Vpp	within (0,5 ÷ 2) $V_{p\text{-}p}$	Yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.0	±	1.0	°C	within (22 ± 4) °C	Yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
45	±	20	%	within (50 ± 30) %	Yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Stanford SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0.25 ns

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22.75	±	0.50	ns
"dn3"	250.10	±	0.50	ns
"dn7"	1509.03	±	0.50	ns
"dn126"	12039.57	±	0.50	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	AHM		
1 pps (yes / no)	Yes		
Frequency	1 Hz	≤ 200 Hz	Yes
Low level	0 V	0 V	Yes
High level (at 50 Ω)	2.24 V	(1,75 ÷ 2,25) V	Yes
Rise time (20% to 80 %)	2.3 ns	< 10 ns	Yes
Duty cycle	<0.001%	≤ 50 %	Yes
Pulse width	25.8 µs	to avoid the pulse widths close **(<± 10 ns)** to the measured time intervals	Yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	n/a	Inλ 100 or Inλ 300	n/a
Inλ 100	Inλ 300	Inλ 20 or Inλ 300	Yes
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	Yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.0	±	1.0	°C	within (22 ± 4) °C	Yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
45	±	20	%	within (50 ± 30) %	Yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Stanford SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0.250

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	n/a	±	n/a	ns	n/a	±	n/a	°C
Inλ 100	104.58	±	0.50	ns	22.4	±	1.4	°C
Inλ 300	307.35	±	0.50	ns	22.4	±	1.4	°C

Peter Whibberley (Name)

08/03/2022 (Date)

Annex 7. Minimum contents for the measurement report

- Identification of the participating laboratory
- Description of the calibration method
- Description of the calibration set-up and equipment
- Traceability chart
- Used relationship/ equation for obtaining estimates of results and uncertainty budget,
- Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects
- Identification and description of the source 10 MHz reference frequency for TIGen standard,
- Description of the used input pulse signals for InLambda standards (low level, high level (amplitude), frequency, pulse width, rise time (20% to 80 %), duty cycle),
- Ambient conditions of measurements (the temperature and the relative humidity) – the temperature for every InLambda standard separately,
- Average date of performing measurements,
- Date and signature.

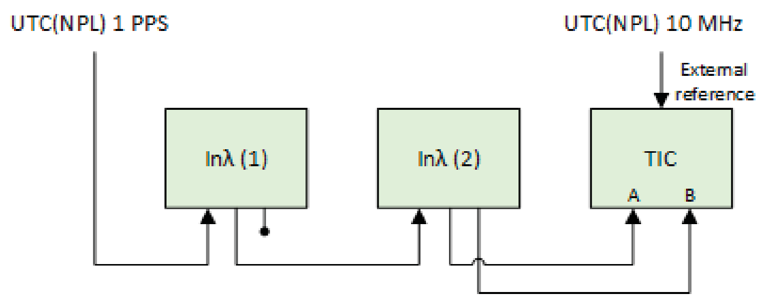
Measurement Report for NPL

National Physical Laboratory (NPL)
Teddington
Middlesex TW11 0LW
UK

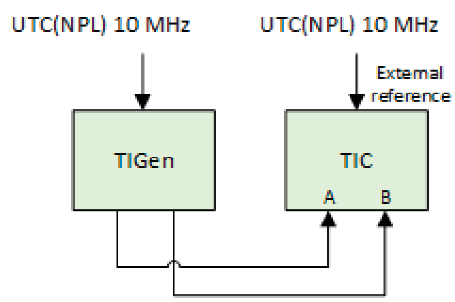
Measurement Setup

The diagrams below show schematically the measurement setup used at NPL.

InLambda Standards



TIGen Standard



Measurement Procedure

At the time of the measurements, UTC(NPL) was based directly on the output signals from a Datum MHM-2010 active hydrogen maser with NPL designation HM2.

The 1 PPS reference signal was generated using a SpectraDynamics PPS-2 pulse generator from a 10 MHz reference signal.

The measurements reported in this Supplementary Comparison (SC) were obtained using a set of 3 Stanford SR620 universal counters (described in this report as time interval counters, TICs).

Each counter was turned on at least 6 hours before the start of the measurements, and the internal Autocal routine was run on each unit before starting to take measurements.

The measurements were performed in the standard time interval measurement configuration, with the two output signals from the delay standard connected to channels A and B of the TIC respectively.

Each counter was provided with a 10 MHz external reference signal derived from UTC(NPL), replacing its internal timebase with one directly traceable to UTC(NPL).

Two pairs of matching test cables were used, all nominally 1 m in length:

Cables 1 and 2: RG316, with SMA connectors. A pair of SMA(f)-BNC(m) adapters was used to connect these cables to the SR620 TIC.

Cables 3 and 4: RG58, with BNC connectors. A pair of SMA(m)-BNC(f) adapters (supplied with the delay standards) was used to connect these cables to the TIGen standard.

Each individual measurement was the mean of 10 readings, as computed by the TIC.

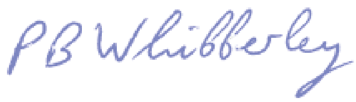
Four measurements were obtained for each combination of delay standard and TIC, using both pairs of cables and interchanging the cables in each pair, as shown in the table.

	Measurement 1	**Measurement 2**	**Measurement 3**	**Measurement 4**
Channel A	Cable 1	Cable 2	Cable 3	Cable 4
Channel B	Cable 2	Cable 1	Cable 4	Cable 3

The combined measurement value for each TIC was computed as the mean of the four individual measurements.

The procedure was repeated 3 times using different SR620 TICs, and the final measurement result for that delay standard was calculated as the mean of the 3 TIC measurement values.

In all other respects the measurements were performed as described in the Technical Protocol for the SC. The measurement and environmental parameters requested for inclusion in the measurement report can be found in Annex 4.



Peter Whibberley 08/03/2022

(Name) (Date)

Appendix R

UME report

Measurements Report of UME
for
TC-TF EURAMET Supplementary Comparison
”Comparison of time interval measurements”
EURAMET Project No:1485

Description of the Measurement

All time interval measurements have been performed by using high speed real time oscilloscope (HSO), (UXR0702A, 70 GHz, 256 GSa/s). TI-Gen, HSO and an external pulse generator (SRS, model DG645) used in the measurements as auxiliary device are trigged by 10 MHz signals distributed by H-maser which is the source of UTC(UME). In the measurement of the inλ standards have been used double configuration as stated in Technical Protocol. The measurement setup has been shown in the Figure 1. In order to measure the ambient temperature and relative humidity during each measurement a digital thermometer has been used.

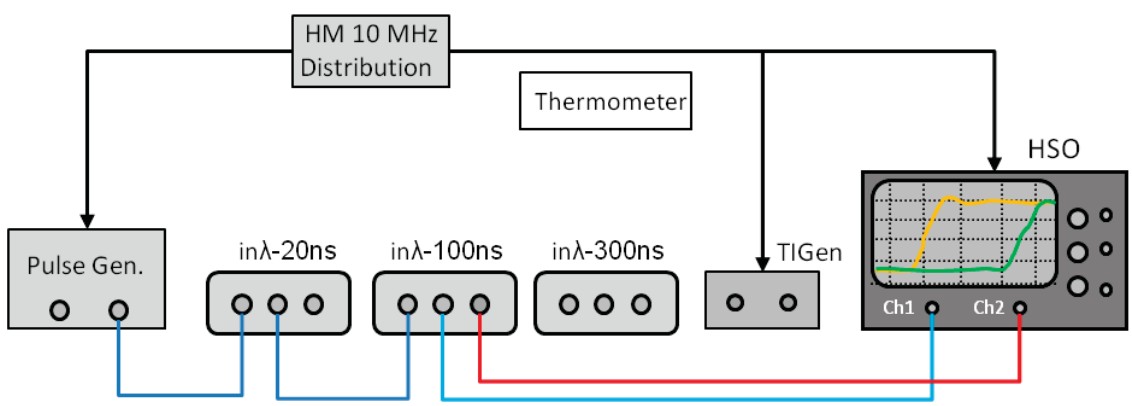


Figure 1. Measurement setup.

Measurement Procedure

In order to reduce differential inter-channel delays of HSO (High Speed Oscilloscope) and differential delays of the used connecting cables between the pulse standards and HSO, each measurement has been performed in two stage as shown in the Figure 2. (a) and (b) with model functions.

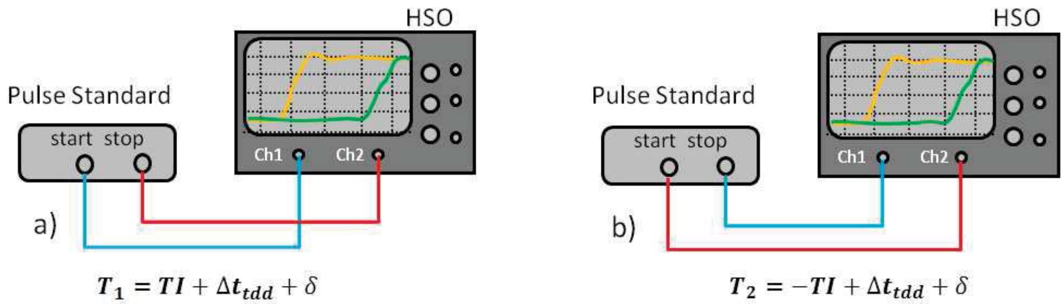


Figure 2. Two stages measurement block diagram: a) First measurement with normal cable configuration. b) Second measurement with cross cable connection. The ends of the start and stop cable-connectors on the pulse standards have been replaced only, while the ends on HSO not change.

Then, the measured time intervals between start and stop pulses will be approximately equal to:

$$TI \approx T_{12} = \frac{(T_1 - T_2)}{2}$$

Measurement Model

$$TI = T_{12} + \delta_{HSO}$$

Where,

$$T_{12} = \frac{(T_1 - T_2)}{2}$$

T_1 and T_2 : The measurement results taken first measurement with normal cable configuration and second one with cross cable configuration respectively, Figure 2.

δ_{HSO} : Total uncertainties from HSO in the time interval measurements. It includes trigger uncertainty, time-base short term stability, intrinsic jitter, inter-channel-skew-drift of HSO and the ambient temperature fluctuation. It has normal distribution.

TI : True time interval measurement between start and stop pulses.

Δt_{tdd} : Total differential delays (inter-channel of HSO and cables). It disappears completely on the calculation process of T_{12}.

Since HSO is triggered by the H-Maser, its long-term stability which is better than 5×10^{-14} has been neglected.

Measurement Results

Measurement model: $TI = T_{12} + \delta_{HSO}$

Table 1. The uncertainty budget of TiGen Measurements

Measurements	T_{12}	u(T_{12})	δ_{HSO}	Uncertainty, (p=95%)	TI	edf
DN0	22.6526 ns	0.00020 ns	0.0019 ns	0.0040 ns	22.6526 ns	1260
DN3	250.0002 ns	0.00025 ns	0.0019 ns	0.0040 ns	250.0002 ns	1505
DN7	1508.9522 ns	0.00029 ns	0.0019 ns	0.0040 ns	1508.9522 ns	1419
DN126	12039.4850 ns	0.00035 ns	0.0019 ns	0.0040 ns	12039.4850 ns	1361

Tablo 2. The uncertainty budget of inλ Measurements

Measurements	T_{12}	u(T_{12})	δ_{HSO}	Uncertainty, (p=95%)	TI	edf
inλ-020ns	24.1870 ns	0.00010 ns	0.0015 ns	0.0030 ns	24.1870 ns	60834
inλ-100ns	104.5025 ns	0.00013 ns	0.0015 ns	0.0030 ns	104.5025 ns	58673
inλ-300ns	307.3302 ns	0.00030 ns	0.0015 ns	0.0030 ns	307.3302 ns	59938

Table 3. The results of TiGen Measurements

Measurements	TI	Uncertainty, (p=95%)
DN0	22.6526 ns	0.0040 ns
DN3	250.0002 ns	0.0040 ns
DN7	1508.9522 ns	0.0040 ns
DN126	12039.4850 ns	0.0040 ns

Tablo 4. The results of inλ Measurements

Measurements	TI	Uncertainty, (p=95%)	Temperature, °C
inλ-020ns	24.1870 ns	0.0030 ns	22.75 ± 0.25
inλ-100ns	104.5025 ns	0.0030 ns	22.75 ± 0.25
inλ-300ns	307.3302 ns	0.0030 ns	22.75 ± 0.25

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: UME Country: TURKEY

Average date of measurements:05-12.01.2021

Remarks:

….

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	HM			10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)	2 V_{p-p}			within (0,5 ÷ 2) V_{p-p}	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.75	±	0.25	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
45	±	15	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Keysight Technologies UXR0702AP Infiniium real-time oscilloscopes
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	≤ 1 ps

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22.6526	±	0.0040	ns
"dn3"	250.0002	±	0.0040	ns
"dn7"	1508.9522	±	0.0040	ns
"dn126"	12039.4850	±	0.0040	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Pulse generator trigged by HM		
1 pps (yes / no)	no		
Frequency	200 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	1.9 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	<300 ps	< 10 ns	yes
Duty cycle	0.02%	≤ 50 %	yes
Pulse width	1 us	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 300	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 300	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 20	Inλ 20 or Inλ 100	yes
Ambient temperature	**Unit of measure**	Required reference	Meet

during measurements				conditions	requirements? yes / no
22.75	±	0.25	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
45	±	15	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Keysight Technologies UXR0702AP Infiniium real-time oscilloscopes
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	≤ 1 ps

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.1870	±	0.0030	ns	22.75	±	0.25	°C
Inλ 100	104.5025	±	0.0030	ns	22.75	±	0.25	°C
Inλ 300	307.3302	±	0.0030	ns	22.75	±	0.25	°C

Mesut Yogun
(Name)

29.01.2021.........
(Date)

Appendix S

BoM report

EURAMET SUPPLEMENTARY COMPARISON:
"Comparison of time interval measurements" EURAMET.TF-S1

Measurement method

The measurement method is direct measurement of the time interval using time interval counter (TIC) with external 10 MHz frequency reference UTC (BoM). The used method is based on three independent measurement of 100 samples time interval between Start and Stop by using a Time Interval Counter CNT 91R with function interpolation (ON).
The reference 1PPS input pulse signals for InLambda standard during the process of calibration is following features:

- Input signal: 0 – 3.6V
- Impedance: 50 Ω
- Coupling : DC
- Gate time: 1 s
- Average repeated per measurement: 100

The reference frequency 10 MHz for TIGen during the process of calibration is following features:

- Frequency: 10 MHz
- Input signal : 0 – 3.6V

Trigger level for each configuration and channel were measured is fixed to 0.5V (at 50 Ω)

Time interval for TIGen and Inlambda T_x is compute from the two subsequent time interval measurement T1 and T2 as:

$$Tx = \frac{T1 + T2}{2}$$

- T1 and T2 are displayed mean value in TIC with the device under test.

Calibration set up and equipment

The laboratory BoM uses 2 principle scheme illustrate In Fig. 1, 1a and Fig. 2, 2a
Scheme for TIGen measurements 20ns, 250ns, 1.5µs, 12µs

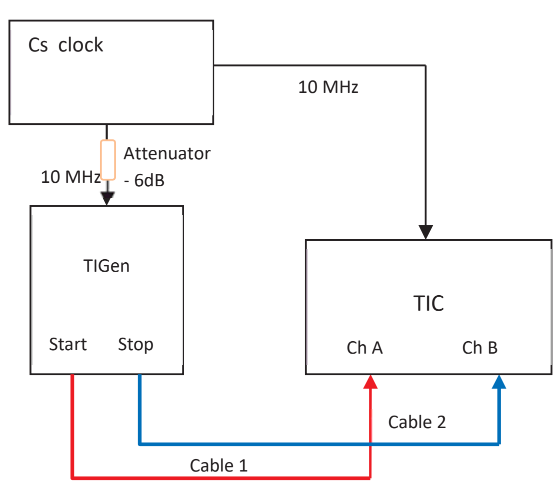


Figure 1 – Scheme of the BoM experimental set up TIGen T1 (TI A to B)

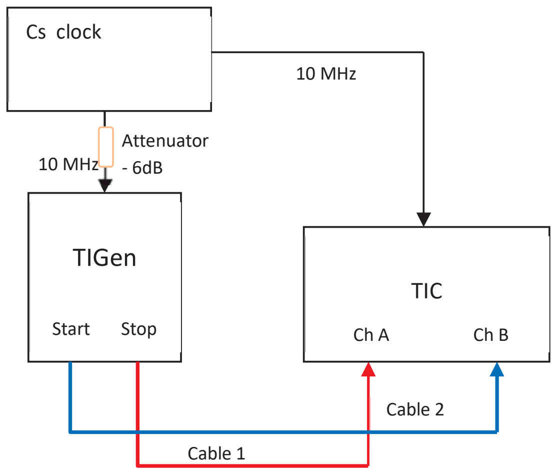


Figure 1a – Scheme of the BoM experimental set up TIGen T2 (TI B to A)

Measurement of time interval T1 and T2 TIGen

The 10 MHz output of Cs clock frequency standard is apply to -6dB attenuator connect to the input external input signal of the device under test TIGen. Star and Stop output is connect with cable 1 and cable 2 to the input Ch A and Ch B of the Time Interval Counter TIC. Cable 1 and cable 2 are approximately 60 cm and delay of the cable is approximately 2 ns. One measurement consist of 100 times the measurements of the time interval between time interval received by the input Ch A and Ch B of the Time interval counter TIC. In Fig. 1 are series of measurement configuration for time interval T1, and with replace the cable between the start and stop output of TIGen Fig 1a for time interval T2.

Scheme for InLambda measurements 20ns, 100ns, 300ns

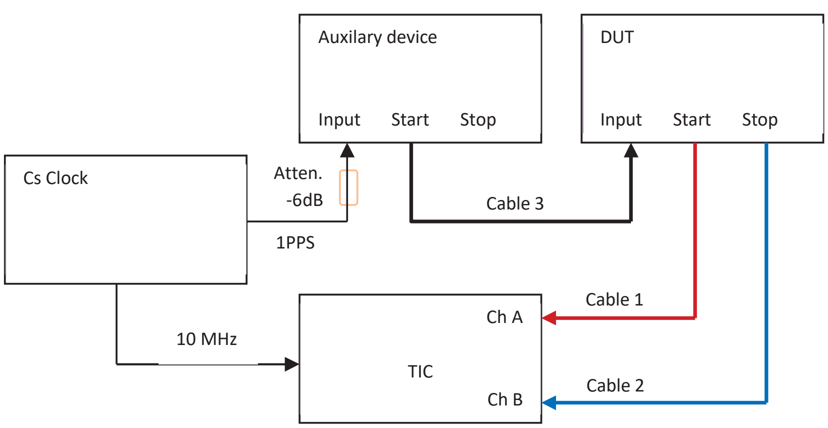


Figure 2 – Scheme of the BoM experimental set up InLambda T1 (TI A to B)

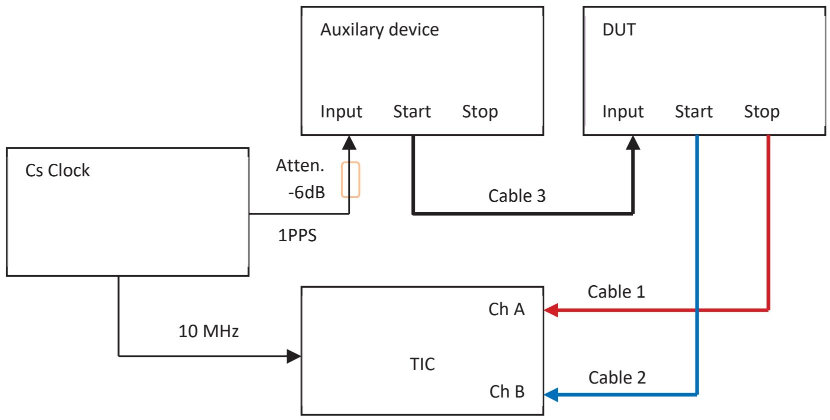


Figure 2a – Scheme of the BoM experimental set up InLambda T2 (TI B to A)

The 1 pps output of Cs clock frequency standard is apply to -6dB attenuator connect to the input external input signal of the Auxiliary device, Ch Start is connect to the input external signal of the DUT Inlambda (20,100,300ns) and channel star and stop output form DUT is connect with cable 1 and cable 2 to the input Ch A and Ch B of the Time Interval Counter TIC. Cable 1 and cable 2 are approximately 60 cm and Delay of the cable is approximately 2 ns. One measurement consist of 100 times the measurements of the time interval between time interval received by the input Ch A and Ch B of the Time interval counter TIC. In Fig. 2 are series of measurement configuration for time interval T1 and with replace the cable between the start and stop output of DUT (InLambda standards) Fig 2a for time interval T2.

Measuring equipment:

Cs Clock -Symmetricom 5071 High performance, national primary standard UTC (BoM)
TIC – Time interval counter CNT 91R synchronize with 10 MHz
Scopometer Fluke 190
Attenuator (– 6dB)

Measurement condition:

All measurement were performed in the period from 02.03.2021 to 03.03.2021 for calibration are:

Temperature: 21.0 to 23.6 °C ± 0.5 °C
Humidity: 24.0 to 33.6 % ± 1 %

Average date of performing measurement: 5 days from 25.02.2021 to 03.03.2021

Traceability:

Traceability of the time interval counter CNT 91is performed every two years.

Evaluation of the measurement result and measurement uncertainty:
Model equation that following from the measurement setup

$$t_x = t\,(1+\delta t_B + \partial\, t_B(\tau)_{ST}) + \delta t_q + \sqrt{(\delta t_j)^2_{start} + (\delta t_j)^2_{stop}} + \sqrt{(\delta t_L)^2_{start} + (\delta t_L)^2_{stop}} + \delta t_{Ch}$$

Description of the quantities in the model equation

Quantity Xi	Description
δt_q	quantization error
δt_j	trigger jitter
$\partial\, t_B(\tau)_{ST})$	short-term instability
δt_L	trigger level timming error
δt_{Ch}	channel asymmetry
δt_B	time base frequency offset

Uncertainty budget for time interval measurement TIGen. (All figures are in nanoseconds)

Uncertainty budget for time interval measurement 20ns (N=100)							
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Tx	22,630	0,026	normal	(A)	1	0.026	99
δtq	0,050	0,050	normal	(B)	1 √100	0,005	
δtj	0.000	0,061	normal	(B)	√2	0,087	
δtb(τ)st	0,000	5,E-13	Rectangular	(B)	1	0,049	
δtl	0.000	0,014	Rectangular	(B)	√2	0,020	
δtch	0.000	0,289	Rectangular	(B)	1	0,289	
δtb	5E-13	5E-12	normal	(A)	t	0,005	
		Combined standard uncertainty			u_c	0,31	
		Effective degrees of freedom			ν_{eff}	1.96E+06	
		Expanded uncertainty ($p \approx 95\%$)			U	0,61	

Uncertainty budget for time interval measurement TIGen 250ns (N=100)							
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Tx	249,976	0,037	normal	(A)	1	0.037	99
δtq	0,050	0,050	normal	(B)	1 √100	0,005	
δtj	0.000	0,061	normal	(B)	√2	0,087	
δtb(τ)st	0,000	5,E-13	Rectangular	(B)	1	0,049	
δtl	0.000	0,014	Rectangular	(B)	√2	0,020	
δtch	0.000	0,289	Rectangular	(B)	1	0,289	
δtb	5E-13	5E-12	normal	(A)	t	0,005	
		Combined standard uncertainty			u_c	0,31	
		Effective degrees of freedom			ν_{eff}	4.83E+05	
		Expanded uncertainty ($p \approx 95\%$)			U	0,61	

Uncertainty budget for time interval measurement TIGen 1,50µs (N=100)							
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Tx	1508,925	0,032	normal	(A)	1	0.032	99
δtq	0,050	0,050	normal	(B)	1 √100	0,005	
δtj	0.000	0,061	normal	(B)	√2	0,087	
δtb(τ)st	0,000	5,E-13	Rectangular	(B)	1	0,049	
δtl	0.000	0,014	Rectangular	(B)	√2	0,020	
δtch	0.000	0,289	Rectangular	(B)	1	0,289	
δtb	5E-13	5E-12	normal	(A)	t	0,005	
		Combined standard uncertainty			u_c	0,31	
		Effective degrees of freedom			ν_{eff}	8.87E+05	
		Expanded uncertainty ($p \approx 95\%$)			U	0,61	

Uncertainty budget for time interval measurement TIGen 12µs (N=100)							
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Tx	12039,452	0,035	normal	(A)	1	0.035	99
δtq	0,050	0,050	normal	(B)	1 √100	0,005	
δtj	0.000	0,061	normal	(B)	√2	0,087	
δtb(τ)st	0,000	5,E-13	Rectangular	(B)	1	0,049	
δtl	0.000	0,014	Rectangular	(B)	√2	0,020	
δtch	0.000	0,289	Rectangular	(B)	1	0,289	
δtb	5E-13	5E-12	normal	(A)	t	0,005	
		Combined standard uncertainty			u_c	0,31	
		Effective degrees of freedom			ν_{eff}	6.19E+05	
		Expanded uncertainty ($p \approx 95\%$)			U	0,61	

Uncertainty budget for time interval measurement InLambda. (All figures are in nanoseconds)

Uncertainty budget for time interval measurement 20ns auxiliary device 100 ns (N=100)							
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Tx	22,147	0,027	normal	(A)	1	0.027	99
δtq	0,050	0,050	normal	(B)	1 √100	0,005	
δtj	0.000	0,061	normal	(B)	√2	0,087	
δtb(τ)st	0,000	5,E-13	Rectangular	(B)	1	0,049	
δtl	0.000	0,014	Rectangular	(B)	√2	0,020	
δtch	0.000	0,289	Rectangular	(B)	1	0,289	
δtb	5E-13	5E-12	normal	(A)	t	0,005	
		Combined standard uncertainty			u_c	0,31	
		Effective degrees of freedom			ν_{eff}	1.73E+06	
		Expanded uncertainty ($p \approx 95\%$)			U	0,61	

Uncertainty budget for time interval measurement 100ns auxiliary device 20 ns (N=100)							
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Tx	104,435	0,031	normal	(A)	1	0.031	99
δtq	0,050	0,050	normal	(B)	1 √100	0,005	
δtj	0.000	0,061	normal	(B)	√2	0,087	
δtb(τ)st	0,000	5,E-13	Rectangular	(B)	1	0,049	
δtl	0.000	0,014	Rectangular	(B)	√2	0,020	
δtch	0.000	0,289	Rectangular	(B)	1	0,289	
δtb	5E-13	5E-12	normal	(A)	t	0,005	
		Combined standard uncertainty			u_c	0,31	
		Effective degrees of freedom			ν_{eff}	1.01E+06	
		Expanded uncertainty ($p \approx 95\%$)			U	0,61	

Uncertainty budget for time interval measurement 300ns auxiliary device 100 ns (N=100)							
Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
Tx	307,229	0,032	normal	(A)	1	0.032	99
δtq	0,050	0,050	normal	(B)	1 √100	0,005	
δtj	0.000	0,061	normal	(B)	√2	0,087	
δtb(τ)st	0,000	5,E-13	Rectangular	(B)	1	0,049	
δtl	0.000	0,014	Rectangular	(B)	√2	0,020	
δtch	0.000	0,289	Rectangular	(B)	1	0,289	
δtb	5E-13	5E-12	normal	(A)	t	0,005	
		Combined standard uncertainty			u_c	0,31	
		Effective degrees of freedom			ν_{eff}	8.50E+05	
		Expanded uncertainty ($p \approx 95\%$)			U	0,61	

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	5071A	10 MHz ± 1 Hz	Yes
Amplitude (at 50 Ω)	1.8V	within (0,5 ÷ 2) V_{p-p}	Yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.0	±	0.5	°C	within (22 ± 4) °C	Yes

Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
30.0	±	1	%	within (50 ± 30) %	no

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Pendulum CNT 91R
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	unknown

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”	22,630	±	0.61	ns
“dn3”	249,976	±	0.61	ns
“dn7”	1508,925	±	0.61	ns
“dn126”	12039,452	±	0.61	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	5071A		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	Yes
Low level	0V	0 V	Yes
High level (at 50 Ω)	1.8V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	1.4 ns	< 10 ns	Yes
Duty cycle	0.002%	≤ 50 %	Yes
Pulse width	2ns	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	100 ns	Inλ 100 or Inλ 300	Yes

Inλ 100			20 ns	Inλ 20 or Inλ 300	Yes
Inλ 300			100 ns	Inλ 20 or Inλ 100	Yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22.0	±	0.5	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
30.0	±	1	%	within (50 ± 30) %	no

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Pendulum CNT 91
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	unknown

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.147	±	0.61	ns	22.3	±	0.5	°C
Inλ 100	104.435	±	0.61	ns	22.3	±	0.5	°C
Inλ 300	307.229	±	0.61	ns	22.3	±	0.5	°C

Armin Mirto

(Name)

26.04.2021

(Date)

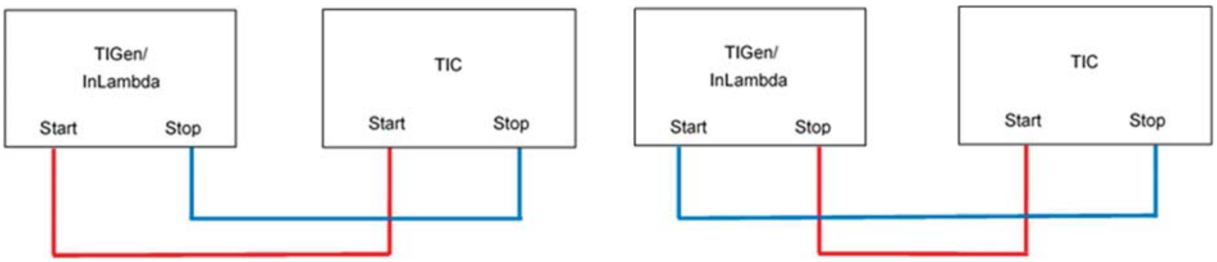
Appendix T

DMDM report

Measurement report DMDM

Method of measurement

According to the recommendation, measurements were performed in such a way to reduce differential channel delays of the used measurement system and differential delays of the used connecting cables between DUT and the measurement system. The method adopted at DMDM for the time interval measurements is method of two consequtive series of measurements: in normal configuration, and with replaced cables between the start and stop outputs of TIGen and InLambda standards.



$T_1 = TI + x$ $T_2 = -TI + x$

Figure 1. Scheme of the applied method

The measured time interval is computed from the two subsequent time interval measurements T_1 and T_2 as:

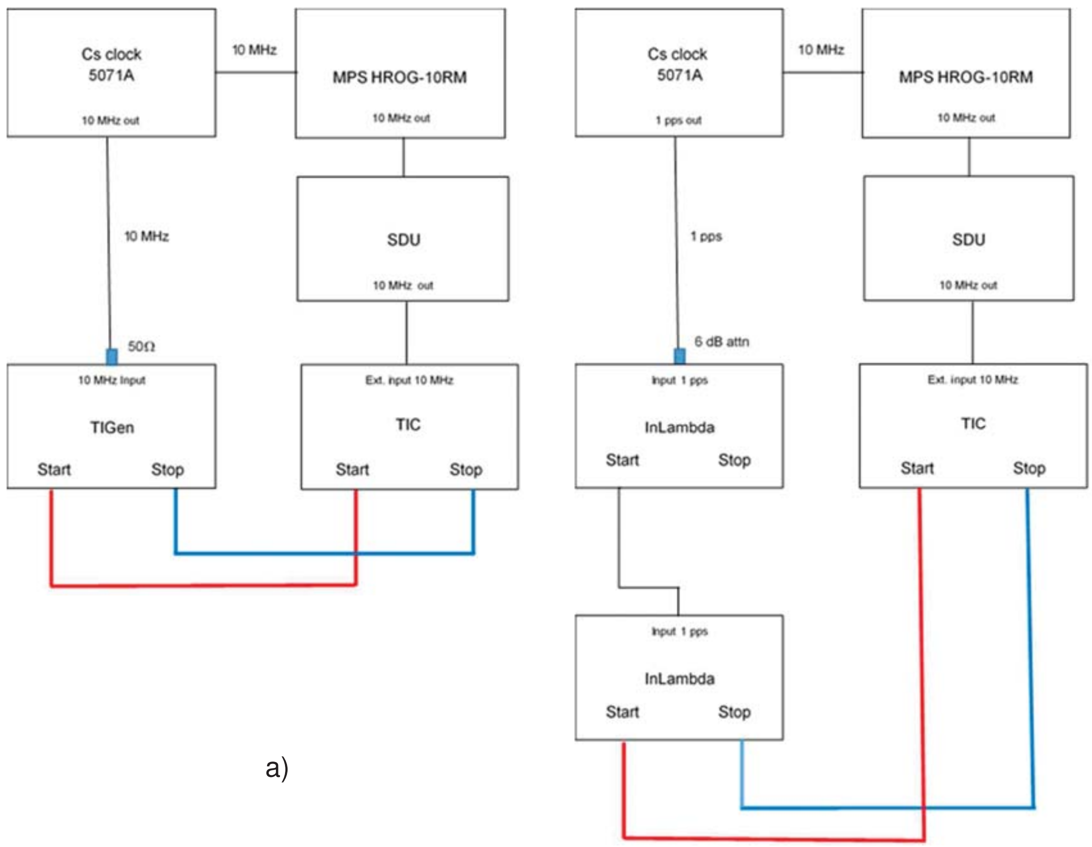
$$TI \approx \frac{T_1 - T_2}{2}$$

Calibration set-up and equipment

In Figures 2a. and 2b. are reported the used experimental set-up. The measured 1PPS signals are obtained from start and stop outputs of a TIGen and InLambda standards. The time base of the time interval counter is a 10 MHz signal from frequency distribution amplifier. The 10 MHz input signal for the TIGen was applied from cesium clock Symmetricom 5071A, using 50 Ω low pass filter, and the input 1pps signal to the InLambda standards was applied from cesium clock Symmetricom 5071A using 6 db attenuator.

All measurements are performed after adaptation to local environmental conditions and after the warm-up time. Measurements for InLambda standards were performed using the required double configuration for measurements (external input pulses are passed onto the input of the auxiliary device and start output signals from the auxiliary device are passed onto the input of the device under tests (DUT)).

Counter settings: time interval A to B, DC, 50 Ω, positive slope, trigger levels 0,5 V, external reference, N=100. All measurements presented here are performed with the 1 m cables.



a) b)

Figure 2. Scheme of the DMDM experimental set-up: a) TIGen, b) InLambda standards

Equipment used	Type	Manufacturer	s/n	Traceability
Cesium clock	5071A Opt. 001 high perf.	Symmetricom	US45312191	BIPM Circular T
MPS	HROG-10RM	Spectradynamics	14FS28-11	
TIC	CNT-91	Pendulum	985754	Internal calibration DMDM
Termohygrometer	177-H1	Testo	01541924/805	Internal calibration DMDM
Switch and distribution unit	9611	Symmetricom	8244	/
6 dB attenuator, 50 Ω		Fluke		/
50 Ω low pass filter		Hewlett Packard		/

Measurement conditions

The measurements were performed after adaptation to local environmental conditions and after the warm-up time.

Laboratory environmental conditions are monitored continuously, using calibrated termohygrometer Testo 177-H1. During the measurements, all equipment were placed in a Faraday cage, with the uninterruptable powering.

A summary of the measurement conditions with the uncertainties (*k* = 2) is given in the table:

	Minimum	Maximum	Uncertainty
Temperature	22,3 °C	23,5 °C	0,6 °C
Humidity	22,7 %	40,1 %	5,0 %

Average date of performing measurements: 4 days, from 20. March 2021. to 23. March 2021.

Participating laboratory: DMDM, Belgrade

Snežana Renovica 18.06.2021.

(Name) (Date)

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

Acronym of institute: DMDM Country: Serbia

Average date of measurements: 4 days, from 20. March 2021. to 23. March 2021.

Model equation that follows from the measurement setup:

$$TI = \frac{T_1 - T_2}{2}(1 + \delta_{TB} + \delta_{TB(\tau)}) + \delta_{tq} + \delta t_j + \delta t_L + \delta t_r$$

Description of the quantities in the model equation:

Quantity X_i	Description
T_1, T_2	consecutive measurements as in Fig. 1 and Fig. 2
$\delta_{TB(\tau)}$	short term stability of time base frequency
δ_{tq}	quantization error
δt_j	start/stop trigger error $\sqrt{(\delta t_j)^2{}_{start} + (\delta t_j)^2{}_{stop}}$
δt_L	trigger level timing error $\sqrt{(\delta t_L)^2{}_{start} + (\delta t_L)^2{}_{stop}}$
δt_r	nonlinearities (residuals) of the system
δ_{TB}	time base frequency offset ≈0

Sources of uncertainty

Uncertainty due to the repeated measurements (uncertainty type A, normal distribution)

The measurements are repeated 100 times at each measurement point. The mean value and the associated experimental standard deviation are calculated. The experimental standard deviation of the mean is reported as standard uncertainty type A for 99 degrees of freedom.

Time interval measurements with Time Interval Counter Pendulum CNT-91*:*

1. Random uncertainties

1.1 quantization error

t_q = 50 ps rms

$\delta t_q = \frac{50\ ps}{\sqrt{100}} = 5\ ps$

1.2 start/stop trigger error

start trigger error = stop trigger error = $\pm \frac{\sqrt{V^2{}_{noise-input} + V^2{}_{noise-signal}}}{\text{Input Signal Slew Rate at Trigger Point}}$

$V^2_{noise-input}$ = 200 μVrms typical

start trigger error = stop trigger error = $\frac{\sqrt{(0{,}20\ mV)^2+(10\ mV)^2}}{1V/ns} \approx 10\ ps\ rms$

start/stop trigger error = $\frac{\sqrt{2}\times 10}{\sqrt{100}} ps = 1{,}4\ ps$

2. Time Base Short-term stability

τ = 1 s; $\sigma_y(2,\tau) \leq 5\times 10^{-12}$

$\delta_{TB(\tau)} = TI \times 2{,}89\times 10^{-12} \approx 0$

Systematic uncertainties

3. start trigger level error = stop trigger level error = $\pm\frac{15\,\text{mV} \pm (1\% \times \text{Start Trigger Level Setting})}{\text{Input Signal Slew Rate at Start Trigger Point}}$

$=\frac{15\ mV \pm 5\ mV}{1V/ns} \approx 20\ ps$

trigger level timing error = $\frac{\sqrt{2}}{\sqrt{3}} \times 20\ ps = 16{,}2\ ps$

4. nonlinearities (residuals) of the system

$$\delta t_r = \frac{100\ ps}{\sqrt{3}} = 57{,}8\ ps$$

Degrees of freedom are calculated as:

$$\nu_{eff} = \frac{u^4(y)}{\sum_{i=1}^{N}\frac{u_i^4(y)}{\nu_i}}$$

Uncertainty budgets for TIGen standard:

All figures are in nanoseconds.

Uncertainty budget table for the “dn0”

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_1		< 0,005	Normal	A	1	< 0,005	99
T_2		< 0,005	Normal	A	1	< 0,005	99
$\frac{T_1 - T_2}{2}$	22,657	0,006	Normal	A	1	0,006	3
δ_{TB}	0	0,000	Normal	B	1	0,000	∞
δ_{tq}	0	0,005	Normal	B	1	0,005	∞
δt_j	0	0,001	Normal	B	1	0,001	∞
δt_L	0	0,016	Normal	B	1	0,016	∞
δt_r	0	0,058	Normal	B	1	0,058	∞

Combined standard uncertainty	u_c	0,061
Effective degrees of freedom	ν_{eff}	>100
Expanded uncertainty ($p \approx 95\%$)	U	0,122

Uncertainty budget table for the "dn3"

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_1		< 0,005	Normal	A	1	< 0,005	99
T_2		< 0,005	Normal	A	1	< 0,005	99
$\frac{T_1 - T_2}{2}$	249,966	0,011	Normal	A	1	0,011	3
δ_{TB}	0	0,000	Normal	B	1	0,000	∞
δ_{tq}	0	0,005	Normal	B	1	0,005	∞
δt_j	0	0,001	Normal	B	1	0,001	∞
δt_L	0	0,016	Normal	B	1	0,016	∞
δt_r	0	0,058	Normal	B	1	0,058	∞

Combined standard uncertainty	u_c	0,062
Effective degrees of freedom	ν_{eff}	>100
Expanded uncertainty ($p \approx 95\%$)	U	0,124

Uncertainty budget table for the "dn7"

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_1		< 0,005	Normal	A	1	< 0,005	99
T_2		< 0,005	Normal	A	1	< 0,005	99
$\frac{T_1 - T_2}{2}$	1508,990	0,009	Normal	A	1	0,009	3
δ_{TB}	0	0,000	Normal	B	1	0,000	∞
δ_{tq}	0	0,005	Normal	B	1	0,005	∞
δt_j	0	0,001	Normal	B	1	0,001	∞
δt_L	0	0,016	Normal	B	1	0,016	∞
δt_r	0	0,058	Normal	B	1	0,058	∞

Combined standard uncertainty	u_c	0,061
Effective degrees of freedom	ν_{eff}	>100
Expanded uncertainty ($p \approx 95\%$)	U	0,122

Uncertainty budget table for the “dn126”

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_1		< 0,005	Normal	A	1	< 0,005	99
T_2		< 0,005	Normal	A	1	< 0,005	99
$\frac{T_1 - T_2}{2}$	12039,490	0,012	Normal	A	1	0,012	3
δ_{TB}	0,000	0,000	Normal	B	1	0,000	∞
δ_{tq}	0,000	0,005	Normal	B	1	0,005	∞
δt_j	0,000	0,001	Normal	B	1	0,001	∞
δt_L	0,000	0,016	Normal	B	1	0,016	∞
δt_r	0,000	0,058	Normal	B	1	0,058	∞
		Combined standard uncertainty			u_c	0,062	
		Effective degrees of freedom			ν_{eff}	>100	
		Expanded uncertainty ($p \approx 95\%$)			U	0,124	

Uncertainty budgets for InLambda standards:

All figures are in nanoseconds.

Uncertainty budget table for the “Inλ 20” (auxiliary used Inλ 300)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_1		< 0,005	Normal	A	1	< 0,005	99
T_2		< 0,005	Normal	A	1	< 0,005	99
$\frac{T_1 - T_2}{2}$	24,210	0,002	Normal	A	1	0,002	3
δ_{TB}	0,000	0,000	Normal	B	1	0,000	∞
δ_{tq}	0,000	0,005	Normal	B	1	0,005	∞
δt_j	0,000	0,001	Normal	B	1	0,001	∞
δt_L	0,000	0,016	Normal	B	1	0,016	∞
δt_r	0,000	0,058	Normal	B	1	0,058	∞
		Combined standard uncertainty			u_c	0,061	
		Effective degrees of freedom			ν_{eff}	>100	
		Expanded uncertainty ($p \approx 95\%$)			U	0,122	

Uncertainty budget table for the "Inλ 100" (auxiliary used Inλ 20)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_1		< 0,005	Normal	A	1	< 0,005	99
T_2		< 0,005	Normal	A	1	< 0,005	99
$\frac{T_1 - T_2}{2}$	104,482	0,001	Normal	A	1	0,001	3
δ_{TB}	0,000	0,000	Normal	B	1	0,000	∞
δ_{tq}	0,000	0,005	Normal	B	1	0,005	∞
δt_j	0,000	0,001	Normal	B	1	0,001	∞
δt_L	0,000	0,016	Normal	B	1	0,016	∞
δt_r	0,000	0,058	Normal	B	1	0,058	∞

Combined standard uncertainty	u_c	0,061
Effective degrees of freedom	ν_{eff}	>100
Expanded uncertainty ($p \approx$ 95%)	U	0,122

Uncertainty budget table for the "Inλ 300" (auxiliary used Inλ 100)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_1		< 0,005	Normal	A	1	< 0,005	99
T_2		< 0,005	Normal	A	1	< 0,005	99
$\frac{T_1 - T_2}{2}$	307,273	0,001	Normal	A	1	0,001	3
δ_{TB}	0,000	0,000	Normal	B	1	0,000	∞
δ_{tq}	0,000	0,005	Normal	B	1	0,005	∞
δt_j	0,000	0,001	Normal	B	1	0,001	∞
δt_L	0,000	0,016	Normal	B	1	0,016	∞
δt_r	0,000	0,058	Normal	B	1	0,058	∞

Combined standard uncertainty	u_c	0,061
Effective degrees of freedom	ν_{eff}	>100
Expanded uncertainty ($p \approx$ 95%)	U	0,122

Снежана Реновица

Snežana Renovica 18. June 2021.

(Name) (Date)

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: DMDM Country: Serbia

Average date of measurements: 4 days, from 20. March 2021. to 23. March 2021.

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)			Cs clock	10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)			0,7 V_{p-p}	within (0,5 ÷ 2) V_{p-p}	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,9	±	0,6	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
31,4	±	8,7	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Pendulum CNT-91
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	100 ps

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
“dn0”	22,66	±	0,12	ns
“dn3”	249,97	±	0,12	ns
“dn7”	1508,99	±	0,12	ns
“dn126”	12039,49	±	0,12	ns

s

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock Symmetricom 5071A		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2,0 V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	1,5 ns	< 10 ns	yes
Duty cycle	≤ 5 %	≤ 50 %	yes
Pulse width	20 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 300	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 20	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
22,9	±	0,6	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
31,4	±	8,7	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Pendulum CNT-91
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	100 ps

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20 (used Inλ 300)	24,21	±	0,12	ns	22,9	±	0,6	°C
Inλ 100 (used Inλ 20)	104,48	±	0,12	ns	22,9	±	0,6	°C
Inλ 300 (used Inλ 100)	307,27	±	0,12	ns	22,9	±	0,6	°C

Snežana Renovica
(Name)

18. June 2021.
(Date)

Appendix U

MBM report

Report for TC-TF EURAMET Supplementary Comparison
"Comparison of time interval measurements"

1. Task goals **2**

2. General information about participating laboratory **2**

3. Measurement method **3**

4. Measuring equipment used **6**

4.1 List of measuring equipment 6

4.2 Auxiliary equipment 7

4.3 Calibration set-up 7

5. Measurement traceability **7**

6. Measurement uncertainty **8**

6.1 Used relationship/equation for obtaining estimates of results and uncertainty budget 8

6.2 Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects 9

6.2.1 Calculation of standard measurement uncertainty 11

6.2.1.1 Type A standard measurement uncertainties 11

6.2.1.2 Type B standard measurement uncertainties 11

6.2.1.3 Expanded measurement uncertainty calculation 14

7. Description of the source 10 MHz reference frequency for TIGen standard **15**

8. Description of the used input pulse signals for InLambda standards **15**

9. Ambiental conditions of measurements **15**

10. Average date of performing measurements **16**

1. Task goals

Task goals were to measure 7 time intervals by two types of traveling standards: TIGen (1 item) and InLambda standards (3 items).

2. General information about participating laboratory

Location where measurements have been carried out:	Montenegrin Bureau of Metrology (MBM), Laboratory for Time and Frequency; Arsenija Boljevića bb, 81000 Podgorica, Montenegro
Measured by:	Alina Musić Jovana Vukoslavović

The Bureau of Metrology is established by the Government of Montenegro on September 14, 2006, by the Decree amending the Decree on State Administration Organization and Manner of Work of September 29, 2006.

The Laboratory for Time and Frequency was established in 2011 within the Laboratory Center of the Bureau of Metrology.

The Laboratory for Time and Frequency carries out the tasks related to:

- Realization, conservation, maintenance and improvement of the national standard for time (frequency) in Montenegro;
- Providing metrological traceability in the field of time and frequency in Montenegro by transferring the unit of time (frequency) from the national measurement standard to secondary and working standards of time (frequency);
- Development of measurement methods for transferring the unit of time;
- Calibration of measurement standards/ measuring instruments for measuring time (frequency);
- Realization and distribution of the national time scale;
- Participation in the calculation of TAI (Temps Atomique International) and UTC (Universal Time Coordinated) time scales;
- Participation in inter-laboratory comparisons;
- Defining the prescribed technical and metrological requirements for determining the type of a measuring instrument used for measuring time (frequency);
- Verification of measuring devices used for measuring time (frequency).

In order to examine compliance with the prescribed technical and metrological requirements to determine the type of a measuring instrument, the Laboratory for Time and Frequency carries out type examination for measuring instruments in the field of time and frequency measurement in accordance with the Decree on legal measuring instruments that are subject to mandatory verification or type approval (Official Gazette of Montenegro 81/09), as follows:

- Main clocks within the telephone exchanges;
- Traffic speed measuring instruments for moving vehicles.

Laboratory has accredited area for:

- Measurement of frequency in the range from 1 mHz to 350 MHz;
- Measurement of time interval in the range from 1 ns to 100 000 s;

- Calibration of frequency counters;
- Calibration of stopwatches;
- Calibration of the time measurement standard.

3. Measurement method

For measuring time intervals by TIGen standard we used the frequency counter Agilent 53230A and 10 MHz from the Cesium clock Microsemi 5071A for the external time base. For measurements by InLambda standards we used also frequency counter Agilent 53230A and signal generator Agilent 33521A.

We made two measurements. For first measurement we connected START and STOP outputs from standards with START and STOP channels on frequency counter (Time Int 1-2). For the second measurement we changed position of the cables on standards (Time Int 2-1).

Skew-delay error between channels is zero because we made this cable replacement.

After connecting equipment, it is necessary to read two values from the frequency counter, the mean measured value (Mean) and the standard deviation (StdDev) for each interval.

For the TIGen standard, we read these values after 100 of countings, and for the InLambda standards after 10 000 of countings.

The equipment connection sheme for TIGen standard is shown in the Figure 1 for first measurement with cables connections 1-2, and in the Figure 2 for second measurement with cables connection 2-1.

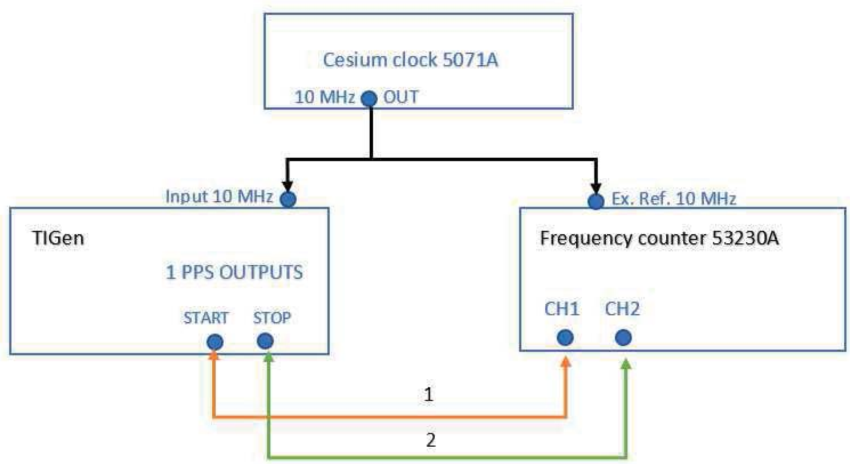


Figure 1. Connection sheme for TIGen standard (1-2)

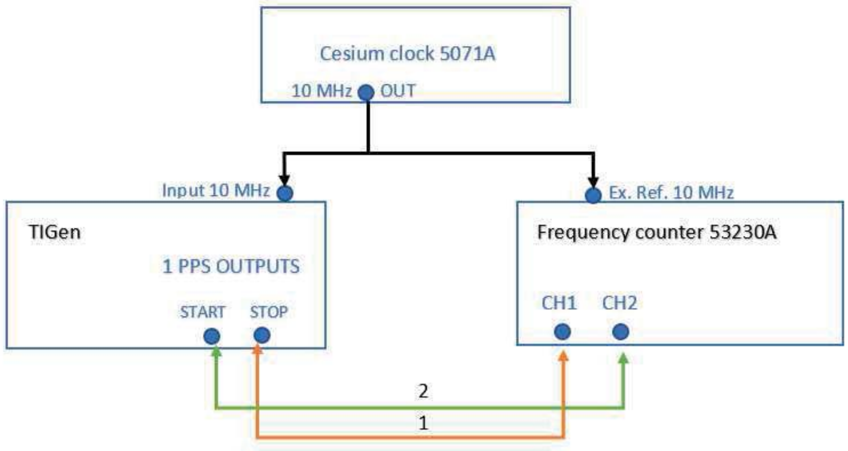


Figure 2. Connection sheme for TIGen standard (2-1)

The equipment connection for TIGen standard is shown in the Figure 3.

Figure 3. Connection of the TIGen standard

The equipment connection sheme for InLambda standards is shown in the Figure 4 for first measurement with cables connections 1-2, and in the Figure 5 for second measurement with cables connection 2-1. The example below is given for measuring time interval of InLambda standard (c. 100 ns).

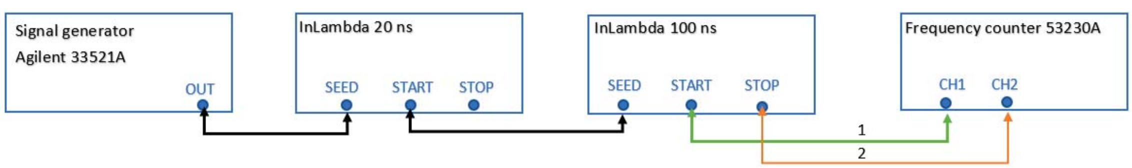


Figure 4. Connection sheme for InLambda standards (1-2)

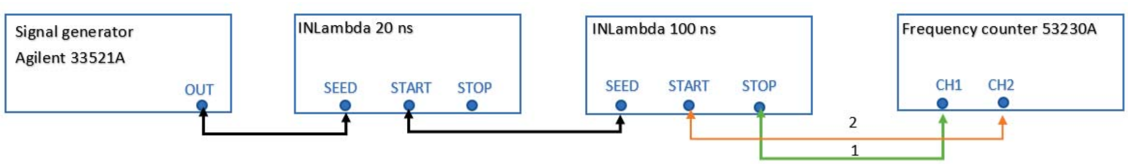


Figure 5. Connection sheme for InLambda standards (2-1)

The equipment connection for InLambda standards is shown in the Figure 6.

Figure 6. Connection of the InLambda standards

4. Measuring equipment used

4.1 List of measuring equipment

- Cesium clock, Microsemi, 5071A, SN US49353925, Calibration date: from October 25, 2019 to November 12, 2019 (DMDM);
- Frequency counter, Agilent, 53230A, SN MY500000544, Calibration date: January 04, 2021 (SIQ).

4.2 Auxiliary equipment

- Oscilloscope, HMO3524, HAMEG, SN 057820040;
- Signal generator, Agilent, 33521A, SN MY50001763;
- BNC cables (2 short cables for time measurement, 2 cables medium length, 1 cable with "T" connector, and one long cable for 10 MHz source).

4.3 Calibration set-up

In the table below are given informations about the base equipment used for time interval measurements.

Table 1. The base equipment used for time interval measurements

The type of time interval counter	Agilent 53230A
Applied trigger level (50 Ω)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results	100 ps (T_{acc}) Accuracy of Time Interval Counter
Coupling	DC
Impedance	50 Ω
Range	5V
Level Setup	Auto Level – Off 500 mV
Count	100 (TIGen) 10 000 (InLambda)

Table 2. Signal generator setup

The type of signal generator	Agilent 33521A
Frequency	100 Hz
Amplitude	2 V_{pp}
Offset	1 V
Pulse Width	1 ms
Lead Edge	8,4 ns
Trail Edge	8,4 ns
Duty cycle	10 %
Rise time	8 ns

5. Measurement traceability

During the measurement, reference standards were used which are traceable to international and national standards, which represents the realization of the physical quantity unit in accordance with the International System of Units (SI). The traceability scheme in the Laboratory for Time and Frequency is shown in Figure 7.

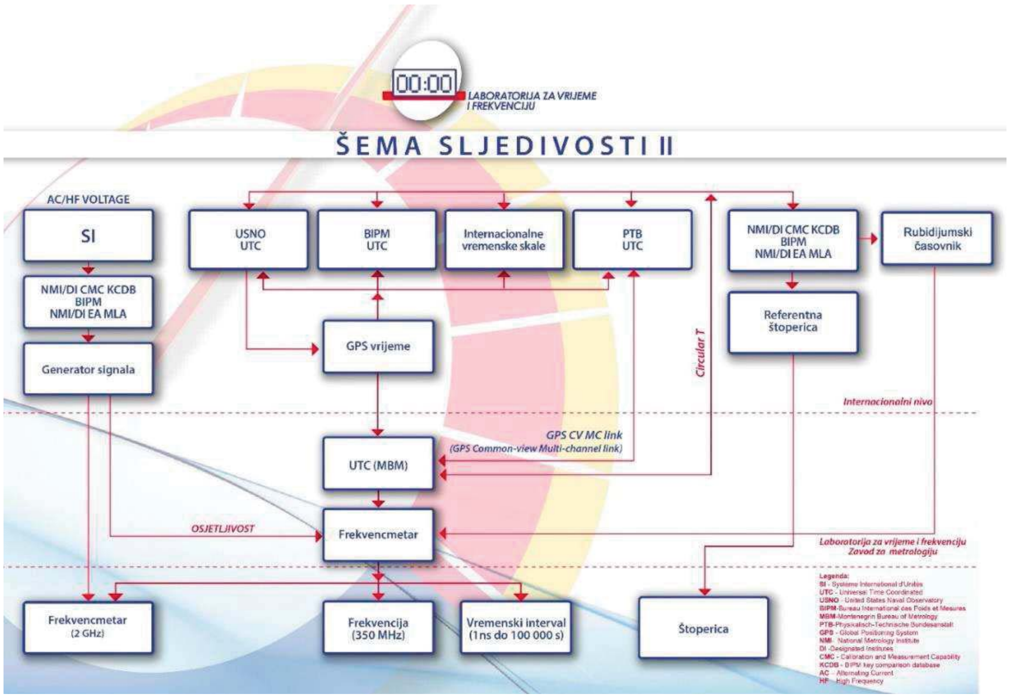


Figure 7. The traceability scheme in the Laboratory for Time and Frequency

6. Measurement uncertainty

6.1 Used relationship/equation for obtaining estimates of results and uncertainty budget

The time interval measured by the frequency counter can be expressed as following equation:

$$ts = t_c + k\_RU + k\_SU + k\_TU \qquad \text{(eq. 1)}$$

Where:

t_c – the mean value of the measured values read from the frequency counter;
k_RU – Random error correction;
k_SU – Systematic Error correction;
k_TU – Timebase error correction.

Random and Systematic error corrections are 0.

The timebase error is a parameter that depends on the time base used (internal time base of the frequency counter or external time base).

The correction due to the timebase error, *k_TU*, is calculated as follows:

$$k\_TU = \frac{\Delta f_{cs}}{f} \cdot t_c \qquad \text{(eq. 2)}$$

Where:

$\frac{\Delta f_{cs}}{f}$ – *relative frequency deviation of the time base.*

The value for the relative frequency deviation of the time base is taken from the last calibration certificate of source used for the time base.
We used this value from the last calibration certificate of Cesium clock from 2019, because we do not have data for new calibration.

The formula below is used to calculate the final results of time interval measurments:

$$t = \frac{t_1 + t_2}{2} \qquad (eq.\ 3)$$

6.2 Obtained results of measurements with the associated standard and expanded uncertainty of measurement and a complete uncertainty budget, including information on the uncertainty components connected with residual non-linearities of the measurement system or other non-compensated effects

Table 3. Uncertainty budget table for InLambda standard – λ 20 ns

Mathematical model of measurement:								
	Linearity =	1.00000E-10 s	Tacc =	100 ps	Skew =	0 ps		
ts=tc+k_RU + k_SU + k_TB	Tlte =	7.5E-12 s	Tss =	20 ps			Start Trig =	0.5 V
	Offset =	1.075E-10 s	Ein =	500 uV	Input noise		Stop Trig =	0.5 V
k_RU =(1,4(Tss^2+Te^2)^1/2)			En =	1000 uV	Signal noise		Tlse_start =	0.006 V
	Te =((Ein^2+En^2+Vx^2)^1/2)/SR		Vx =	2000 uV	Cross Talk		Tlse_stop =	0.006 V
k_SU = Linearity + Offset			SRstart =	1.6.E+09 V/s	SRstop =	1.6.E+09 V/s		
	Te =	3.7.E-14 s	U0start =	2.000 V	U0stop =	2.000 V	Vh =	0.020 V
Tlte = (Tlse_start/Srstart + Tlse_stop/Srstop) + (1/2Vh/Srstart - 1/2Vh/Srstop)			Rtstart =	1.0E-09 s	Rtstop =	1.0E-09 s		
			U(Δfcs/f)=	1.00E-13				
			Δfcs/f=	4.00E-14				
			δ(Gate)=	1.00E-11				

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty of the estimate	*ui^4(y)/vi*
tc	2.4067E-08 s	1.300E-11 s	normal	1	1.0	1.3000E-11 s	9999	1.300E-11 s	2.86E-48
k_RU	0 s	3.615E-12 s	rectangular	1.73	1.0	3.6149E-12 s	1E+99	6.261E-12 s	1.7E-145
k_SU	0 s	1.198E-10 s	rectangular	1.73	1.0	1.1980E-10 s	1E+99	2.075E-10 s	2.1E-139
k_TB	9.63E-22 s	1.403E-19 s	rectangular	1.73	1.0	1.4034E-19 s	1E+99	2.43E-19 s	3.9E-175
ts	2.407E-08					1.206E-10 s	73954140		2.86E-48
		Expanded uncertainty of measurement:				2.411E-10 s			
						1.0E-02			

Table 4. Uncertainty budget table for InLambda standard – λ 100 ns

Mathematical model of measurement:								
	Linearity =	1.00000E-10 s	Tacc =	100 ps	Skew =	0 ps		
ts=tc+k_RU + k_SU + k_TB	Tlte =	7.5E-12 s	Tss =	20 ps			Start Trig =	0.5 V
	Offset =	1.075E-10 s	Ein =	500 uV	Input noise		Stop Trig =	0.5 V
k_RU =(1,4(Tss^2+Te^2)^1/2)			En =	1000 uV	Signal noise		Tlse_start =	0.006 V
	Te =((Ein^2+En^2+Vx^2)^1/2)/SR		Vx =	2000 uV	Cross Talk		Tlse_stop =	0.006 V
k_SU = Linearity + Offset			SRstart =	1.6.E+09 V/s	SRstop =	1.6.E+09 V/s		
	Te =	3.7.E-14 s	U0start =	2.000 V	U0stop =	2.000 V	Vh =	0.020 V
Tlte = (Tlse_start/Srstart + Tlse_stop/Srstop) + (1/2Vh/Srstart - 1/2Vh/Srstop)			Rtstart =	1.0E-09 s	Rtstop =	1.0E-09 s		
			U(Δfcs/f)=	1.00E-13				
			Δfcs/f=	4.00E-14				
			δ(Gate)=	1.00E-11				

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty of the estimate	*ui^4(y)/vi*
tc	1.0436E-07 s	1.100E-11 s	normal	1	1.0	1.1000E-11 s	9999	1.100E-11 s	1.46E-48
k_RU	0 s	3.615E-12 s	rectangular	1.73	1.0	3.6149E-12 s	1E+99	6.261E-12 s	1.7E-145
k_SU	0 s	1.198E-10 s	rectangular	1.73	1.0	1.1980E-10 s	1E+99	2.075E-10 s	2.1E-139
k_TB	4.17E-21 s	6.086E-19 s	rectangular	1.73	1.0	6.0856E-19 s	1E+99	1.05E-18 s	1.4E-172
ts	1.044E-07					1.204E-10 s	143315062		1.46E-48
		Expanded uncertainty of measurement:				2.407E-10 s			
						2.3E-03			

Table 5. Uncertainty budget table for InLambda standard – λ 300 ns

Mathematical model of measurement:

	Linearity =	1.00000E-10 s	Tacc =	100 ps	Skew =	0 ps		
ts=tc+k_RU + k_SU + k_TB	Tlte =	7.5E-12 s	Tss =	20 ps			Start Trig =	0.5 V
	Offset =	1.075E-10 s	Ein =	500 uV	Input noise		Stop Trig =	0.5 V
k_RU =(1,4(Tss^2+Te^2)^1/2)			En =	1000 uV	Signal noise		Tlse_start =	0.006 V
	Te =((Ein^2+En^2+Vx^2)^1/2)/SR		Vx =	2000 uV	Cross Talk		Tlse_stop =	0.006 V
k_SU = Linearity + Offset			SRstart =	1.6.E+09 V/s	SRstop =	1.6.E+09 V/s		
	Te =	3.7.E-14 s	U0start =	2.000 V	U0stop =	2.000 V	Vh =	0.020 V
Tlte = (Tlse_start/Srstart + Tlse_stop/Srstop) + (1/2Vh/Srstart - 1/2Vh/Srstop)			Rtstart =	1.0E-09 s	Rtstop =	1.0E-09 s		
			U(Δfcs/f)=	1.00E-13				
			Δfcs/f=	4.00E-14				
			δ(Gate)=	1.00E-11				

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty of the estimate	*ui^4(y)/vi*
tc	3.0718E-07 s	1.300E-11 s	normal	1	1.0	1.3000E-11 s	9999	1.300E-11 s	2.86E-48
k_RU	0 s	3.615E-12 s	rectangular	1.73	1.0	3.6149E-12 s	1E+99	6.261E-12 s	1.7E-145
k_SU	0 s	1.198E-10 s	rectangular	1.73	1.0	1.1980E-10 s	1E+99	2.075E-10 s	2.1E-139
k_TB	1.23E-20 s	1.791E-18 s	rectangular	1.73	1.0	1.7912E-18 s	1E+99	3.10E-18 s	1E-170
ts	3.072E-07					1.206E-10 s	73954140		2.86E-48
		Expanded uncertainty of measurement:				2.411E-10 s			
						7.8E-04			

Table 6. Uncertainty budget table for TiGen standard – dn0

Mathematical model of measurement:

	Linearity =	1.00000E-10 s	Tacc =	100 ps	Skew =	0 ps		
ts=tc+k_RU + k_SU + k_TB	Tlte =	6.66667E-12 s	Tss =	20 ps			Start Trig =	0.5 V
	Offset =	1.06667E-10 s	Ein =	500 uV	Input noise		Stop Trig =	0.5 V
k_RU =(1,4(Tss^2+Te^2)^1/2)			En =	1000 uV	Signal noise		Tlse_start =	0.006 V
	Te =((Ein^2+En^2+Vx^2)^1/2)/SR		Vx =	2250 uV	Cross Talk		Tlse_stop =	0.006 V
k_SU = Linearity + Offset			SRstart =	1.8.E+09 V/s	SRstop =	1.8.E+09 V/s		
	Te =	3.4.E-14 s	U0start =	2.250 V	U0stop =	2.250 V	Vh =	0.020 V
Tlte = (Tlse_start/Srstart + Tlse_stop/Srstop) + (1/2Vh/Srstart - 1/2Vh/Srstop)			Rtstart =	1.0E-09 s	Rtstop =	1.0E-09 s		
			U(Δfcs/f)=	1.00E-13				
			Δfcs/f=	4.00E-14				
			δ(Gate)=	7.50E-11				

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty of the estimate	*ui^4(y)/vi*
tc	2.2554E-08 s	9.000E-12 s	normal	1	1.0	9.0000E-12 s	99	9.000E-12 s	6.63E-47
k_RU	0 s	3.615E-12 s	rectangular	1.73	1.0	3.6149E-12 s	1E+99	6.261E-12 s	1.7E-145
k_SU	0 s	1.193E-10 s	rectangular	1.73	1.0	1.1932E-10 s	1E+99	2.067E-10 s	2E-139
k_TB	9.02E-22 s	9.779E-19 s	rectangular	1.73	1.0	9.7792E-19 s	1E+99	1.69E-18 s	9.1E-172
ts	2.255E-08					1.197E-10 s	3099021		6.63E-47
		Expanded uncertainty of measurement:				2.394E-10 s			
						1.1E-02			

Table 7. Uncertainty budget table for TiGen standard – dn3

Mathematical model of measurement:

	Linearity =	1.00000E-10 s	Tacc =	100 ps	Skew =	0 ps		
ts=tc+k_RU + k_SU + k_TB	Tlte =	6.66667E-12 s	Tss =	20 ps			Start Trig =	0.5 V
	Offset =	1.06667E-10 s	Ein =	500 uV	Input noise		Stop Trig =	0.5 V
k_RU =(1,4(Tss^2+Te^2)^1/2)			En =	1000 uV	Signal noise		Tlse_start =	0.006 V
	Te =((Ein^2+En^2+Vx^2)^1/2)/SR		Vx =	2250 uV	Cross Talk		Tlse_stop =	0.006 V
k_SU = Linearity + Offset			SRstart =	1.8.E+09 V/s	SRstop =	1.8.E+09 V/s		
	Te =	3.4.E-14 s	U0start =	2.250 V	U0stop =	2.250 V	Vh =	0.020 V
Tlte = (Tlse_start/Srstart + Tlse_stop/Srstop) + (1/2Vh/Srstart - 1/2Vh/Srstop)			Rtstart =	1.0E-09 s	Rtstop =	1.0E-09 s		
			U(Δfcs/f)=	1.00E-13				
			Δfcs/f=	4.00E-14				
			δ(Gate)=	7.50E-11				

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty of the estimate	*ui^4(y)/vi*
tc	2.4990E-07 s	1.100E-11 s	normal	1	1.0	1.1000E-11 s	99	1.100E-11 s	1.48E-46
k_RU	0 s	3.615E-12 s	rectangular	1.73	1.0	3.6149E-12 s	1E+99	6.261E-12 s	1.7E-145
k_SU	0 s	1.193E-10 s	rectangular	1.73	1.0	1.1932E-10 s	1E+99	2.067E-10 s	2E-139
k_TB	1.00E-20 s	1.084E-17 s	rectangular	1.73	1.0	1.0835E-17 s	1E+99	1.88E-17 s	1.4E-167
ts	2.499E-07					1.199E-10 s	1396512		1.48E-46
		Expanded uncertainty of measurement:				2.398E-10 s			
						9.6E-04			

Table 8. Uncertainty budget table for TiGen standard – dn7

Mathematical model of measurement:								
	Linearity =	1.00000E-10 s	Tacc =	100 ps	Skew =	0 ps		
ts=tc+k_RU + k_SU + k_TB	Tlte =	6.66667E-12 s	Tss =	20 ps			Start Trig =	0.5 V
	Offset =	1.06667E-10 s	Ein =	500 uV	Input noise		Stop Trig =	0.5 V
k_RU =(1,4(Tss^2+Te^2)^1/2)			En =	1000 uV	Signal noise		Tlse_start =	0.006 V
	Te =((Ein^2+En^2+Vx^2)^1/2)/SR		Vx =	2250 uV	Cross Talk		Tlse_stop =	0.006 V
k_SU = Linearity + Offset			SRstart =	1.8 E+09 V/s	SRstop =	1.8 E+09 V/s		
	Te =	3.4 E-14 s	U0start =	2.250 V	U0stop =	2.250 V	Vh =	0.020 V
Tlte = (Tlse_start/Srstart + Tlse_stop/Srstop) + (1/2Vh/Srstart - 1/2Vh/Srstop)			Rtstart =	1.0E-09 s	Rtstop =	1.0E-09 s		
			U(Δfcs/f)=	1.00E-13				
			Δfcs/f=	4.00E-14				
			δ(Gate)=	7.50E-11				

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty of the estimate	*ui^4(y)/vi*
tc	1.5088E-06 s	1.200E-11 s	normal	1	1.0	1.2000E-11 s	99	1.200E-11 s	2.09E-46
k_RU	0 s	3.615E-12 s	rectangular	1.73	1.0	3.6149E-12 s	1E+99	6.261E-12 s	1.7E-145
k_SU	0 s	1.193E-10 s	rectangular	1.73	1.0	1.1932E-10 s	1E+99	2.067E-10 s	2E-139
k_TB	6.04E-20 s	6.542E-17 s	rectangular	1.73	1.0	6.5422E-17 s	1E+99	1.13E-16 s	1.8E-164
ts	1.509E-06					1.200E-10 s	989190		2.09E-46
		Expanded uncertainty of measurement:				**2.400E-10** s			
						1.6E-04			

Table 9. Uncertainty budget table for TiGen standard – dn126

Mathematical model of measurement:								
	Linearity =	1.00000E-10 s	Tacc =	100 ps	Skew =	0 ps		
ts=tc+k_RU + k_SU + k_TB	Tlte =	6.66667E-12 s	Tss =	20 ps			Start Trig =	0.5 V
	Offset =	1.06667E-10 s	Ein =	500 uV	Input noise		Stop Trig =	0.5 V
k_RU =(1,4(Tss^2+Te^2)^1/2)			En =	1000 uV	Signal noise		Tlse_start =	0.006 V
	Te =((Ein^2+En^2+Vx^2)^1/2)/SR		Vx =	2250 uV	Cross Talk		Tlse_stop =	0.006 V
k_SU = Linearity + Offset			SRstart =	1.8 E+09 V/s	SRstop =	1.8 E+09 V/s		
	Te =	3.4 E-14 s	U0start =	2.250 V	U0stop =	2.250 V	Vh =	0.020 V
Tlte = (Tlse_start/Srstart + Tlse_stop/Srstop) + (1/2Vh/Srstart - 1/2Vh/Srstop)			Rtstart =	1.0E-09 s	Rtstop =	1.0E-09 s		
			U(Δfcs/f)=	1.00E-13				
			Δfcs/f=	4.00E-14				
			δ(Gate)=	7.50E-11				

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*	Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty of the estimate	*ui^4(y)/vi*
tc	1.2039E-05 s	1.300E-11 s	normal	1	1.0	1.3000E-11 s	99	1.300E-11 s	2.88E-46
k_RU	0 s	3.615E-12 s	rectangular	1.73	1.0	3.6149E-12 s	1E+99	6.261E-12 s	1.7E-145
k_SU	0 s	1.193E-10 s	rectangular	1.73	1.0	1.1932E-10 s	1E+99	2.067E-10 s	2E-139
k_TB	4.82E-19 s	5.220E-16 s	rectangular	1.73	1.0	5.2202E-16 s	1E+99	9.04E-16 s	7.4E-161
ts	1.204E-05					1.201E-10 s	720673		2.88E-46
		Expanded uncertainty of measurement:				**2.402E-10** s			
						2.0E-05			

We have candidated CMC for time interval measurements with an uncertainty of 0,5. For this measurements we have calculated uncertainity value 0,34. If our measurement results will be good, that means we should decrease our CMC for time and frequency.

6.2.1 Calculation of standard measurement uncertainty

During calculation of the standard measurement uncertainty, it is necessary to define the contributions of type A and type B of the standard measurement uncertainty.

6.2.1.1 Type A standard measurement uncertainties

Type A of the standard measurement uncertainty, *(u(∂A))*, represents the standard deviation of the arithmetic mean value when measuring the time interval. Normal distribution corresponds to this type of measurement uncertainty.

6.2.1.2 Type B standard measurement uncertainties

During the measuring of time interval, there are three contributions of type B standard measurement uncertainty, as follows:

- Random Error Uncertainty;
- Systematic Error Uncertainty;

- Timebase Error Uncertainty.

Random Error Uncertainty

This contribution to the measurement uncertainty, *(∂RU)*, is calculated as follows (taken from the Agilent 53230A frequency counter specification):

$$\partial RU = \frac{1{,}4 \cdot (T_{SS}^2 + T_E^2)^{1/2}}{t_c} \qquad (eq.\ 4)$$

Where:

T_{SS} – frequency shot timer resolution (single shot timing);
(The value for the time resolution of the frequency counter is given in the specification of the Agilent 53230A frequency counter and is 20 ps.)

T_E – threshold error, is calculated according to the formula given in the manufacturer's specification:

$$\text{For 5V: } \frac{(500\,\mu V^2 + E_N{}^2 + Vx^2)^{1/2}}{SR_{TRIGPOINT}} \qquad (eq.\ 5)$$

$$\text{For 50V: } \frac{(5000\,\mu V^2 + E_N{}^2 + Vx^2)^{1/2}}{SR_{TRIGPOINT}} \qquad (eq.\ 6)$$

Where:

E_N – input noise of signal;
(The value which is taken for the input noise is 1000 µV, and it is checked by oscilloscope.)

V_X – overlap due to another signal (cross talk);
(For the overlap value is taken - 60 dB.)

$SR_{TRIGPOINT}$ – maximum response rate (slew rate);
For rectangular signals and pulses, the maximum slew rate, SR, is calculated by the formulas:

$$SR_{START} = 0.8 * V_{PP}/t_{rise\_start} \qquad (eq.\ 7)$$

$$SR_{STOP} = 0.8 * V_{PP}/t_{rise\_stop} \qquad (eq.\ 8)$$

Where:

V_{PP} – signal amplitude;
t_{rise_start} – initial trigger time;
t_{rise_stop} – final trigger time.

Measurement uncertainty due to Random error is a Type B measurement uncertainty with a rectangular distribution, and the standard uncertainty, *(u(∂RU))*, is calculated as follows:

$$u(\partial RU) = \frac{\partial RU}{\sqrt{3}} \cdot t_c \qquad \text{(eq. 9)}$$

Systematic Error Uncertainty

This contribution to the measurement uncertainty, *(∂SU)*, is calculated as follows (taken from the Agilent 53230A frequency counter specification):

$$\partial SU = Linearity + Offset \qquad \text{(eq. 10)}$$

Where:

$$Linearity = \frac{T_{accuracy}}{t_c} \qquad \text{(eq. 11)}$$

$$Offset = \frac{T_{LTE} + skew + T_{accuracy}}{t_c} \qquad \text{(eq. 12)}$$

$T_{accuracy}$ – accumulated time error.
It is given in the manufacturer's specification of Agilent 53230A, the value is 100 ps.

T_{LTE} – threshold level timing error, a parameter calculated by the formula given in the manufacturer's specification:

$$T_{LTE} = \pm \frac{T_{LSE\_START}}{SR_{START}} \pm \frac{T_{LSE\_STOP}}{SR_{STOP}} \pm \left[\frac{1/2V_H}{SR_{START}} - \frac{1/2V_H}{SR_{STOP}}\right] \qquad \text{(eq. 13)}$$

T_{LSE_START} – error due to threshold setting, and is calculated according to the following formula:

$$T_{LSE} = \pm\ (0.2\%START_{trig} + 0.1\%range) \qquad \text{(eq. 14)}$$

where the range is ± 5V or ± 50V from the frequency counter specification.

T_{LSE_STOP} – error due to threshold setting, and is calculated according to the following formula:

$$T_{LSE} = \pm\ (0.2\%STOP_{trig} + 0.1\%range) \qquad \text{(eq. 15)}$$

where the range is ± 5V or ± 50V from the frequency counter specification.

For our measurements for $START_{trig}$ / $STOP_{trig}$ we used value of 0,5V from specification of standards (TIGen and InLambda).

V_H – is 20 mV or 40 mV when the Noise Reject option is ON.

Duplicate values are used when measuring a frequency greater than 100 MHz.

Skew – additional error calculated if two channels are used.
In our case the value of skew is zero, because we did the cable compensation (for the second measurement we replaced the cable locations at the inputs of the standards in regard to first measurement).

Systematic Error Uncertainty is a Type B measurement uncertainty with a rectangular distribution, and the standard uncertainty, *(u(∂SU))*, is calculated as follows:

$$u(\partial SU) = \frac{\partial SU}{\sqrt{3}} \cdot t_c \qquad (eq.\ 16)$$

Timebase Error Uncertainty

The contribution to the measurement uncertainty, *(∂TU)*, is calculated as follows:

$$\partial TU = U(\frac{\Delta f_{cs}}{f}) + \partial(Gate) \qquad (eq.\ 17)$$

Where:

$U(\frac{\Delta f_{cs}}{f})$ – the value is taken from the last calibration certificate of Cesium clock;

∂(Gate) – values for time base stability are taken from the technical specification of Cesium clock.

Measurement uncertainty due to timebase error (Timebase Error Uncertainty) is a Type B measurement uncertainty with a rectangular distribution, and the standard uncertainty *(u(∂TU))*, is calculated as follows:

$$u(\partial TU) = \frac{\partial TU}{\sqrt{3}} \cdot t_c \qquad (eq.\ 18)$$

6.2.1.3 Expanded measurement uncertainty calculation

The expanded measurement uncertainty, (U), is calculated as follows:

$$U = 2 \cdot \sqrt{c_{\partial A}^2 \cdot u(\partial A)^2 + c_{\partial RU}^2 \cdot u(\partial RU)^2 + c_{\partial SU}^2 \cdot u(\partial SU)^2 + c_{\partial TU}^2 \cdot u(\partial TU)^2} \qquad (eq.\ 19)$$

Where $c_{\partial A} = c_{\partial RU} = c_{\partial SU} = c_{\partial TU} = 1$.

In case we calculate the delay per cable, the expanded measurement uncertainty (U) is calculated as follows:

$$U = \sqrt{U_1^2 + U_2^2} \qquad (eq.\ 20)$$

Where:

U_1 – *expanded measurement uncertainty calculated during the first measurement;*

U_2 – *expanded measurement uncertainty calculated during the second measurement.*

7. Description of the source 10 MHz reference frequency for TIGen standard

For TIGen standard, as the reference frequency source of 10 MHz was used the Cesium clock. The manufacturer of the Cs clock is Microsemi and the model is 5071A (Figure 8).

Accuracy of this Cs clock is ±1 x 10^{-12} and long-term stability ≤5.0 x 10^{-14} for 30 days.

Signal is sinusoidal, 1 Vrms into 50 Ω. Connector type of this output is N female.

Figure 8. Cesium clock 5071 A

8. Description of the used input pulse signals for InLambda standards

In the table below there are characteristics of the signals applied on InLambda standards.

Table 10. Characteristics of the signals applied on InLambda standards

Source	Function Generator Agilent 33521A
Frequency	100 Hz
Low level	0 V
High level (at 50 Ω)	2 V
Rise time (20% to 80%)	8 ns
Duty cycle	10 %
Pulse width	1 ms

9. Ambiental conditions of measurements

The measurements were performed at an ambient temperature of 23 °C ± 2 °C and relative humidity 50 % ± 20 %.

In the table below there are average temperature during measurements with InLambda standards.

Table 11. Average temperatures during measurements with InLambda standards

The source of the measured Time Interval	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)	Unit of measure
Inλ 20	23,4 ± 0,5	°C
Inλ 100	23,4 ± 0,5	°C
Inλ 300	22,8 ± 0,5	°C

10. Average date of performing measurements

Date of performing measurements is April 15, 2021.

Alina Musić **April 29, 2021**

Jovana Vukoslavović

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: .....MBM Country: Montenegro

Average date of measurements: ..15.04.2021.

Remarks:

...

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, ...)	Cs Clock			10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)	1,4Vpp			within (0.5 ÷ 2) V_{p-p}	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	2	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
50	±	20	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, ...)	Agilent 53230A
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0.150 ns/2 for SR620, unknown, ≤ ..., ...)	100 ps (Tacc) Accuracy of Time Interval Counter

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty ($p \approx 95$ %) (in ns)			Unit of measure
"cn0"	22,65	±	0.34	ns
"cn3"	249,99	±	0.34	ns
"cn7"	1508,93	±	0.34	ns
"cn126"	12039,48	±	0.34	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Function Generator Agilent 33521A		
1 pps (yes / no)	no		
Frequency	100 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2V	(1,75 ÷ 2,25) V	yes
Rise time (20% to 80 %)	8 ns	< 10 ns	yes
Duty cycle	10 %	≤ 50 %	yes
Pulse width	1 ms	to avoid the pulse widths close (**<± 10 ns**) to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	In 100	Inλ 100 or Inλ 300	yes
Inλ 100	In 20	Inλ 20 or Inλ 300	yes
Inλ 300	In 20	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	**Required reference conditions**	Meet requirements? yes / no
23	±	2	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	**Required reference conditions**	Meet requirements? yes / no
50	±	20	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, ..)	Agilent 53230A
Applied trigger level (50 Ω) (Required: 0,5 V)	0,5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ ..., ...)	100 ps (Tacc) Accuracy of Time Interval Counter

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24,17	±	0,34	ns	23,4	±	0,5	°C
Inλ 100	104,46	±	0,34	ns	23,4	±	0,5	°C
Inλ 300	307,27	±	0,34	ns	22,8	±	0,5	°C

Alina Musić *Alina Musić*
Jovana Vukoslavović *Jovana Vukoslavović* 29.04.2021.
....

(Name) (Date)

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: MBM Country: Montenegro

Average date of measurements: 15.04.2021.

Remarks:

Model equation that follows from the measurement setup:

$TI = ...$ ts = tc + k_RU + k_SU + k_TU

Description of the quantities in the model equation:

Quantity X	Description
tc	the mean value of the measured values read from the frequency counter
k_RU	Random error correction
k_SU	Systematic Error correction
k_TU	Timebase error correction

Uncertainty budget 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 $c_i \cdot u(x_i)$	Degrees of freedom ν_i
... tc	2,2554E-08	9E-12	normal	A	1	9E-12	99
...							
...							

Combined standard uncertainty	u_c	1,197E-10
Effective degrees of freedom	ν_{eff}	3099021
Expanded uncertainty ($p \approx 95\%$)	U	2,394E-10

Alina Musić *Alina Musić*
Jovana Vukoslavović *Jovana Vukoslavović* 29.04.2021.

(Name) (Date)

Appendix V

IMBIH report

EURAMET.TF-S1 Supplementary Comparison
”Comparison of time interval measurements”
(performed within EURAMET Project #1485)

Measurements report for IMBIH

Prepared by: Osman Sibonjic and Sani Sarcevic

June 2021

1. Identification of the participating laboratory

Institute: Institute of Metrology of Bosnia and Herzegovina
Acronym: IMBIH
Address: Augusta Brauna 2, Sarajevo, 71000
Country: Bosnia and Herzegovina
Contact Name Osman Sibonjic
Telephone 38733568923
Email osman.sibonjic@met.gov.ba

2. Description of the calibration method

IMBIH used direct measurement procedure using time interval counter (TIC) with compensation of the cable delay differences. For the reference TIC, SR620 Stanford Research Systems was used.

Cables delay difference was estimated using Stanford Research Systems Digital Delay Generator DG645. With nominal DG645 delay set to zero, and the signal shape (amplitude and rise time) similar to DUT signals, the cable delay differences were measured using reference TIC. This value was then subtracted from measurements results.

3. Description of the calibration set-up and equipment

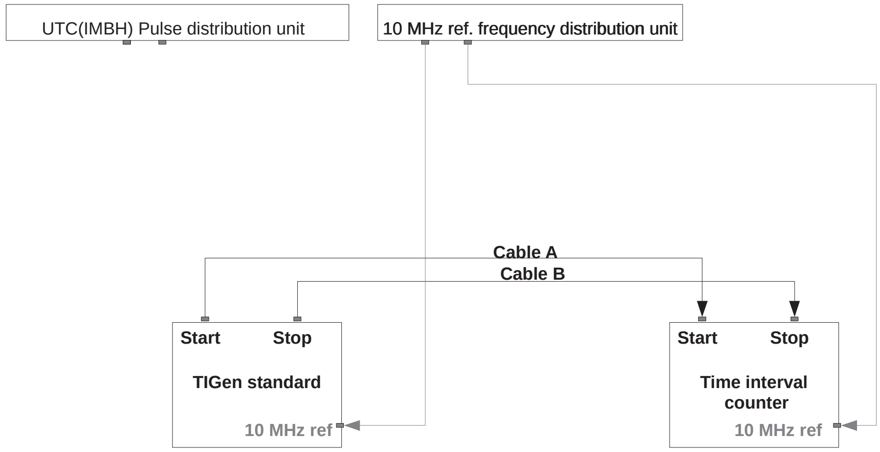
The calibration set-up for cases 1 and 2 are shown on Figure 1 and 2 respectively.

For all measurements, external reference for TIC was 10 MHz laboratory reference frequency coherent with UTC(IMBH). For the first case, this frequency was also connected to TIGen standard. In the second case, reference PPS pulses for InLambda aux device comes from UTC(IMBH) pulse distribution unit.

In order to minimize cables delay difference, start and stop cables were of the same nominal length, type and producer. These cables directly connects start and stop ports of the DUT and TIC.

Equipment used:

Reference TIC: SR620 Stanford Research Systems
Stanford Research Systems Digital Delay Generator DG645 (for cables delay estimation)
Cable A, cable B: Pomona RG58C/U BNC 50Ω (1.5m)
Timetech Pulse Distribution Unit, output levels 2.5Vpp @50Ω
Frequency Distribution Amplifier, 10MHz sine wave outputs



Set-up 1: TIGen standard

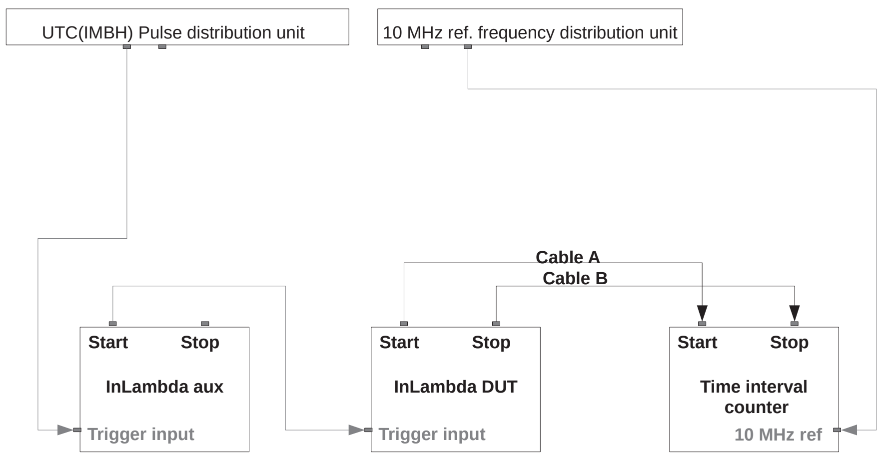


Figure 1 and 2: Measurement set-up

4. Traceability chart

IMBIH’s Laboratory for Time and Frequency participates in realization of Coordinated Universal Time (UTC) and achieves international traceability through BIPM Key comparison CCTF-K001.UTC. National time scale is generated using high performance 5071A cesium atomic clock and steered by High Resolution Offset Generator. Outputs from HROG are connected to pulse and frequency distribution units which represent laboratory reference planes.

Traceability chain is shown on Figure 3.

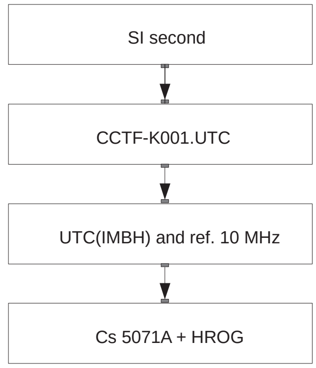


Figure 3: Traceability chain

5. Used relationship / model equation

Estimated values of time interval measurements are given by the model equation that follows from the measurement setup:

$$TI = X_{TIC} - X_{Cables} + (X_{LSD}+X_{non\text{-}lin}+X_{res}+X_{ss}+X_{q}+X_{imp}+X_{filter})$$

where:

Quantity X_i	Description
X_{TIC}	Average value of N=100 TIC readings
X_{Cables}	Estimated cables delay difference
X_{LSD}	TIC Least significant digit
$X_{non\text{-}lin}$	TIC Diff. Non-linearity
X_{res}	TIC Resolution
X_{ss}	TIC StartStopTriggerError
X_{q}	TIC Quantization error
X_{imp}	TIC Impedance missmatch
X_{filter}	TIC Input filter

6. Obtained results of measurements and corresponding uncertainties

Uncertainty budget table, all values in s:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
X_{TIC}	2.2598E-08	5.0E-12	Normal	A	1	5.0E-12	99
X_{Cables}	-7.5E-11	4.0E-11	Rectangular	B	0.577	2.3E-11	1.0E+99
X_{LSD}	0	4.0E-12	Normal	B	1	4.0E-12	1.0E+99
$X_{non-lin}$	0	7.5E-11	Normal	B	1	7.5E-11	1.0E+99
X_{res}	0	2.5E-11	Normal	B	1	2.5E-11	1.0E+99
X_{ss}	0	2.0E-11	Normal	B	1	2.0E-11	1.0E+99
X_q	0	1.0E-11	Rectangular	B	0.577	5.8E-12	1.0E+99
X_{imp}	0	1.5E-11	Normal	B	1	1.5E-11	1.0E+99
X_{filter}	0	5.0E-11	Normal	B	1	5.0E-11	1.0E+99
		Combined standard uncertainty			u_c	9.98E-11	
		Effective degrees of freedom			ν_{eff}		1.57E+07
		Expanded uncertainty ($p \approx$ 95%)			U	2.00E-10	

Date of measurements: 20.05.2021.

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	Cs clock			10 MHz ± 1 Hz	yes
Amplitude (at 50 Ω)	3.0			within (0,5 ÷ 2) V_{p-p}	no
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23.6	±	0.2	˚C	within (22 ± 4) ˚C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
42.6	±	2.3	%	within (50 ± 30) %	yes
The base equipment used for time interval measurements					
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)				SR620	
Applied trigger level (50 Ω) (Required: 0,5 V)				0.5 V	

Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0.150 ns/2

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22.674	±	0.2	ns
"dn3"	250.052	±	0.2	ns
"dn7"	1508.987	±	0.2	ns
"dn126"	12039.603	±	0.2	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Cs clock		
1 pps (yes / no)	yes		
Frequency	1 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	2.88	(1,75 ÷ 2,25) V	no
Rise time (20% to 80 %)	< 5 ns	< 10 ns	yes
Duty cycle	0.002 %	≤ 50 %	yes
Pulse width	20 µs	to avoid the pulse widths close **(<± 10 ns**) to the measured time intervals	yes

Application of a double configuration					
DUT – Device Under Test			Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20			Inλ 300	Inλ 100 or Inλ 300	yes
Inλ 100			Inλ 300	Inλ 20 or Inλ 300	yes
Inλ 300			Inλ 100	Inλ 20 or Inλ 100	yes
Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23.6	±	0.2	˚C	within (22 ± 4) ˚C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
42.6	±	2.3	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	SR620
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	0.150 ns/2

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.217	±	0.2	ns	23.7	±	0.2	˚C
Inλ 100	104.526	±	0.2	ns	23.7	±	0.2	˚C
Inλ 300	307.358	±	0.2	ns	23.7	±	0.2	˚C

Appendix W

SASO report

Saudi Standards, Metrology and Quality Org (SASO)
National Measurement and Calibration Center (NMCC)
Report of Time Interval Measurement with Universal Frequency Counter / Timer 53230A

1. Measurement Method

Time Intervals between start and stop signals of T-Gen were measured using counter. We connect start signal to channel 1 and stop signal to channel 2 of counter (Fig.1). And adjustment channel 1 & 2 according as a recommended in Technical protocol.

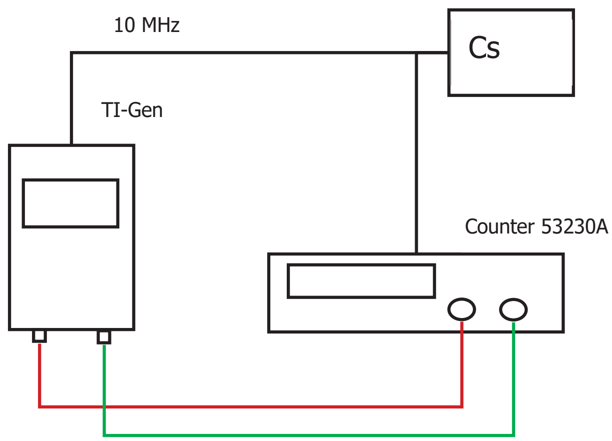


Fig 1. Time Interval Measurement of T-Gen with counter.

2. Measurement Method

Time Intervals between start and stop signals of λ1, λ2 and λ3 were measured using counter. First, using externally trigger signal by the pulse generator with. First, the external trigger signal from the pulse generator roughly was synchronized with the trigger signal of λx, It was (low level 0 V, high level 0.77 , frequency 200 Hz , duty cycle 50%) .Then We connect start signal to channel 1 and stop signal to channel 2 of counter (Fig.2).). And adjustment channel 1 & 2 according as a recommended in Technical protocol.

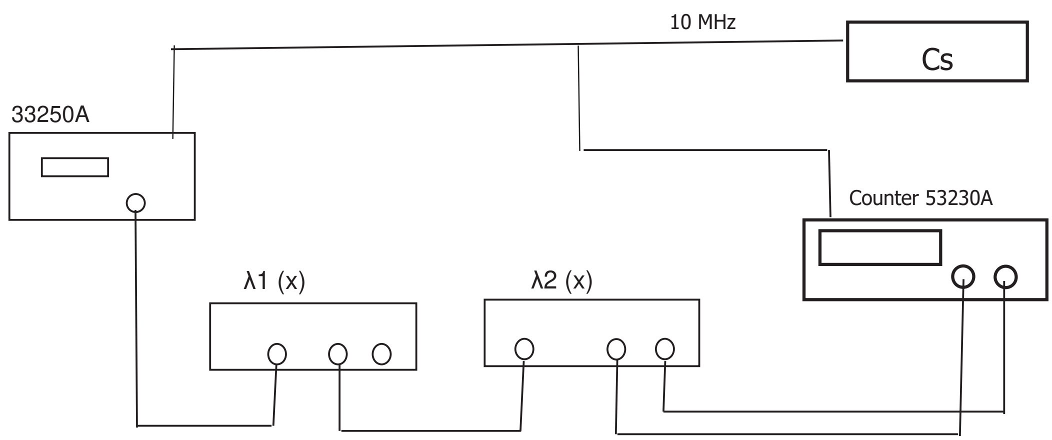


Fig 2. Time Interval Measurement of λ1, λ2 and λ3 with counter.

Equipment Used

No.	Instrument Name	Manufacturer	Type/Model	Serial No.	Traceability
1	Primary Frequency Standard	Symmetricom	5071A	US49352931	BIPM, Circular T 401, 09 Jul. 2021
2	Universal Frequency Counter / Time	Agilent	53230A	MY50006121	SASO-NMCC, 2021-1200-TF-TF- 6 C
3	Function / Arbitrary Waveform Generator	Agilent	33250A	MY40030398	SASO-NMCC, 2021-1221-TF-TF- 13 C

The Environmental Conditions During Measurements : The environmental conditions during the calibration was:

Temperature:	Relative Humidity:
(23 ± 2) ºC	(40 ± 15) %rh

Annex 3. Typical scheme for an uncertainty budget

Supplementary comparison EURAMET.TF-S1
Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: SASO Country: Saudi Arabia

Average date of measurements: 27/06/2021

Remarks:

Model equation that follows from the measurement setup:

$$TI = T_s\left(1+\frac{\Delta f}{f}\right) + \delta T_{RND} + \delta T_{TLTE} + \delta T_{SYS} + \delta T_{DR}$$

Description of the quantities in the model equation:

Quantity X_i	Description
TI	Measurement result
T_s	Average of measured values
$\frac{\Delta f}{f}$	Frequency counter's time base accuracy
δT_{RND}	Random effect
δT_{TLTE}	Trigger Level Timing Error
δT_{SYS}	Systematic effect of the frequency counter
δT_{DR}	Display resolution effect

Uncertainty budget table (dn 0)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	2.282E-08 s	9.00E-12 s	Normal	A	1	9.00E-12 s	999
$\frac{\Delta f}{f}$	0 Hz/Hz	2.00E-12 Hz/Hz	Normal	B	2.282E-08 s	4.56E-20 s	10000
δT_{RND}	0 s	2.29E-11 s	Rectangular	B	1	2.29E-11 s	1000
δT_{TLTE}	0 s	1.75E-11 s	Rectangular	B	1	1.75E-11 s	1000
δT_{SYS}	0 s	1.44E-10 s	Rectangular	B	1	1.44E-10 s	1000
δT_{DR}	0 s	2.89E-23 s	Rectangular	B	1	2.89E-23 s	1000
		Combined standard uncertainty			u_c	1.45E-10 s	
		Effective degrees of freedom			ν_{eff}	1007	
		Expanded uncertainty ($p \approx 95\%$)			U	2.90E-10 s	

Uncertainty budget table (dn 3)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	2.5018E-07 s	1.08E-11 s	Normal	A	1	1.08E-11 s	999
$\frac{\Delta f}{f}$	0 Hz/Hz	2.00E-12 Hz/Hz	Normal	B	2.5018E-07 s	5.00E-19 s	10000
δT_{RND}	0 s	2.29E-11 s	Rectangular	B	1	2.29E-11 s	1000
δT_{TLTE}	0 s	1.75E-11 s	Rectangular	B	1	1.75E-11 s	1000
δT_{SYS}	0 s	1.44E-10 s	Rectangular	B	1	1.44E-10 s	1000
δT_{DR}	0 s	2.89E-22 s	Rectangular	B	1	2.89E-22 s	1000

Combined standard uncertainty	u_c	1.45E-10 s
Effective degrees of freedom	ν_{eff}	1010
Expanded uncertainty ($p \approx 95\%$)	U	2.90E-10 s

Uncertainty budget table (dn 7)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A. B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	1.50911E-06 s	1.25E-11 s	Normal	A	1	1.25E-11 s	999
$\frac{\Delta f}{f}$	0 Hz/Hz	2.00E-12 Hz/Hz	Normal	B	1.50911E-06 s	3.02E-18 s	10000
δT_{RND}	0 s	2.29E-11 s	Rectangular	B	1	2.29E-11 s	1000
δT_{TLTE}	0 s	1.75E-11 s	Rectangular	B	1	1.75E-11 s	1000
δT_{SYS}	0 s	1.44E-10 s	Rectangular	B	1	1.44E-10 s	1000
δT_{DR}	0 s	2.89E-21 s	Rectangular	B	1	2.89E-21 s	1000

Combined standard uncertainty	u_c	1.45E-10 s
Effective degrees of freedom	ν_{eff}	1014
Expanded uncertainty ($p \approx 95\%$)	U	2.90E-10 s

Uncertainty budget table (dn 126)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A. B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	1.203961E-05 s	1.01E-11 s	Normal	A	1	1.01E-11 s	999
$\frac{\Delta f}{f}$	0 Hz/Hz	2.00E-12 Hz/Hz	Normal	B	1.203961E-05 s	2.41E-17 s	10000
δT_{RND}	0 s	2.29E-11 s	Rectangular	B	1	2.29E-11 s	1000
δT_{TLTE}	0 s	1.75E-11 s	Rectangular	B	1	1.75E-11 s	1000
δT_{SYS}	0 s	1.44E-10 s	Rectangular	B	1	1.44E-10 s	1000
δT_{DR}	0 s	2.89E-20 s	Rectangular	B	1	2.89E-20 s	1000

Combined standard uncertainty	u_c	1.45E-10 s
Effective degrees of freedom	ν_{eff}	1009
Expanded uncertainty ($p \approx 95\%$)	U	2.90E-10 s

Uncertainty budget table (λ1 (20))

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A. B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	2.416E-08 s	1.05E-11 s	Normal	A	1	1.05E-11 s	999
$\frac{\Delta f}{f}$	0 Hz/Hz	2.00E-12 Hz/Hz	Normal	B	2.416E-08 s	4.83E-20 s	10000
δT_{RND}	0 s	2.29E-11 s	Rectangular	B	1	2.29E-11 s	1000
δT_{TLTE}	0 s	1.75E-11 s	Rectangular	B	1	1.75E-11 s	1000
δT_{SYS}	0 s	1.44E-10 s	Rectangular	B	1	1.44E-10 s	1000
δT_{DR}	0 s	2.89E-23 s	Rectangular	B	1	2.89E-23 s	1000

Combined standard uncertainty	u_c	1.45E-10 s
Effective degrees of freedom	ν_{eff}	1010
Expanded uncertainty ($p \approx 95\%$)	U	2.90E-10 s

Uncertainty budget table (λ1 (100))

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A. B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	1.0446E-07 s	9.30E-12 s	Normal	A	1	9.30E-12 s	999
$\frac{\Delta f}{f}$	0 Hz/Hz	2.00E-12 Hz/Hz	Normal	B	1.0446E-07 s	2.09E-19 s	10000
δT_{RND}	0 s	2.29E-11 s	Rectangular	B	1	2.29E-11 s	1000
δT_{TLTE}	0 s	1.75E-11 s	Rectangular	B	1	1.75E-11 s	1000
δT_{SYS}	0 s	1.44E-10 s	Rectangular	B	1	1.44E-10 s	1000
δT_{DR}	0 s	2.89E-22 s	Rectangular	B	1	2.89E-22 s	1000
		Combined standard uncertainty			u_c	1.45E-10 s	
		Effective degrees of freedom			ν_{eff}	1007	
		Expanded uncertainty ($p \approx 95\%$)			U	2.90E-10 s	

Uncertainty budget table (λ1 (300))

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Method of evaluation (A. B)	Sensitivity coefficient c_i	Uncertainty contribution $c_i \cdot u(x_i)$	Degrees of freedom ν_i
T_s	3.0727E-07 s	1.19E-11 s	Normal	A	1	1.19E-11 s	999
$\frac{\Delta f}{f}$	0 Hz/Hz	2.00E-12 Hz/Hz	Normal	B	3.0727E-07 s	6.15E-19 s	10000
δT_{RND}	0 s	2.29E-11 s	Rectangular	B	1	2.29E-11 s	1000
δT_{TLTE}	0 s	1.75E-11 s	Rectangular	B	1	1.75E-11 s	1000
δT_{SYS}	0 s	1.44E-10 s	Rectangular	B	1	1.44E-10 s	1000
δT_{DR}	0 s	2.89E-22 s	Rectangular	B	1	2.89E-22 s	1000
		Combined standard uncertainty			u_c	1.45E-10 s	
		Effective degrees of freedom			ν_{eff}	1013	
		Expanded uncertainty ($p \approx 95\%$)			U	2.90E-10 s	

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: SASO Country: Saudi Arabia

Average date of measurements: 27/06/2021

Remarks:

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

<table>
<tr><th colspan="4">External standard 10 MHz reference frequency applied for TIGen standard</th><th>Required reference conditions</th><th>Meet requirements? yes / no</th></tr>
<tr><td colspan="2">Source
(Cs clock, HM, …)</td><td colspan="2">Cs 5071A</td><td>10 MHz ± 1 Hz</td><td>Yes</td></tr>
<tr><td colspan="2">Amplitude (at 50 Ω)</td><td colspan="2">1.26 V</td><td>within (0,5 ÷ 2) V_{p-p}</td><td>Yes</td></tr>
<tr><th colspan="3">Ambient temperature during measurements</th><th>Unit of measure</th><th>Required reference conditions</th><th>Meet requirements? yes / no</th></tr>
<tr><td>23</td><td>±</td><td>2</td><td>°C</td><td>within (22 ± 4) °C</td><td>Yes</td></tr>
<tr><th colspan="3">Ambient humidity during measurements</th><th>Unit of measure</th><th>Required reference conditions</th><th>Meet requirements? yes / no</th></tr>
<tr><td>40</td><td>±</td><td>15</td><td>%</td><td>within (50 ± 30) %</td><td>Yes</td></tr>
<tr><th colspan="6">The base equipment used for time interval measurements</th></tr>
<tr><td colspan="4">The type / brand of time interval counter/ digital oscilloscope
(eg. SR620, 53230A, …)</td><td colspan="2">53230A</td></tr>
<tr><td colspan="4">Applied trigger level (50 Ω)
(Required: 0,5 V)</td><td colspan="2">Yes</td></tr>
<tr><td colspan="4">Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results
(eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)</td><td colspan="2">Systematic Uncertainty= 1.44E-10 s
Without Expended</td></tr>
</table>

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22.81	±	2.90E-1	ns
"dn3"	250.18	±	2.90E-1	ns
"dn7"	1509.11	±	2.90E-1	ns
"dn126"	12039.61	±	2.90E-1	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	yes		
1 pps (yes / no)	no		
Frequency	200 Hz	≤ 200 Hz	yes
Low level	0 V	0 V	yes
High level (at 50 Ω)	1.125 V	(1,75 ÷ 2,25) V	no
Rise time (20% to 80 %)	< 10 ns	< 10 ns	yes
Duty cycle	50 %	≤ 50 %	yes
Pulse width	2.5 ms	to avoid the pulse widths close **(<± 10 ns)** to the measured time intervals	yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	Inλ 100	Inλ 100 or Inλ 300	yes
Inλ 100	Inλ 20	Inλ 20 or Inλ 300	yes
Inλ 300	Inλ 100	Inλ 20 or Inλ 100	yes

Ambient temperature during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
23	±	2	°C	within (22 ± 4) °C	yes
Ambient humidity during measurements			**Unit of measure**	Required reference conditions	Meet requirements? yes / no
40	±	15	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	53230A
Applied trigger level (50 Ω) (Required: 0,5 V)	yes
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	Systematic Uncertainty= 1.44E-10 s Without Expended

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.16	±	2.90E-1	ns	23	±	2	°C
Inλ 100	104.46	±	2.90E-1	ns	23	±	2	°C
Inλ 300	307.27	±	2.90E-1	ns	23	±	2	°C

Khalid S. Aldawood
Waleed M. Alharbi
(Name)

26/07/2021
(Date)

Appendix X

JV report

JV results for EURAMET.TF-S1

Report on supplementary comparison EURAMET.TF-S1 time interval

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Justervesenet (JV) - Norwegian Metrology Service

Version 2 - 2023-03-17

Preface

The full version of this document is a Mathematica notebook (.nb) containing code for data import, processing and presentation. A portable document format version (.pdf) is generated from the full version with hidden input/code cells.

1. Method and Setup

1.1 Description of objects

There are in total seven different time intervals to be measured, generated by two different objects.

1. TIGen is an electronic based time interval generator developed by AGH University of Science and Technology and GUM(Poland). TIGen is property of GUM. TIGen requires external 10 MHz input frequency and generates 127 different time intervals between 1 pps outputs. The set of generated time intervals is determined by the applied PLL lines and programmable logic and counters. All signal inputs/outputs are ended with SMA-female connectors. TIGen is equipped with DC power supplier which has to be connected to the input terminal in the rear panel. Three auxiliary SMA-male-BNC-female adapters are attached in order to facilitate the measurements if the usage of BNC-connectors is possible only. From [TF-S1].
2. InLambda delay standards were developed by InLambda company (Instrumentation Technologies) in cooperation with SIQ (Slovenia) and are based on temperature stabilised fiber delays of approximately 20 ns, 100 ns and 300 ns respectively. InLambda standards are purchased and owned by SIQ. InLambda standards require external input pulses and should be used in pairs (in double configuration)–details are described in further sections precisely. Small influence of external temperature on the measured time intervals between output signals is recognized. All signal inputs/outputs are ended with BNC-female connectors. Power supplying–230VAC, IEC C14 socket. From [TF-S1].

Four of the 127 time intervals of TIGen are to be measured; D00, D03, D07, D126. All three of the InLambda intervals are to be measured.

1.2 Measurement method

To cancel out delays associated with the instrument setup, i.e. differential cable delays and input channel bias, each time interval was measured with four different configurations, as shown in figure 1.

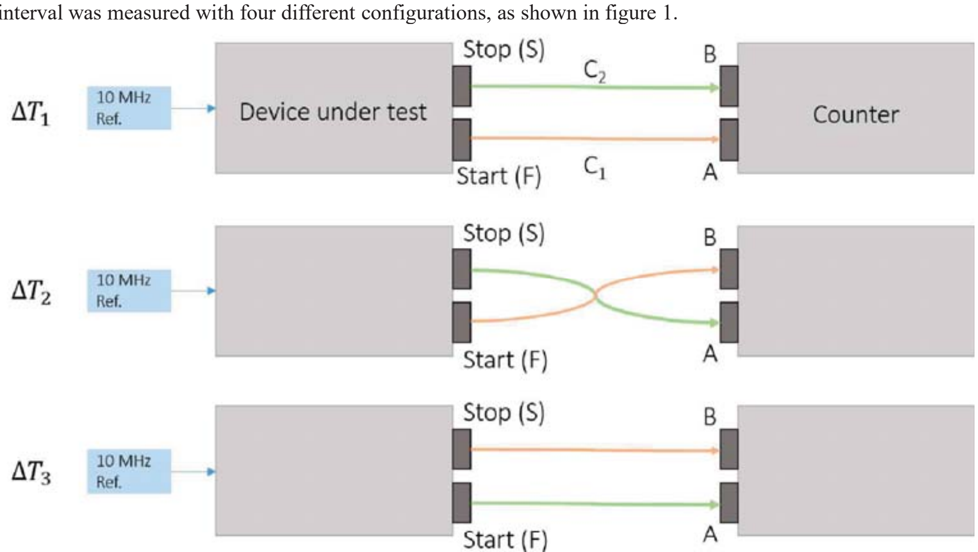


Figure 1: Illustration of the four possible permutations, given two cables and four connections.

1. Start - C1 - Input A, Stop - C2 - Input B
2. Start - C2 - Input A, Stop - C2 - Input B
3. Start - C2 - Input B, Stop - C1 - Input A
4. Start - C1 - Input B, Stop - C1 - Input A

1.3 Measurements and calculations

The time interval ΔT between pulses generated by the DUT is related to the measured time intervals for each permutation as follows:

$$\begin{pmatrix} \Delta BA + \Delta C21 + \Delta T \\ \Delta BA - \Delta C21 + \Delta T \\ -\Delta BA - \Delta C21 + \Delta T \\ -\Delta BA + \Delta C21 + \Delta T \end{pmatrix} = \begin{pmatrix} \Delta T1 \\ \Delta T2 \\ \Delta T3 \\ \Delta T4 \end{pmatrix} \tag{1}$$

Here ΔBA is the differential delay between inputs B and A, ΔC21 is the difference in cable delay between cable 2 and cable 1, and ΔT1 to ΔT4 are the time interval readings from the counter for each of the permutations shown in figure 1. The measurement (mixing) equation can be written in terms of the observation vector y, the mixing matrix x and the parameter vector $\boldsymbol{\beta}$ as follows:

$$x.\beta = y \tag{2}$$

with mixing matrix

$$x = \begin{pmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 1 & -1 & -1 \\ 1 & 1 & -1 \end{pmatrix}, \tag{3}$$

vector of unknowns

$$\beta = \begin{pmatrix} \Delta T \\ \Delta C21 \\ \Delta BA \end{pmatrix} \tag{4}$$

and vector of measurements

$$y = \begin{pmatrix} \Delta T1 \\ \Delta T2 \\ \Delta T3 \\ \Delta T4 \end{pmatrix}. \tag{5}$$

Relation (1) is an over-determined set of equations which in general has no exact solution. A solution, $\tilde{\beta}$, in the least squares minimum sense can be computed from the pseudo-inverse:

$$\hat{\beta} = (x^{\mathsf{T}}.x)^{-1}.x^{\mathsf{T}}.y \tag{6}$$

The pseudo-inverse solution for (1) is

$$\begin{pmatrix} \Delta T \\ \Delta C21 \\ \Delta BA \end{pmatrix} = \frac{1}{4} \begin{pmatrix} \Delta T1 + \Delta T2 + \Delta T3 + \Delta T4 \\ \Delta T1 - \Delta T2 - \Delta T3 + \Delta T4 \\ \Delta T1 + \Delta T2 - \Delta T3 - \Delta T4 \end{pmatrix}. \tag{7}$$

Note that the unknowns ΔBA (differential input delay) and ΔC21 (differential cable delay) can be determined from subsets of the equation system (1) as

$$\Delta C21 = \begin{matrix} (\Delta T1 - \Delta T2)/2 \\ \text{or} \\ (\Delta T4 - \Delta T3)/2 \end{matrix} \tag{8}$$

and

$$\Delta\text{BA} = \begin{matrix} (\Delta\text{T1} - \Delta\text{T4})/2 \\ \text{or} \\ (\Delta\text{T2} - \Delta\text{T3})/2 \end{matrix}. \qquad (9)$$

The pseudo-inverse solution (7) for ΔC21 and ΔBA is simply the average of the solutions in (8) and (9), respectively. The residuals of the equation set (1) is given by

$$y - \tilde{\beta}.x = \frac{\Delta\text{T1} - \Delta\text{T2} + \Delta\text{T3} - \Delta\text{T4}}{4} \begin{pmatrix} 1 \\ -1 \\ 1 \\ -1 \end{pmatrix}. \qquad (10)$$

The magnitude of the residuals are identical and equal to the magnitude of the difference between the solutions (8,9) and the pseudo-inverse (best fit) solutions (7).

■ 1.4 Measurement model and uncertainty estimate

The measurement quantity ΔT to be determined - the time interval between the rising edge of the start pulse and stop pulse of the DUT reaching a voltage 0.5 V - is computed from four time intervals corresponding to the permutations shown in figure 1 and according to the best fit solution (7). The full measurement function for ΔT is

$$\Delta\text{T} = (\Delta\text{T1} + \Delta\text{T2} + \Delta\text{T3} + \Delta\text{T4})/4 + \Delta\text{residual} + \Delta\text{nonLinearity} + \Delta\text{filter} \qquad (11)$$

The input quantities ΔT1 to ΔT4 are based on a number of repeated readouts from the time interval counter. These are treated as type A uncertainties using the mean of sampled values as the central estimate. Inspection of a time series of samples show that samples are not independent, but show some weak autocorrelation. The standard uncertainties of ΔT1 to ΔT4 are therefore based on the sample standard deviation of the series and not the standard error of the mean. An additional type A uncertainty contribution come from the best fit pseudo-inverse with a standard uncertainty contribution due to inconsistencies (residuals) in the mixing equation (1)

$$u_{\text{residual}} = \frac{|\Delta\text{T1} - \Delta\text{T2} + \Delta\text{T3} - \Delta\text{T4}|}{4 \quad 2}. \qquad (12)$$

Additional type B contributions to the uncertainty are due to counter non-linearities and counter input circuit bandwidth. See [Rovera2019] for a discussion. Relevant non-linearity data for Keysight 53230A are taken from the data sheet [Keysight, pp. 21-22] and input filter contribution consistent with a 350 MHz bandwidth [Rovera2019]. All input quantities are treated as uncorrelated and combined accoring to GUM.

An example uncertainty estimate is shown below for measurements of the TIGen00 using a Keysight 53230A counter. Uncertainty estimates for all combinations of time-interval objects and instruments and settings are given in appendices B and C.

Input variables	Estimate	Standard uncertainty	Sensitivity factor	Uncertainty contribution	Relative contribution	Degrees of freedom
ΔT_1	2.2710605×10^4 ps	1.2235498×10^1 ps	$\frac{1}{4}$	3.0588744 ps	0.1	50
ΔT_2	2.271793×10^4 ps	9.7201789 ps	$\frac{1}{4}$	2.4300447 ps	0.1	50
ΔT_3	2.2731995×10^4 ps	6.9166045 ps	$\frac{1}{4}$	1.7291511 ps	0.0	50
ΔT_4	2.2646351×10^4 ps	9.227121 ps	$\frac{1}{4}$	2.3067802 ps	0.0	50
Δresidual	0 ps	1.3845206×10^1 ps	1	1.3845206×10^1 ps	1.6	2
ΔnonLinearity	0 ps	100 ps	1	100 ps	83.0	1000
Δfilter	0 ps	43 ps	1	43 ps	15.0	1000
Results						Efective degrees of freedom
ΔT	2.270172×10^4 ps		Combined uncertainty u	1.0983744×10^2 ps		1195
			Expanded uncertainty U	2.1967488×10^2 ps	Coverage factor	2.

Comments: The dominant uncertainty contributions are fixed magnitude (type B) contributions due counter non-linearity and input filter bandwidth. See Appendix A for an overview of the uncertainty contribution from residuals for all objects and instruments used. See appendix B (TiGen) and C (InLambda) for uncertainty estimates for all calibration results.

2 Equipment and software

2.1 Time interval counters

Keysight 53230A - serial no MY61160301

Spectracom CNT-91 - serial no 189461

2.2 Cables and connectors

Coaxial cables used are of type RG-223 of nominal length 1.5 m and terminated with BNC connectors.

Cable 1 marking: TF-RG223-1.5m-BNC-02

Cable 2 marking: TF-RG223-1.5m-BNC-04

2.3 Reference frequency for TiGen

10 MHz from passive Hydrogen maser Vremya-CH VCH 1008, serial no. 04618. Amplitude of 10 MHz reference signal: 1.32 V. Relative frequency offset < 10^{-12}.

2.4 Start pulse for InLambda

Start pulses for InLambda instruments were generated with the auxilliary output of a Pendulum CNT-91 counter.

Frequency: 10 Hz Low level: 0.0 V High level: 2.21 V Rise time: 1.3 ns Duty cycle: 0.0005 % Pulse width: 500 ns

Software

Caluclations are performed using Mathematica version 13, including JV developed libraries ‘Uncertainty.m’ version 1.14 for GUM uncertainty estimates ‘Units.m’ version 2.0 for handling physical units.

3 Reported calibration results

Calibration data reported in Annex 4 were measured with the Keysight 53230A counter at 0.5 V trigger level. Reported calibration results are shown below. In addition, measurements of TIGen were also performed with the 53230A counter with a 1.0 V trigger level as well as with a Pendulum CNT-91 counter at trigger level 0.5 V. A summary of all calibrations are given in section 4,

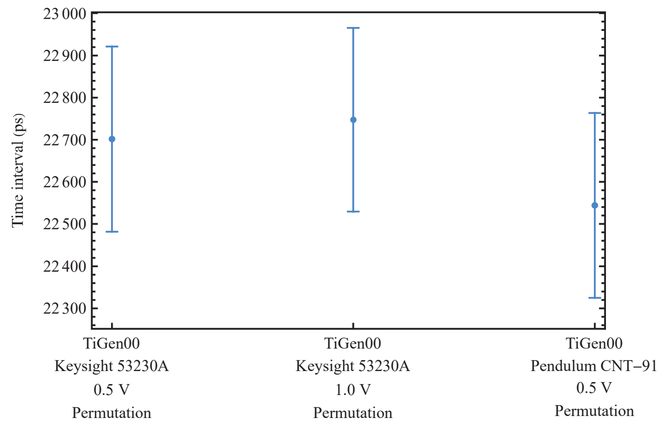
Object	Estimate	Expanded uncertainty	Unit
TIGen00	22.70	0.22	ns
TIGen03	250.08	0.22	ns
TIGen07	1509.01	0.22	ns
TIGen126	12 039.50	0.22	ns

Object	Estimate	Expanded uncertainty	Unit
InLambda20	24.21	0.22	ns
InLambda100	104.51	0.22	ns
InLambda300	307.31	0.22	ns

4 Summary of all calibration results

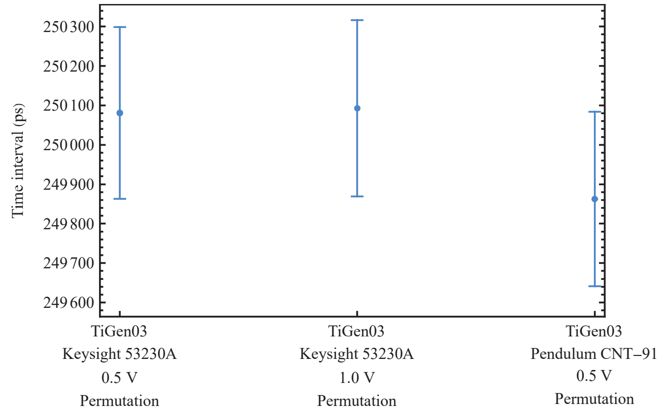
■ 4.1 TiGen00

Object	Instrument	Trigger	Date	Method	Result		2u		degrees of freedom
TiGen00	Keysight 53230A	0.5 V	{2021-10-14 13:35, 2021-10-14 14:12, 2021-10-14 14:18, 2021-10-14 14:06}	Permutation	22702.	ps	219.7	ps	1195
TiGen00	Keysight 53230A	1.0 V	{2021-09-06 05:23, 2021-09-06 06:09, 2021-09-06 05:58, 2021-09-06 05:44}	Permutation	22747.	ps	217.9	ps	1361
TiGen00	Pendulum CNT-91	0.5 V	{2021-10-18 08:32, 2021-10-18 09:12, 2021-10-18 09:03, 2021-10-18 08:42}	Permutation	22544.	ps	219.6	ps	1402



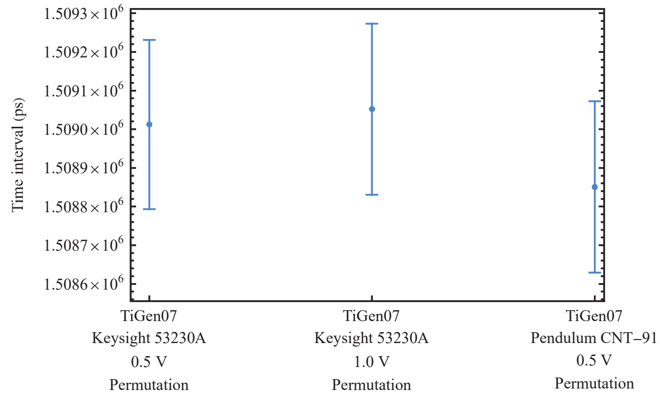
4.2 TiGen03

Object	Instrument	Trigger	Date	Method	Result		2u		degrees of freedom
TiGen03	Keysight 53230A	0.5 V	{2021-10-14 13:37, 2021-10-14 14:13, 2021-10-14 14:19, 2021-10-14 14:07}	Permutation	250081.	ps	218.1	ps	1366
TiGen03	Keysight 53230A	1.0 V	{2021-09-06 05:25, 2021-09-06 06:11, 2021-09-06 06:01, 2021-09-06 05:46}	Permutation	250093.	ps	223.5	ps	533
TiGen03	Pendulum CNT−91	0.5 V	{2021-10-18 08:35, 2021-10-18 09:13, 2021-10-18 09:08, 2021-10-18 08:45}	Permutation	249862.	ps	221.4	ps	1446



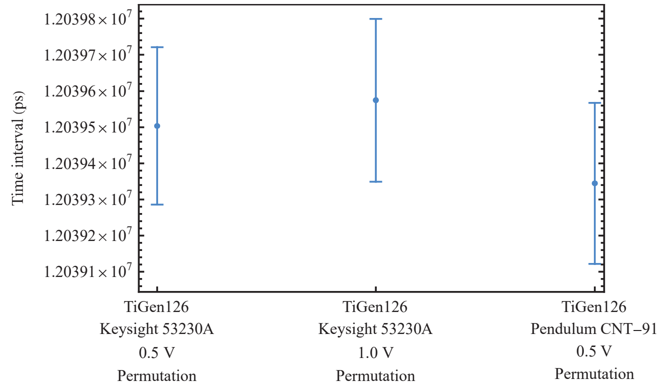
■ 4.3 TiGen07

Object	Instrument	Trigger	Date	Method	Result		2u		degrees of freedom
TiGen07	Keysight 53230A	0.5 V	{2021-10-14 13:38, 2021-10-14 14:14, 2021-10-14 14:20, 2021-10-14 14:08}	Permutation	1509012.	ps	218.8	ps	1330
TiGen07	Keysight 53230A	1.0 V	{2021-09-06 05:35, 2021-09-06 06:13, 2021-09-06 06:03, 2021-09-06 05:49}	Permutation	1509052.	ps	221.2	ps	897
TiGen07	Pendulum CNT-91	0.5 V	{2021-10-18 08:37, 2021-10-18 09:00, 2021-10-18 09:11, 2021-10-18 08:48}	Permutation	1508851.	ps	221.5	ps	1435



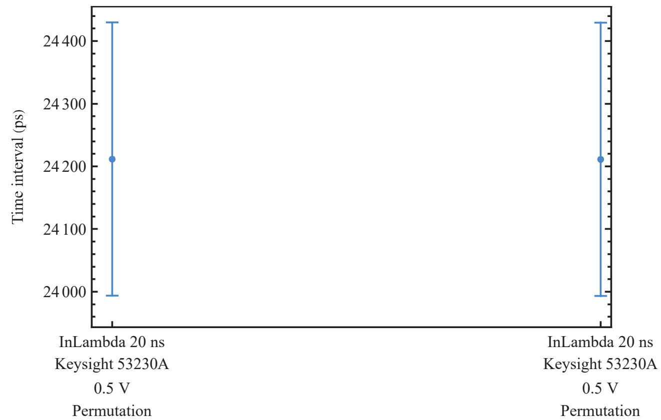
■ 4.4 TiGen126

Object	Instrument	Trigger	Date	Method	Result		2u		degrees of freedom
TiGen126	Keysight 53230A	0.5 V	{2021-10-14 13:58, 2021-10-14 14:11, 2021-10-14 14:17, 2021-10-14 14:05}	Permutation	12039503.	ps	217.9	ps	1362
TiGen126	Keysight 53230A	1.0 V	{2021-09-06 05:39, 2021-09-06 06:16, 2021-09-06 06:05, 2021-09-06 05:52}	Permutation	12039574.	ps	225.3	ps	369
TiGen126	Pendulum CNT-91	0.5 V	{2021-10-18 08:30, 2021-10-18 08:52, 2021-10-18 09:06, 2021-10-18 08:40}	Permutation	12039344.	ps	222.8	ps	1221



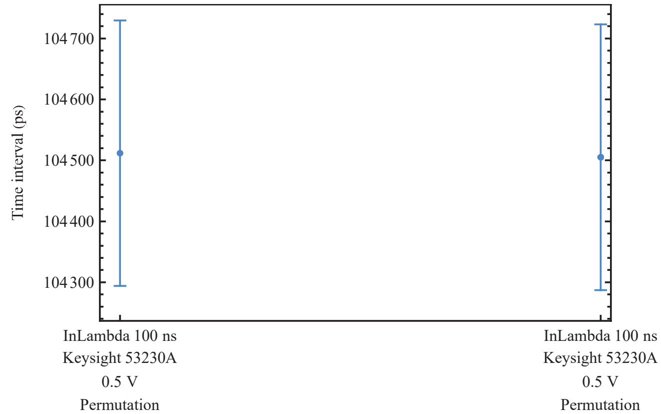
4.5 InLambda 20

Object	Instrument	Trigger	Date	Method	Result		2u		degrees of freedom
InLambda 20 ns	Keysight 53230A	0.5 V	{2021-09-09 09:58, 2021-09-09 09:59, 2021-09-09 10:00, 2021-09-09 09:58}	Permutation	24212.	ps	218.1	ps	1366
InLambda 20 ns	Keysight 53230A	0.5 V	{2021-09-13 08:05, 2021-09-13 08:06, 2021-09-13 08:07, 2021-09-13 08:05}	Permutation	24211.	ps	218.0	ps	1364



▪ 4.6 InLambda 100

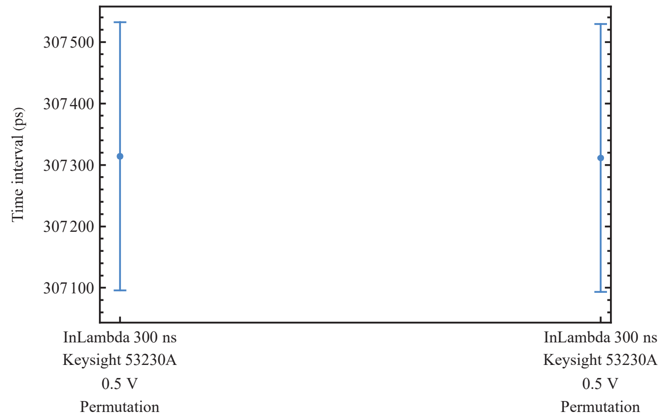
Object	Instrument	Trigger	Date	Method	Result		2u		degrees of freedom
InLambda 100 ns	Keysight 53230A	0.5 V	{2021-09-08 09:51, 2021-09-08 09:54, 2021-09-08 09:54, 2021-09-08 09:53}	Permutation	104512.	ps	218.0	ps	1363
InLambda 100 ns	Keysight 53230A	0.5 V	{2021-09-13 08:12, 2021-09-13 08:13, 2021-09-13 08:15, 2021-09-13 08:13}	Permutation	104505.	ps	218.0	ps	1363



■ 4.7 InLambda 300

Object	Instrument	Trigger	Date	Method	Result		2u		degrees of freedom
InLambda 300 ns	Keysight 53230A	0.5 V	{2021-09-08 09:57, 2021-09-08 10:03, 2021-09-08 10:01, 2021-09-08 09:58}	Permutation	307314.	ps	218.0	ps	1365
InLambda 300 ns	Keysight 53230A	0.5 V	{2021-09-13 08:09, 2021-09-13 08:10, 2021-09-13 08:11, 2021-09-13 08:09}	Permutation	307311.	ps	218.1	ps	1367

Out[ ]=



References

[TF-S1] EURAMET TF-S1 protocol

[Rovera2019] “Time delay measurements: estimation of the error budget”, G D Rovera *et al* 2019 *Metrologia* **56** 035004

[Keysight] Keysight 53200 series counters data sheet, no date. URL: www.keysight.com/us/en/assets/7018-02642/data-sheets/5990-6283.pdf

Appendix A. Comparison of residuals

The largest variable contribution to the uncertainty budgets comes from the residuals of the permutation mixing equation. Recall that the residuals reflect the inconsistency in an overdetermined set of measurements. The table below summarizes this contribution for the different measurement objects and intruments/settings analyzed. For TiGen, measurements were made with Keysight 53230A at 0,5 V and 1.0 V trigger level as well as Pendulum CNT-91 at 0.5 V trigger. InLambda objects were only measured with Keysight 53230A at 0.5 V, but repeated after 5 days. There is a marked difference in the magnitude of residuals/degree of inconsistency: For measurements on the TiGen objects residuals of magnitude 10-30 ps are seen for all combinations of instrument and trigger setting, but not in a consistent manner. The largest residual of correspond to a difference of approx 80 ps between the highest and lowest estimates of input bias ΔBA and cable delay ΔC21 (eq. 8 and 9). For measurements on the InLambda objects, all residuals are less than 1 ps.

Object	Instrument	Trigger [V]	△residual [ps]
TiGen00	Keysight 53 230 A	0.5	13.8
TiGen00	Keysight 53 230 A	1.0	< 1
TiGen00	Pendulum CNT − 91	0.5	3.9
TiGen03	Keysight 53 230 A	0.5	1.9
TiGen03	Keysight 53 230 A	1.0	24.8
TiGen03	Pendulum CNT − 91	0.5	1.2
TiGen07	Keysight 53 230 A	0.5	9.6
TiGen07	Keysight 53 230 A	1.0	18.9
TiGen07	Pendulum CNT − 91	0.5	6.8
TiGen126	Keysight 53 230 A	0.5	< 1
TiGen126	Keysight 53 230 A	1.0	28.6
TiGen126	Pendulum CNT − 91	0.5	14.5
InLambda20	Keysight 53 230 A	0.5	< 1
InLambda20	Keysight 53 230 A	0.5	< 1
InLambda100	Keysight 53 230 A	0.5	< 1
InLambda100	Keysight 53 230 A	0.5	< 1
InLambda300	Keysight 53 230 A	0.5	< 1
InLambda300	Keysight 53 230 A	0.5	< 1

Annex 4. Summary of results

Supplementary comparison EURAMET.TF-S1

Time interval measurements

In addition to your measurement report, please send this information by e-mail to GUM e-mail: (albin.czubla@gum.gov.pl).

Acronym of institute: JV ..... Country: NO .....

Average date of measurements: … 2021-10-10

Remarks:

….

Measurement results with uncertainty and conditions met during measurements:

A1. TIGen standard – conditions met during measurements

External standard 10 MHz reference frequency applied for TIGen standard				Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, …)	Passive HM			10 MHz ± 1 Hz	Yes
Amplitude (at 50 Ω)	1.32 V			within (0,5 ÷ 2) V_{p-p}	Yes
Ambient temperature during measurements			Unit of measure	Required reference conditions	Meet requirements? yes / no
22.5	±	0.5	°C	within (22 ± 4) °C	Yes
Ambient humidity during measurements			Unit of measure	Required reference conditions	Meet requirements? yes / no
42	±	2	%	within (50 ± 30) %	yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Keysight 53230A
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5 V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	100 ps

A2. TIGen standard - measurement results with uncertainty:

Number of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure
"dn0"	22.70	±	0.22	ns
"dn3"	250.08	±	0.22	ns
"dn7"	1509.01	±	0.22	ns
"dn126"	12039.50	±	0.22	ns

B1. InLambda standards – conditions met during measurements

External input pulses applied to an auxiliary InLambda standard		Required reference conditions	Meet requirements? yes / no
Source (Cs clock, HM, frequency generator, ..)	Passive HM		
1 pps (yes / no)	Yes		
Frequency	10 Hz	≤ 200 Hz	Yes
Low level	0.0 V	0 V	Yes
High level (at 50 Ω)	2.21 V	(1,75 ÷ 2,25) V	Yes
Rise time (20% to 80 %)	1.3	< 10 ns	ns
Duty cycle	5E-4 %	≤ 50 %	Yes
Pulse width	500 ns	to avoid the pulse widths close (<± 10 ns) to the measured time intervals	Yes
Application of a double configuration			
DUT – Device Under Test	Auxiliary used device	Required reference conditions	Meet requirements? yes / no
Inλ 20	InL 100	Inλ 100 or Inλ 300	Yes
Inλ 100	InL300	Inλ 20 or Inλ 300	Yes
Inλ 300	InL 20	Inλ 20 or Inλ 100	Yes

Ambient temperature during measurements			Unit of measure	Required reference conditions	Meet requirements? yes / no
22.5	±	0.5	°C	within (22 ± 4) °C	Yes
Ambient humidity during measurements			**Unit of measure**	**Required reference conditions**	**Meet requirements? yes / no**
42	±	5	% RH	within (50 ± 30) %	Yes

The base equipment used for time interval measurements	
The type / brand of time interval counter/ digital oscilloscope (eg. SR620, 53230A, …)	Keysight 53230A
Applied trigger level (50 Ω) (Required: 0,5 V)	0.5V
Standard uncertainty component related to a residual nonlinearities or other not reduced systematic effects and included in the uncertainty budget of measurement results (eg. 0,150 ns/2 for SR620, unknown, ≤ …, …)	100 ps

B2. InLambda standards - measurement results with uncertainty:

The source of the measured Time Interval	Determined value of the measured Time Interval with expanded uncertainty (p ≈ 95 %) (in ns)			Unit of measure	Ambient temperature during measurements (for every standard separately – including expanded uncertainty, 95%)			Unit of measure
Inλ 20	24.21	±	0.22	ns	22.5	±	0.5	°C
Inλ 100	104.51	±	0.22	ns	22.7	±	0.5	°C
Inλ 300	307.31	±	0.22	ns	22.7	±	0.5	°C

....

(Name) (Date)