EUROMET Supplementary Comparison, Project 875

Steel tape measure

Final report

Wabern, June 2006, R. Thalmann

Contents

1 Introduction

The metrological equivalence of national measurement standards and of calibration certificates issued by national metrology institutes is established by a set of key and supplementary comparisons chosen and organized by the Consultative Committees of the CIPM and by the regional metrology organizations, respectively.

At the EUROMET TC Length meeting in October 2005, the project partners decided to carry out a comparison for steel tape measurements. It is a follow up comparison of EUROMET.L-S14, project # 677. The Swiss Federal Office of Metrology (METAS) acts as the pilot laboratory and provides the link to EUROMET.L-S14. The results of this international comparison will support the Calibration and Measurement Capabilities (CMCs) declared by the NMIs in the CIPM Mutual Recognition Arrangement (MRA).

2 Organisation

2.1 Conditions for participation

The participating laboratories are NMIs fulfilling the following conditions:

- signatory (or applicant) of the CIPM MRA;
- having submitted CMCs for steel tape calibration (or intending to do so);
- calibrating steel tapes for their customers as a regular service;
- being well trained in handling steel tapes without the risk to damage the tapes.

2.2 Participants

Institute	Adress	Contact
METAS **Coordinator**	Swiss Federal Office of Metrology Lindenweg 50 CH-3003 Bern-Wabern Switzerland	Ruedi Thalmann Tel. +41 31 323 33 85 Fax +41 31 323 3210 rudolf.thalmann@metas.ch
UME	Ulusal Metroloji Enstitüsü (UME) P.O. Box 21 41470 Gebze, Kocaeli Turkey	Tanfer Yandayan Tel. +90 262 646 6355 Fax. +90 262 646 5914 Tanfer.yandayan@ume.tubitak.gov.tr
Metrosert	AS Metrosert Aru 10 EE-10317 Tallinn Estonia	Lauri Lillepea Tel. +372 6 019 508 Fax. +372 6 020 081 lauri.lillepea@metrosert.ee

2.3 Time schedule

The comparison was carried out in the form of a circulation.

Each laboratory had one month for calibration, including transportation.

Laboratory	Country	Date	Report received
METAS	CH	September 2005	-
UME	TR	December 2005	3 March 2006
Metrosert	EE	January 2006	22 May 2006

2.4 Transportation

Transportation was on each laboratory's own responsibility and cost. No ATA carnet was used. After comparison, the tape has been sent back to METAS.

3 Description of the tape and measurement instructions

Length	Width	Nominal load, therm. expansion	Identification	Material	Manufacturer	Line marks
10 m	10 mm	50 N $(11.5 \pm 1) \cdot 10^{-6}$ K^{-1}	metas 05L104019	steel, white painted	Richter	painted

Any further details may be taken from the photographs below:

10 m tape

The tape had to be measured in the following intervals starting from 0 mm:

250 mm	2750 mm	5250 mm	7750 mm
500 mm	3000 mm	5500 mm	8000 mm
750 mm	3250 mm	5750 mm	8250 mm
1000 mm	3500 mm	6000 mm	8500 mm
1250 mm	3750 mm	6250 mm	8750 mm
1500 mm	4000 mm	6500 mm	9000 mm
1750 mm	4250 mm	6750 mm	9250 mm
2000 mm	4500 mm	7000 mm	9500 mm
2250 mm	4750 mm	7250 mm	9750 mm
2500 mm	5000 mm	7500 mm	10000 mm

The tape had to be calibrated in horizontal position, loaded by the nominal force (50 N). Any deviation of this position or force has to be appropriately corrected. The measurement results have to be corrected to the reference temperature of 20°C using the thermal expansion coefficient indicated above.

The uncertainty of measurement shall be estimated according to the *ISO Guide for the Expression of Uncertainty in Measurement*. The laboratories are asked to report a detailed uncertainty budget. For this, the form in the annex may be used. In both, the results tables and the uncertainty budget, the measurement uncertainty has to be expressed in a length dependent form (typically $\mathrm{sqrt}[(a\ \mathrm{mm})^2 + (b \cdot L)^2]$) using a coverage factor of k = 2.

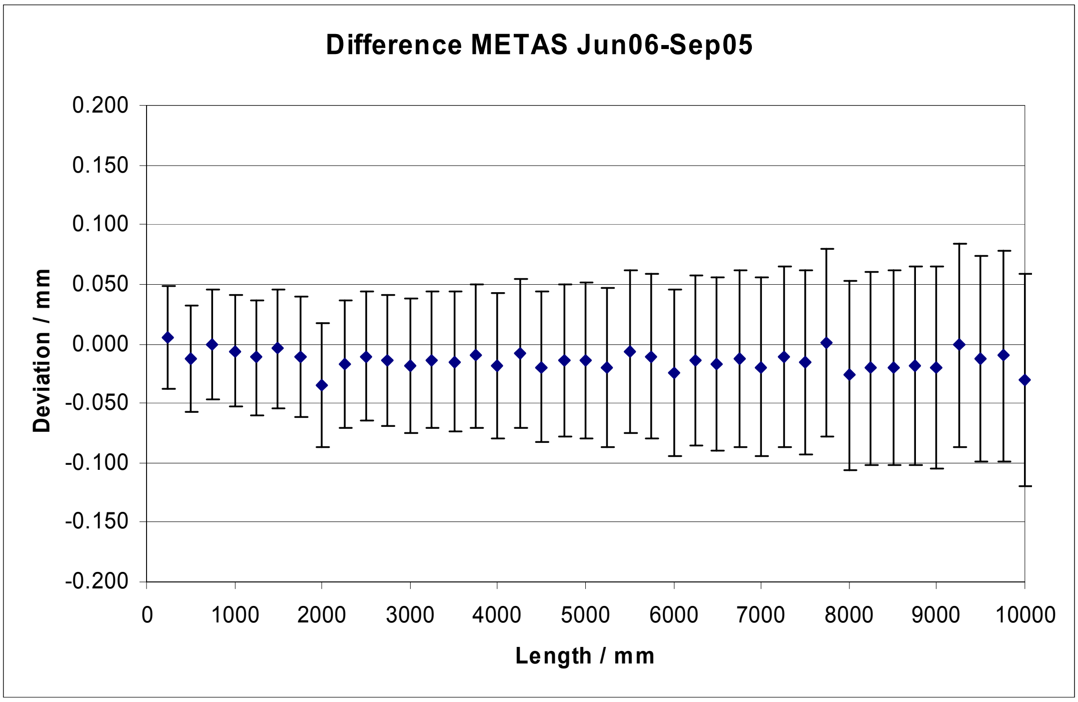
4 Measurement equipment and methods used by the participants

The participating laboratories gave a short description in their measurement report about the equipment and method used for tape calibration. These reports are given in the Appendix. All laboratories used horizontal measurement benches, mostly built in house, of lengths varying between 6 m and 50 m. All labs used a laser interferometer system for the length measurement. In the table below, the most important points are summarized:

Lab	Bench length	Reference	Tape support	Scale mark localisation
METAS	50 m	Laser interferometer	Flat aluminium profile with low friction, high slip, Teflon support	Photo-electric microscope
UME	6 m	Laser interferometer	Flat aluminium profile measurement table	Video b/w-camera
METRO-SERT	21 m	Laser interferometer	Steel rolls at 0.5-m distances	Visual, micro-scope cross-hair

5 Stability of the tape

METAS has calibrated the tape before the circulation in September 2005 and after the circulation in June 2006. The difference between the two measurements is shown in the graph below. It is well within the uncertainty of this difference (shown with error bars at k = 2). The systematically smaller values of the second calibration is due to the fact, that at the initial calibration, the scale marks were localized close to the tape border, whereas for the second measurements they were localized more towards the centre of the tape. The scale marks were systematically curved, in the worst case up to 0.04 mm across the full width of the tape. The marks with maximum curvature were at 2 m, 6 m, 8 m and 10 m, where the largest deviations in the graph can bee seen. It has to be noted, that the influence of scale mark curvature is well with METAS' measurement uncertainty and that such effects should usually be part of the uncertainty budget.



6 Measurement results

In table 1, the measurement results and the expanded measurement uncertainties are given for all three laboratories. The METAS results taken into account were those of the second calibration from June 2006. No reference value was calculated from these results. Instead, the deviations from UME to METAS and from METROSERT to METAS were calculated together with their respective uncertainty. By this, the link is provided to EUROMET.L-S14, where METAS provided satisfactory results. The combined uncertainties of the difference to METAS were calculated by

$$U_{LAB-METAS} = \sqrt{U_{LAB}^2 + U_{METAS}^2} \ .$$

In addition, the En-values were calculated for UME and METROSERT with respect to METAS' results according to the following formula:

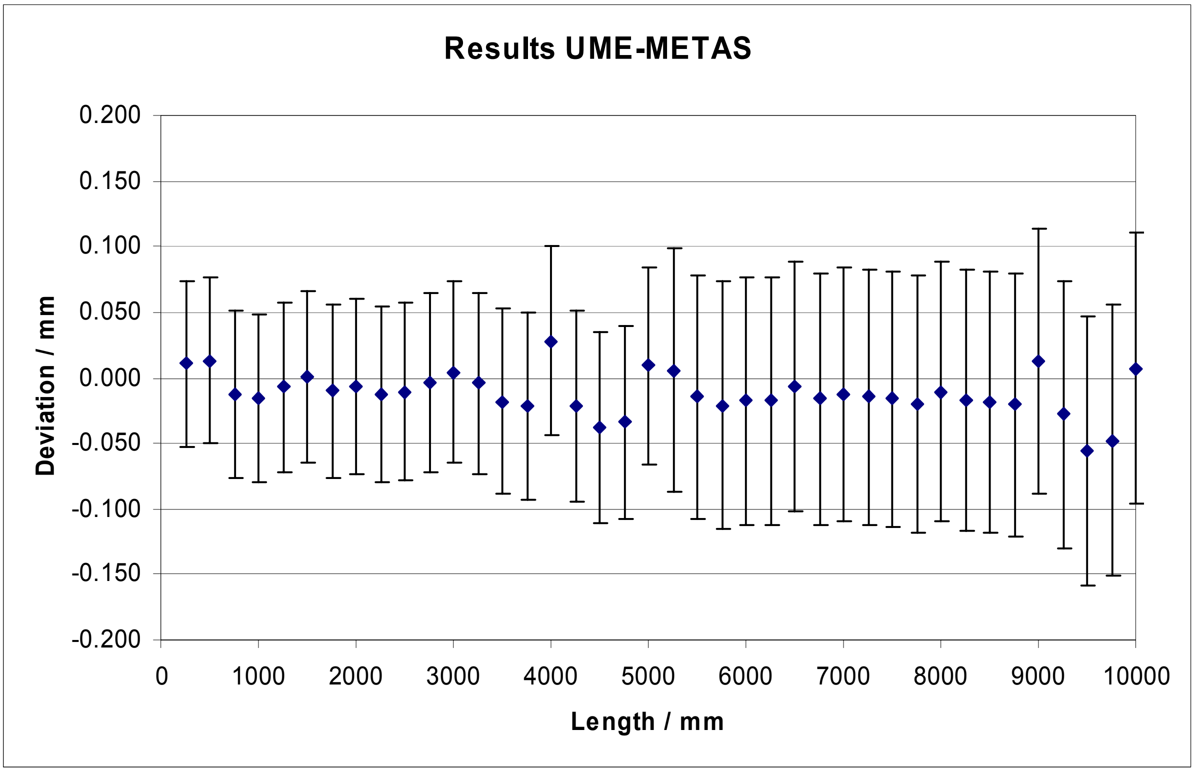
$$En = \frac{x_{LAB} - x_{METAS}}{U_{LAB-METAS}} \ .$$

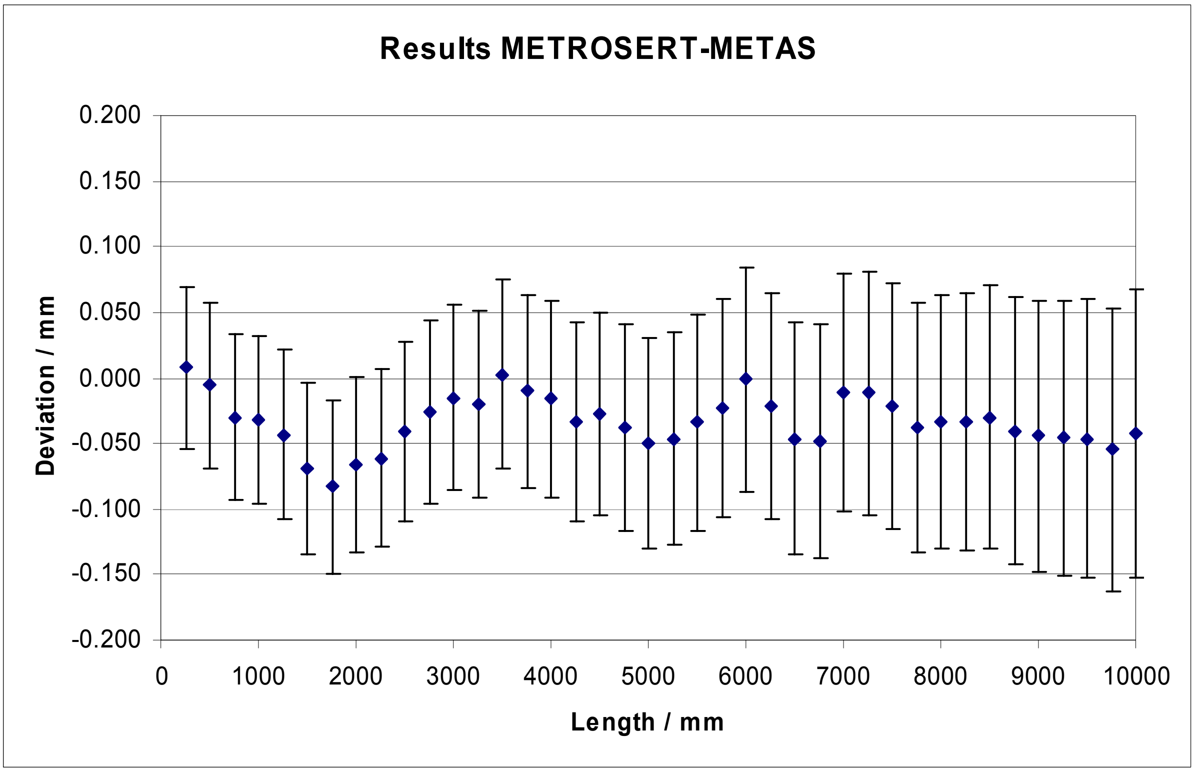
The graphs on the following page show the deviations from UME to METAS and from METROSERT to METAS together with their respective expanded uncertainty $U_{LAB\text{-}METAS}$.

UME has provided two sets of measurement results, one obtained with their laser interferometer facility (as described in the appendix), and a second one based on an incremental line scale in the measurement bench. The latter one is considered to be a secondary method with a larger measurement uncertainty. Therefore, these results were not taken into account for this comparison and thus not reported here.

Nominal	METAS	U_{METAS}	UME	U_{UME}	METROSERT	$U_{METROSERT}$	UME-METAS	$U_{UME-METAS}$	En_{UME}	METROSERT-METAS	$U_{METROSERT-METAS}$	$En_{METROSERT}$
250	250.2353	0.031	250.246	0.055	250.243	0.054	0.011	0.063	0.17	0.008	0.062	0.12
500	500.1779	0.032	500.191	0.055	500.172	0.054	0.013	0.063	0.21	-0.006	0.063	-0.09
750	750.1193	0.032	750.107	0.055	750.089	0.054	-0.012	0.064	-0.19	-0.030	0.063	-0.48
1000	999.8839	0.033	999.868	0.055	999.852	0.054	-0.016	0.064	-0.25	-0.032	0.064	-0.50
1250	1249.8681	0.034	1249.861	0.055	1249.825	0.055	-0.007	0.065	-0.11	-0.043	0.065	-0.67
1500	1499.8157	0.035	1499.817	0.055	1499.747	0.055	0.001	0.065	0.02	-0.069	0.065	-1.05
1750	1749.7689	0.036	1749.759	0.055	1749.686	0.055	-0.010	0.066	-0.15	-0.083	0.066	-1.26
2000	1999.5446	0.037	1999.538	0.056	1999.478	0.056	-0.007	0.067	-0.10	-0.067	0.067	-1.00
2250	2249.6030	0.037	2249.59	0.056	2249.542	0.056	-0.013	0.067	-0.19	-0.061	0.068	-0.90
2500	2499.6494	0.038	2499.639	0.056	2499.608	0.057	-0.010	0.068	-0.15	-0.041	0.069	-0.60
2750	2749.6259	0.039	2749.622	0.056	2749.6	0.058	-0.004	0.068	-0.06	-0.026	0.070	-0.37
3000	2999.4119	0.040	2999.416	0.056	2999.397	0.058	0.004	0.069	0.06	-0.015	0.071	-0.21
3250	3249.5064	0.041	3249.502	0.057	3249.486	0.059	-0.004	0.070	-0.06	-0.020	0.072	-0.29
3500	3499.5551	0.042	3499.537	0.057	3499.558	0.060	-0.018	0.070	-0.26	0.003	0.073	0.04
3750	3749.5299	0.042	3749.508	0.057	3749.52	0.060	-0.022	0.071	-0.31	-0.010	0.074	-0.13
4000	3999.3911	0.043	3999.419	0.057	3999.375	0.061	0.028	0.072	0.39	-0.016	0.075	-0.21
4250	4249.5514	0.044	4249.53	0.058	4249.518	0.062	-0.021	0.072	-0.29	-0.033	0.076	-0.44
4500	4499.5405	0.045	4499.503	0.058	4499.513	0.063	-0.038	0.073	-0.51	-0.028	0.077	-0.36
4750	4749.5058	0.046	4749.472	0.058	4749.468	0.064	-0.034	0.074	-0.46	-0.038	0.079	-0.48
5000	4999.3460	0.047	4999.355	0.059	4999.296	0.065	0.009	0.075	0.12	-0.050	0.080	-0.63
5250	5249.4406	0.047	5249.446	0.080	5249.394	0.066	0.005	0.093	0.06	-0.047	0.081	-0.57
5500	5499.4937	0.048	5499.479	0.080	5499.46	0.067	-0.015	0.093	-0.16	-0.034	0.082	-0.41
5750	5749.5190	0.049	5749.498	0.080	5749.496	0.068	-0.021	0.094	-0.22	-0.023	0.084	-0.27
6000	5999.3853	0.050	5999.368	0.080	5999.384	0.069	-0.017	0.094	-0.18	-0.001	0.085	-0.02
6250	6249.4557	0.051	6249.438	0.080	6249.434	0.070	-0.018	0.095	-0.19	-0.022	0.087	-0.25
6500	6499.4832	0.051	6499.476	0.080	6499.437	0.071	-0.007	0.095	-0.08	-0.046	0.088	-0.52
6750	6749.4871	0.052	6749.471	0.080	6749.439	0.073	-0.016	0.096	-0.17	-0.048	0.090	-0.54
7000	6999.3304	0.053	6999.318	0.080	6999.319	0.074	-0.012	0.096	-0.13	-0.011	0.091	-0.13
7250	7249.4487	0.054	7249.434	0.081	7249.437	0.075	-0.015	0.097	-0.15	-0.012	0.092	-0.13
7500	7499.5638	0.055	7499.548	0.081	7499.542	0.076	-0.016	0.097	-0.16	-0.022	0.094	-0.23
7750	7749.5506	0.056	7749.53	0.081	7749.513	0.078	-0.021	0.098	-0.21	-0.038	0.095	-0.39
8000	7999.3336	0.056	7999.323	0.081	7999.3	0.079	-0.011	0.099	-0.11	-0.034	0.097	-0.35
8250	8249.4494	0.057	8249.432	0.081	8249.416	0.080	-0.017	0.099	-0.18	-0.033	0.099	-0.34
8500	8499.4799	0.058	8499.461	0.081	8499.45	0.082	-0.019	0.100	-0.19	-0.030	0.100	-0.30
8750	8749.4917	0.059	8749.471	0.081	8749.451	0.083	-0.021	0.100	-0.21	-0.041	0.102	-0.40
9000	8999.3701	0.060	8999.383	0.082	8999.326	0.084	0.013	0.101	0.13	-0.044	0.103	-0.43
9250	9249.5388	0.061	9249.511	0.082	9249.493	0.086	-0.028	0.102	-0.27	-0.046	0.105	-0.44
9500	9499.5272	0.061	9499.471	0.082	9499.481	0.087	-0.056	0.102	-0.55	-0.046	0.107	-0.43
9750	9749.5198	0.062	9749.472	0.082	9749.465	0.089	-0.048	0.103	-0.46	-0.055	0.108	-0.51
10000	9999.3398	0.063	9999.347	0.082	9999.297	0.090	0.007	0.104	0.07	-0.043	0.110	-0.39

Table 1. Measurement results for 10 m steel tape, expanded measurement uncertainties ($k = 2$), deviations to METAS and uncertainty of these deviations, and En-values for UME and METROSERT.


Results UME-METAS
Deviation / mm
Length / mm
0.200
0.150
0.100
0.050
0.000
-0.050
-0.100
-0.150
-0.200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000


Results METROSERT-METAS
Deviation / mm
Length / mm
0.200
0.150
0.100
0.050
0.000
-0.050
-0.100
-0.150
-0.200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

7 Measurement uncertainties

The participants were asked to report detailed measurement uncertainty budgets evaluated according to the ISO Guide. In the following, the budgets as presented by the participants are shown.

7.1 METAS

Description	*Quantity* x_i	*Standard uncertainty* $u(x_i)$	*Sensitivity coefficient* $c_i = \partial l / \partial x_i$	*Standard uncertainty* $u_i(l)$ / mm
Laser frequency	λ	$3 \cdot 10^{-9}$	L	$0.003 \cdot 10^{-6} \cdot L$
Air pressure (refractive index)	p	0.29 hPa	$0.27 \cdot 10^{-6} \cdot L$	$0.078 \cdot 10^{-6} \cdot L$
Air temperature (refractive index)	t	0.09 °C	$0.92 \cdot 10^{-6} \cdot L$	$0.080 \cdot 10^{-6} \cdot L$
Air humidity (refractive index)	rH	2.89 %	$0.01 \cdot 10^{-6} \cdot L$	$0.029 \cdot 10^{-6} \cdot L$
Edlén formula	n	$1.2 \cdot 10^{-8}$	L	$0.012 \cdot 10^{-6} \cdot L$
Cosine error	cos α	0.06 mm/m	-	$0.003 \cdot 10^{-6} \cdot L$
Scale mark localisation	ΔLm	11.6 µm	1	0.007
Scale mark quality	ΔLm	11.6 µm	1	0.011
Abbe error		57.8 µm/m	0.08 m	0.005
Measurement force	F	0.87 N	$1.5 \cdot 10^{-6} \cdot L$	$1.3 \cdot 10^{-6} \cdot L$
Calibration temp. sensors	δt	0.01 °C	$11.5 \cdot 10^{-6} \cdot L$	$0.058 \cdot 10^{-6} \cdot L$
Material temperature measurement	δt	0.09 °C	$11.5 \cdot 10^{-6} \cdot L$	$1 \cdot 10^{-6} \cdot L$
Expansion coefficient	$\delta\alpha * \Delta$t	0.58 ppm/°C	0.20 °C	$0.12 \cdot 10^{-6} \cdot L$

Expanded uncertainty: $U = \sqrt{(0.03\ \text{mm})^2 + (3.3 \cdot 10^{-6} \cdot L)^2}$

7.2 UME

Description	*Quantity* x_i	*Standard uncertainty* $u(x_i)$	*Sensitivity coefficient* $c_i = \partial l / \partial x_i$	*Standard uncertainty* $u_i(l)$ / mm
Reference Standards: LASER				
Length measurement using laser interferometer gives an uncertainty of 1.5ppm in the given lab conditions.	1.5E-06	7.50E-07	1	7.50E-07 x L
Resolution of laser interferometer is 0.01micron.	0.01	0.003	1	0.000003
ABBE ERROR:				
PITCH error: There is an ABBE offset between Laser measurement axis and tape measurement axis in Pitch direction. Considering max. angular error in pitch direction is 320", the Abbe offset is 25mm, the error is about 39 micron	39.0	22.517	1	0.023
Temperature and Expansion Coefficient				
Tape temperature: Tape temperature is measured using three HP laser PT100 temperature sensors along the 5m bench. The uncertainty of such measurement is estimated to be 0.10°C.	0.1	5.0E-02	1.15E-05	5.75E-07 x L
Thermal expansion coefficient of the tape: The tape is made of steel, the thermal expansion coefficient of which is 11.5E-06(1/K). Considering that maximum deviation from 20.0°C is less than ±0,5°C, the uncertainty contribution is 1.0E-06x0.5xL.	1.0E-06	5.8E-07	0.5	2.89E-07 x L
ALIGNMENT				
Cossine error is calculated as 0.08E-6 x L	8.0E-08	4.62E-08	1	4.62E-08 x L
LOADING				
Uncertainty contribution due to load force is about 3.0E-06 x L.	3.0E-06	1.73E-06	1	1.73E-06 x L
OPTICAL PROBING (Line Mark Definition)				
This is estimated to be about 30µm.	30.0	15.000	1	0.015

Expanded uncertainty:

L = 0 .. 5 m: $U = \sqrt{(0.055\ \text{mm})^2 + (4 \cdot 10^{-6} \cdot L)^2}$

L = 5 .. 10 m: $U = \sqrt{(0.08\ \text{mm})^2 + (4 \cdot 10^{-6} \cdot (L - 5\ m))^2}$

7.3 METROSERT

Description	*Quantity* x_i	*Standard uncertainty* $u(x_i)$	*Sensitivity coef-ficient* $c_i = \partial l/\partial x_i$	*Standard uncertainty* $u_i(l)$ / mm
Line mark definition	0 mm	0.0250 mm	1.0	0.0250
Abbe error	0 mm	0.019 mm	0.577	0.0110
Laser-interferometer fixed part	0,001 mm	0.0003 mm	1.0	0.0003
Cosine error, alignment	0	0.0005 rad	$2.5 \cdot 10^{-8} \cdot l$	$1.25 \cdot 10^{-7} \cdot l$
Laser-interferometer propor-tional part	0	0.002 mm	$1 \cdot 10^{-4} \cdot l$	$2 \cdot 10^{-7} \cdot l$
Deadpath	0 mm	150 mm	$1.6 \cdot 10^{-10} \cdot l$	$2.5 \cdot 10^{-8} \cdot l$
Tape temperature	20,3 ºC	0.1 ºC	$3.32 \cdot 10^{-4}$ ºC$^{-1} \cdot l$	$3.32 \cdot 10^{-6} \cdot l$
Temperature coefficient	$11,5 \cdot 10^{-6}$ ºC^{-1}	$1 \cdot 10^{-6}$ ºC^{-1}	3.46 ºC$\cdot l$	$3.46 \cdot 10^{-7} \cdot l$
Load	5 kg	0.0001 kg	$1.2 \cdot 10^{-3} \cdot l$	$1.2 \cdot 10^{-7} \cdot l$
Catenary	0 mm	0.008 mm	$1 \cdot 10^{-4} \cdot l$	$8 \cdot 10^{-7} \cdot l$

Expanded uncertainty: $U = \sqrt{(0.054 \text{ mm})^2 + (7.2 \cdot 10^{-6} \cdot L)^2}$

8 Conclusions

This was a follow up comparison to EUROMET.L-S14 in order to give two labs, which ware not yet in a position to participate in S14, the possibility to demonstrate their capability for tape calibrations. Whereas in S14 three tapes had to be calibrated, in the following comparison only one short tape was measured, adapted in its length to the limited measurement range capacity of the two labs. On the other hand, more measurement intervals had to be calibrated.

METAS provided the link between the two comparisons. For analysis of the measurement data and the determination of the degrees of equivalence, the METAS results were considered to be the reference values. The degrees of equivalence from the two labs to METAS were expressed as En-values. The En-values were all smaller than unity, except for METROSERT for two scale marks between 1 m and 2 m, where En > 1. The comparison results can therefore be considered as satisfactory for both, UME and METROSERT, and will thus support their CMC claims within the measurement uncertainties stated in this comparison.

The author would like to thank Michel Degoumois from METAS for performing the initial and the final calibrations of the tape, and the participants for the good cooperation.

9 Corrective actions

Comment Metrosert after Draft A report:

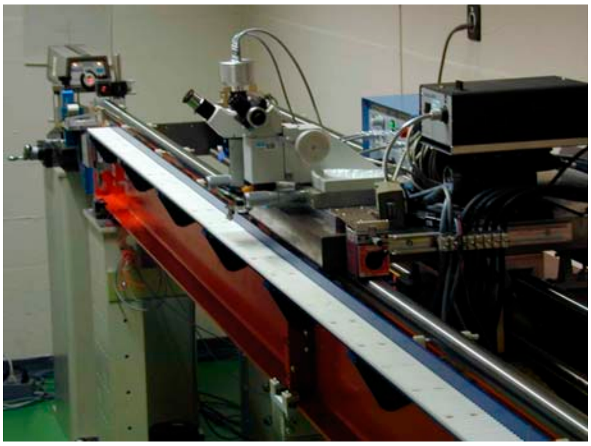
Thank you for fast analysis of the results. We have an idea what is the reason for deviation of our results in region from 1.5 m to 2 m, it appears to be related with pitch error of the rails of our bench. We will undertake necessary corrective actions but for the sake of the time-schedule of this comparison, we are not proposing any corrections.

10 Appendix
Description of the laboratories' measurement equipment

10.1 METAS

Short description of measurement bench

50 m bench with laser interferometer (see photo, detailed description in: Michel Degoumois, *Un long laboratoire de mesure*, OFMETinfo Vol.5, No 2, 1998).



Length measurement instrument

HP 5529 B laser interferometer, range 80 m.

Principle of tape support

Flat aluminium profile measurement table with low friction, high slip, Teflon tape.

Microscope for localisation of scale marks

Photoelectric microscope (with double photo diode as detecting element) for good quality scale marks. Visual microscope for low contrast scale marks.

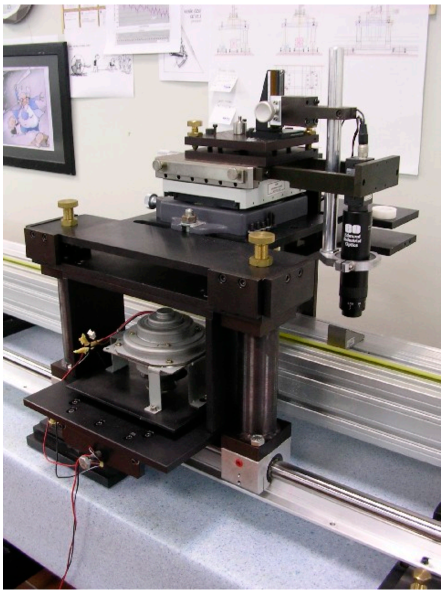
Temperature measurement system, number and location of sensors

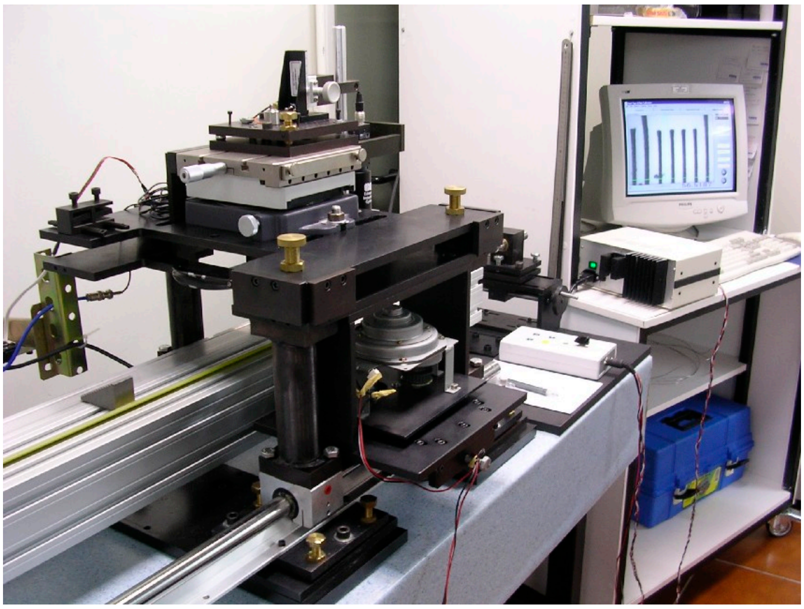
10 thermistors regularly spaced along the measurement bench. For thermal expansion correction, the average temperature is used.

10.2 UME

Short description of measurement bench

UME made 5m Bench was used for tape measurement. It mainly consists of marble base construction, 6 m rail system, mechanical parts and optical units. The rails are kinematically located on a heavy marble construction and a carriage, which employs a camera for probing of the scales on the tapes, is moved a long the rails during the measurement. The image of the scale taken by the camera is viewed on the monitor screen together with software. The operator can perform the probing process by simply placing the measured scales on the viewed target with the help of a motorized system on the carriage. The carriage movement is measured by a 6 m incremental linear encoder integrated to the system or optionally by a laser interferometer. The measurement values are transferred to the computer and an error correction file is applied to the values taken from incremental linear encoder.





Length measurement instrument

Two type length measurement systems were used.

- HP5528A Laser Interferometer System with standard linear interferometer and HP 10751A air sensor.
- 6m HEIDENHEIN LB 302 linear encoder.

Principle of tape support

Flat aluminium profile measurement table.

Microscope for localisation of scale marks

Localization of scale marks is carried out with help of a camera. An analogue black and white camera with a magnifying lens is used to transfer the image of the scale on the monitor screen. The system magnification is (30X). The cross target is made by the software and can be adjusted according to scale mark widths by the user.

Temperature measurement system, number and location of sensor

3 HP Material temperature sensors (10757) are used every 2 meters. Automatic temperature compensation mechanism of HP laser interferometer is used.

Additional remarks

As the measurement bench have 5m measurement range, 10m tape was measured in two steps. 0-5m part was first measured. Then 5-10m part was measured. This was also taken into account during calculation of the uncertainty budget. Two separate uncertainty values are given depending on the length of the tape, (0-5m or 5-10m part)

10.3 METROSERT

Short description of measurement bench (ev. photo)

The 21-m bench is located in the designated corridor-like laboratory room. The lab is air-conditioned and the stability of temperature is ± 0.5 ºC. Two stainless steel rails running in parallel are made of 3-m long rods. The rails lay without fixed attachment on metal supports which are mounted on concrete base. The base rests on pillars made of bricks.

Length measurement instrument
Laser-interferometer system Renishaw ML10 was used in the tape measurements.

Principle of tape support

Measurement tape is supported by steel rolls at 0.5 m distances.

Microscope for localisation of scale marks

The microscope is attached on carriage. The microscope cross-hair is driven to the measurement position and focused on mark line manually.

Temperature measurement system, number and location of sensors

Three temperature sensors from Renishaw are attached to the tape in equal distances. The uncertainty of the temperature measurement is ± 0.2 ºC (k=2) In addition, the air temperature, relative humidity and pressure sensors are located in the measurement room. All sensors are connected to climate station EC10 from Renishaw.