

# Upgrade of 5m-Bench System for Traceable Measurements of Tapes and Rules at SASO-NMCC Dimensional Laboratory

Bülent ÖZGÜR<sup>1,\*</sup>, Okhan GANİOĞLU<sup>1</sup>, Nasser Al-Qahtani<sup>2</sup>, Faisal Al-Qahtani<sup>2</sup>

<sup>1</sup>TÜBİTAK, National Metrology Institute (UME) – Dimensional Laboratory

P.K. 54 41470 Gebze – KOCAELİ, TURKEY

<sup>2</sup>SASO NMCC, Saudi Standards, Metrology and Quality Org. of Kingdom of Saudi Arabia,

National Measurement and Calibration Center

\*Corresponding author: [bulent.ozgur@tubitak.gov.tr](mailto:bulent.ozgur@tubitak.gov.tr)

## Abstract

TÜBİTAK UME and SASO-NMCC have signed the project named "STAGE D-3 Development Consultancy Service Program for SASO-NMCC" in 2014. One part of the project was the upgrade of the old 5m-Bench system of SASO-NMCC that was previously constructed by NPL India. Therefore after transporting and set-up process of the old system to the new building of SASO-NMCC, upgrade process has been started.

The old system, which was demounted, was moved to its new location and the parts and main body to be used were cleaned and installation was completed. The new carrier was designed, manufactured and assembled. All system are located on a special design approximately 7.25 m long tables that are previously constructed. The new carrier is designed such that it can carry a camera for probing of the scales, adjustable x-y tables, laptop pc and a retro-reflector of laser interferometer. New tape clamping and tensioning system are designed and manufactured. A carriage, which employs a camera for probing of the scales on the tapes, is moved along the rails during the measurement. The image of the scale taken by the camera is viewed on the monitor screen with the help of a software. The operator can perform the probing process by simply placing the measured scales on the viewed target with the help of an X-Y table located on the carriage. The X-Y table and the carriage movement are measured by a laser interferometer. The measurement values are obtained and evaluated according to (OIML R 35-1), European legal metrology (73/362/EEC) standards, or with the user specifications. The developed software for monitoring the position of the scale that is running under windows environment but temperature measurement and required corrections are made through laser interferometer. The overall uncertainty for the system is  $U_{k=2} = [(80)^2 + (4.1 \cdot L)^2]^{1/2} \mu\text{m}$ , where L is measured length of the tape or rule in meters.

In this paper the upgrade process and the upgraded 5m-Bench System of SASO-NMCC Dimensional Laboratory is explained and its performance results are shown.

## 1. Introduction

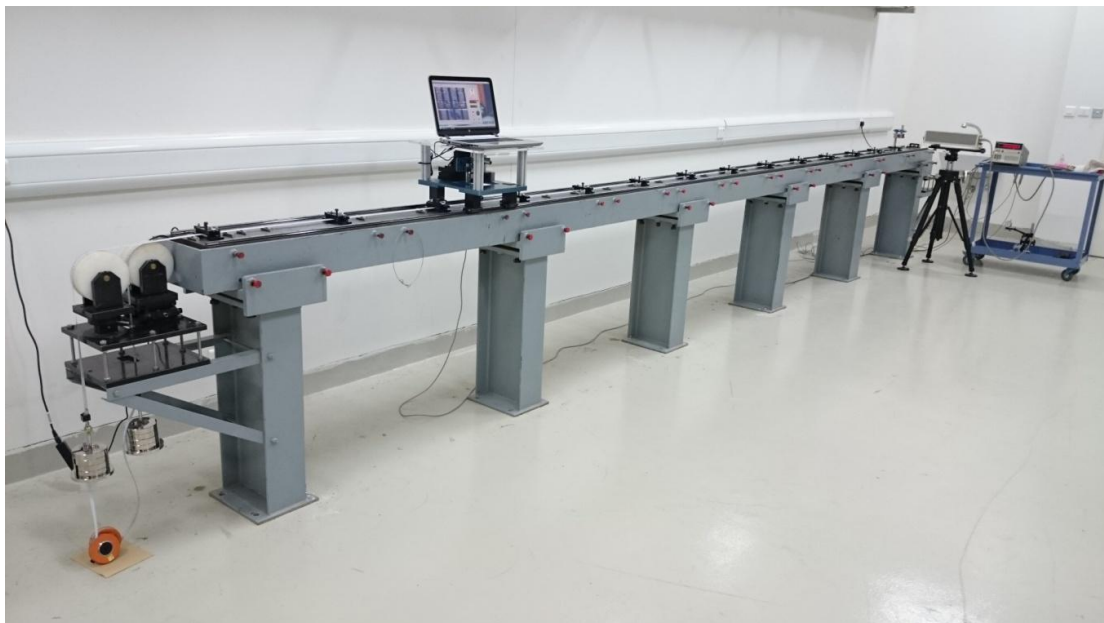
SASO-NMCC has worked on a measurement system named 5m-Bench related to steel tape and ruler calibration in 3 different time periods in 2014-2016. The current system of SASO-NMCC was produced and serviced by NPL-India. However, new metrology building has constructed and this system has not been moved to new building and left as demounted and thus became out of service.

As TÜBİTAK UME, one part of the SASO development project was to make 5m-Bench system operational again in a feasible way for the purpose of providing services related to steel tape and ruler calibrations. Work flow was as follows;

- Inspection of the existing 5m-Bench system, reassembly and installation of existing parts and construction.
- Removal of rust and dust from the old construction due to being out of service for long time and lack of maintenance.
- Installation of new system components, calibration work and test measurements
- Describing the working principles of the existing laser interferometers and equipment and showing how they are used on the system. Performing sample calibration studies with the new system.

The work summarized above and the upgraded system is called as 5m-Bench, "Steel Tape and Ruler" measuring system. As a result, with the upgraded 5m-Bench system, it is now possible for SASO-NMCC to provide services in accordance with international (OIML R 35-1) and European legal metrology (73/362/EEC) standards.

## 2. 5m-Bench Measurement System Structures and Functions



*Figure 1: 5m-Bench system general view*

The aim of the work was to modify and upgrade the Steel Tape and Ruler measurement system to make it operational again for the calibration of rulers up to 5 m in SASO-NMCC dimensional laboratory. Calibration of the steel tapes and rulers can be done in one step up to 5 m and multiple steps for longer rulers by using stitching method. The traceability of the measurement system is provided directly through the laser interferometer.

System body which is about 7.25 m in length, is designed and manufactured from steel material. The system is equipped with a CCD camera and a laser interferometer optics and a carrier that moves on a double row rail. Laser interferometer and distance optics are used in the system as a reference for calibrating the steel tapes and rulers. At the beginning of the measurement, the laser interferometer indicator is reset to zero. The movement of the system is done manually. The distance between the optics on the main body changes with the manual motion of the carriage. The resulting distance value is read directly through the laser interferometer indicator.

## 2.1. 5m-Bench system installation and general construction structure

The entire system is approximately 7.25 m in length and 0.3 m in width and about 1 m in height. System consists of 7.25 m long steel profile body, 6 steel profile stand, 2 line linear rail and various apparatus. It is operating at  $20 \pm 0.5$  °C. Angular errors (pitch and yaw) of rails was minimized by measurement with laser interferometer angle optics. The appearance of the system during reassembly is similar to that of Fig. 2.



Figure 2: Reassembling 5m-Bench system in the laboratory

First, 6 pieces of steel profile legs are located. The main body is placed on these legs with the help of a crane. Once the main body is in place on the legs, the linearity in the pitch and yaw directions is also adjusted to the maximum level with the adjustment screws on the legs.

## 2.2. The Carrier Mechanism

The Carrier is connected to 4 sliding bearings on the main body. It can move manually on the rails. The carrier has a 3-axis micrometer moving table carrying the laser interferometer distance optics attached on the CCD camera body. With this mechanism, it is easy to adjust the distance optics or the view on the software screen.

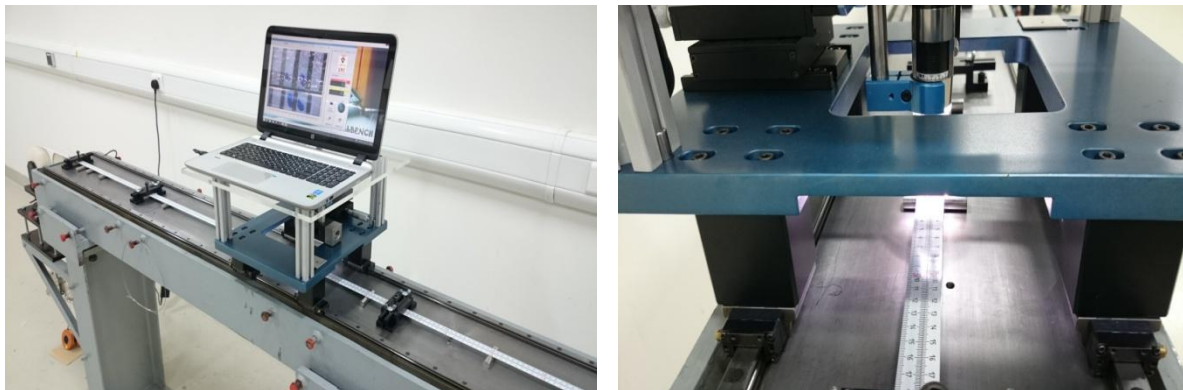


Figure 3: Carrier mechanism

## 2.3. Steel Ruler and Stretching Unit

Steel tapes or rulers are connected to the system with the aid of special apparatus. With this apparatus, the ruler to be measured can be connected to the system on proper conditions. In addition, the carrier movement and the camera images can be performed in parallel.

As it can be seen in the standards, it is necessary to stretch the values of the straight sections of the tape on the meter. These values can range from 10N to 50N. Steel weights and clips are used for the use of these weights.



Figure 4: Stretching unit

#### 2.4. Layout of target lines on ruler scale lines and optical probing

On the software screen there are target lines to assist the user during the measurement. (Fig. 5)

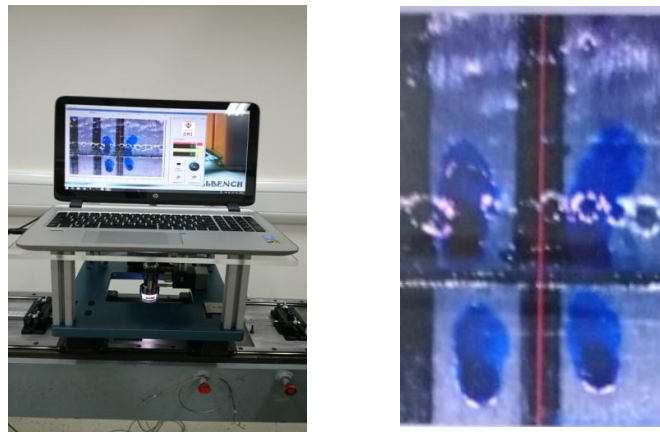


Figure 5: Software screen, target and scale line

With the help of these lines, the positioning and alignment of the steel tape and ruler on the system are allowed to be adjusted during the measurement movement. It is also possible to move the camera with the aid of the XYZ stage and micrometer on the carriage car and thus possible to reach the desired position using the target lines. Target lines make it possible to make a visual decision to find the midpoints of the target lines. This movement with micrometers is called optical probing mechanism. Precise adjustment between each measuring points of the carriage while approaching the target point is made by micrometers manually. Thus, the desired measurement point is reached on the video image with the help of precise motion.

## 2.5. Length Measurement System

The meter is defined as "the length of the path travelled by light in a vacuum during the time interval of  $1/c=1/299\,792\,458$  of a second." This definition establishes a fixed value for the speed of light, "c", in a vacuum. Laser interferometers have high linearity, and also metrologically traceable length measurement system.

In the 5m-Bench measuring system, He-Ne HP 5528A Laser interferometer with a wavelength of 633 nm and accuracy of 3 ppm is used as reference device along with its display screen, peripheral sensors and distance optics. HP 5528A Laser interferometer used Michelson interferometer as its optical principle.

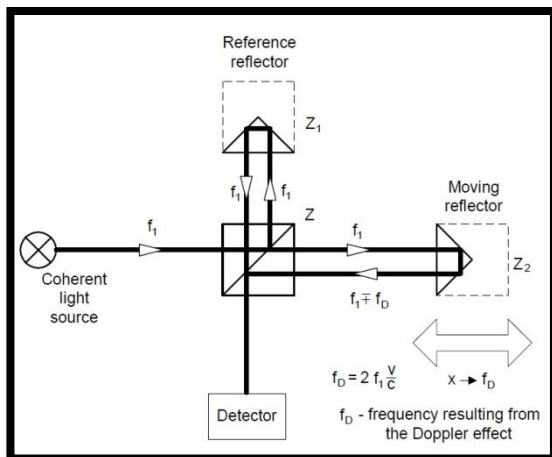


Figure 6: Michelson interferometer method



Figure 7: Laser interferometer accessories

The laser measurement system is connected to the center of the two tracks and to the position closest to the ruler to be measured. This distance was determined as 18 mm in the pitch direction and 2 mm in the yaw direction. In this way the measurement accuracy is increased and the Abbe offset is reduced greatly.

## 2.6. Temperature measuring system

Platinum Resistor Thermometers (100 ohm: Pt100) are used to determine the temperature values of the ruler to be measured in the system. Three sensors are located near the ruler along the 5 meter system.

## 2.7. Software

The homemade software is written in Visual Basic 6.0 and works on Windows 7 operating system. The software basically allows the display of the meter to be transferred to the screen in the software. This allows us to enlarge the image and make precise decisions at the destination. In addition, image on the screen can be further enhanced by digital zoom by software.

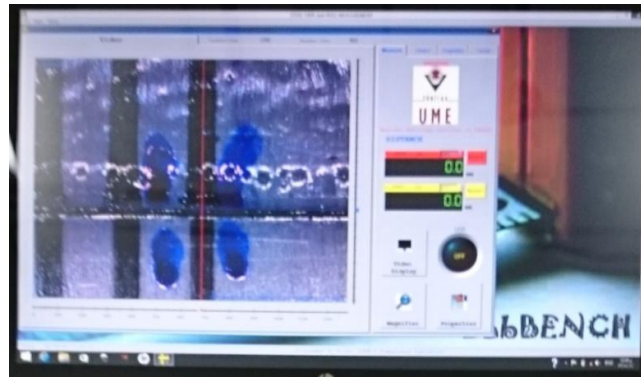


Figure8: General view of software

## 2.8. Data collection and evaluation

Calibration of the steel tapes and rulers is performed at 10 equal intervals unless the customer has a specific request. The acquisition of the data from the laser interferometer display unit is taken manually. Unidirectional data collection method is applied. The starting point '0' is accepted and started. The measurement steps are increased step by step up to the maximum measuring point and the distance value at each point is collected and evaluated in manually created excel spreadsheets. Measurement is repeated at least three times at the same target point and average on these data is collected as measurement result.

## 3. Verification of Measurement System

During the calibration of the 5m-Bench system, following steps are carried out;

- Determination of the angular (pitch and yaw) errors of the carrier vehicle
- The accuracy of the measurement due to the design of the carrier vehicle.
- Detection of defects in optical probe with micrometer

### 3.1. Angular (pitch and yaw) errors that occur during the motion of the carrier

Pitch and yaw error are determined by angle optics during 5 m movement of the carriage car. Pitch error = 500 arcseconds, Yaw error = 500 arcseconds. The largest angular error in the system is the angular error in the direction of pitch in terms of pitch or yaw. If the Abbe offset value is assumed to be 25 mm, then the maximum error value  $e = \sin(500/3600) \times 25 = 60.6 \mu\text{m}$  will result in the uncertainty budget  $(60.6 / (3))^{1/2} = 35 \mu\text{m}$ . If the Abbe offset value in the same direction is assumed to be 2mm, then the maximum error value that will result from this is  $e = \sin(500/3600) \times 2 = 4.85 \mu\text{m}$ , which is  $4.85 / (3)^{1/2} \text{ inch} / 2 = 2.8 \mu\text{m}$  the uncertainty budget

### 3.2. Accuracy of measurement due to the design of the carrier

It is not possible to combine the optical axis of the laser interferometer and the measuring axis of the steel tape or ruler to the same axis during the investigation of the accuracy of the length measurement process while the carrier is in motion. In this design, however, the laser interferometer axis and steel tape or ruler axis are as close as possible to each other. In this work, it is necessary to ensure that the Abbe offset, in which the differences in angular values caused by the separation of the axes from each other, is as low as possible. The position of Abbe offset and angular errors in our system is the lowest at the position where the laser interferometer is closest to the meter axis is shown below (Fig. 9)

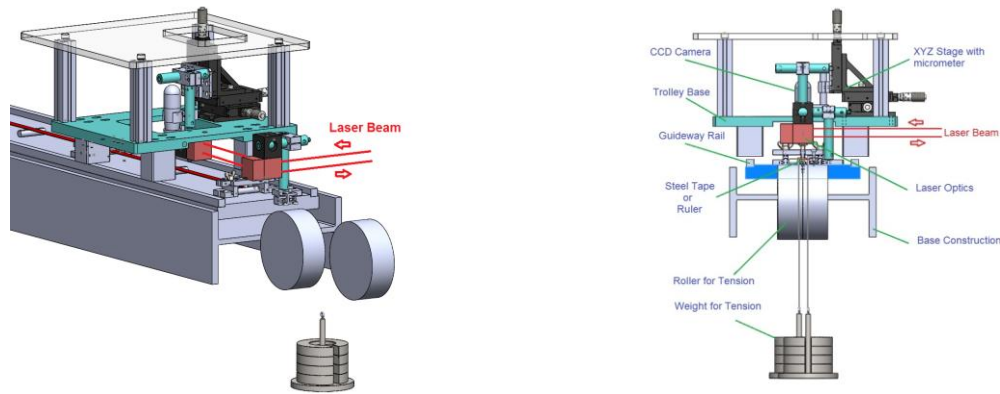


Figure 9: 5m-Bench design view

### 3.3. Detection of defects in optical probe with micrometer

The micrometer movement on the X-Y table is controlled by moving the bearings in different directions and distances, so that the measuring effects of the carrier vehicle at different positions on the rail are checked. As a result of these effects, it was determined that the maximum optic probing accuracy obtained was 20  $\mu\text{m}$  and the maximum optic probing reproducibility was 5  $\mu\text{m}$ . This value is also included in the uncertainty budget.

### 4. Performance Test of 5m-Bench System

Performance of the 5m-Bench measurement system; The Richter brand 10 m ruler calibrated by the Swiss National Metrology Institute (METAS) in 2015 was used as reference at the SASO-NMCC laboratories for a 5m-Bench measurement system. Measurements and results of SASO-NMCC were used to determine uncertainty values, METAS measurement results and uncertainty values using the  $E_n$  formula. Evaluated measurement results and uncertainty values are shown in Fig.10. SASO-NMCC 5m-Bench calibration system ensures that the calibration results of the Swiss National Institute of Metrology are agreed.

SASO and METAS Steel tape measurement results evaluated with respect to $E_n$ Value	
Nominal Length (mm)	$E_n$ Value
500	0,00
1000	0,37
1500	0,21
2000	0,11
2500	1,13
3000	0,21
3500	0,13
4000	0,52
4500	0,46
5000	0,50

Table 1: Steel Tape measurement results evaluated with respect to  $E_n$  Value

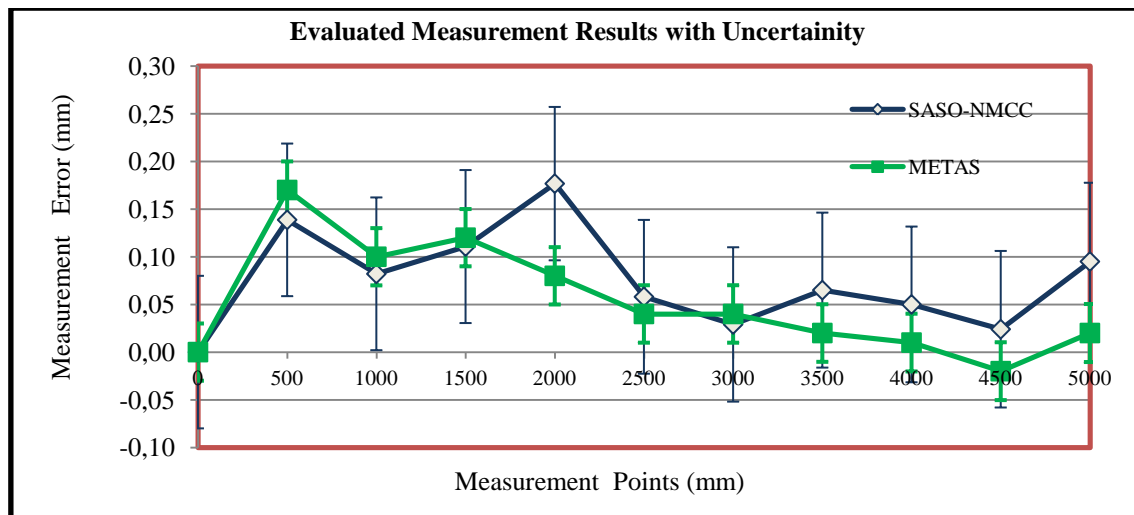


Figure 10: Evaluated measurement results with uncertainty

## 5. Measurement Uncertainty

In the following, the main error sources of the bench are characterized and their uncertainty contributions are estimated [7]. The uncertainty of measurement has been estimated according to “The Guide to the Expression of Uncertainty in Measurement (GUM)”, and has been expressed in a length dependent form of  $[(a)^2 + (b \times 10^{-6} \cdot L)^2]^{1/2}$  using a coverage factor of  $k=2$ . Here,  $a$  is the constant value,  $b$  is the length dependent value and  $L$  is the measured length. Analysis of the uncertainty contributions has been investigated in detail and has been combined with the length dependent format. The uncertainty budgets are given for calibration of test tape using a laser interferometer.

### The accuracy of laser interferometer:

Agilent HP5529A laser interferometer [6] used as a reference of the bench has an accuracy of  $3.0 \times 10^{-6} \times L$  for displacement measurements in laboratory conditions. This length dependent value is considered as rectangular distribution resulting in  $(3.0 \times 10^{-6} \times L) / \sqrt{3} = 1.73 \times 10^{-6} \times L$

### Resolution of laser interferometer:

The resolution of the interferometer is  $0.1 \mu\text{m}$ . This value is taken as digital resolution resulting in  $0.1 / (2 \times \sqrt{3}) = 0.0288 \mu\text{m}$  uncertainty contribution with rectangular distribution.

### The standard deviation of the mean value:

The standard deviation of the mean value of typically 3 series of repeat measurements is better than  $20 \mu\text{m}$  for tape measurements. Uncertainty contribution is estimated as  $20 / \sqrt{3} = 11.55 \mu\text{m}$

### Uncertainty contribution from pitch angular error:

Maximum peak to peak angular pitch error is 500 arcseconds. The measurement axis is measured in  $\pm 18 \text{ mm}$  in the vertical direction. Abbe error due to pitch error can be calculated as  $\text{Sin}(500/3600) \times 25 = 60.6 \mu\text{m}$ . This leads to  $60.6 / \sqrt{3} = 35 \mu\text{m}$  uncertainty contribution with rectangular distribution.

### Uncertainty contribution from yaw angular error:

Maximum peak to peak angular yaw error is 500 arcseconds. The measurement axis is measured in  $\pm 2 \text{ mm}$  in the horizontal direction.

Abbe error due to yaw error is  $\text{Sin}(500/3600) \times 2 = 4.85 \mu\text{m}$ , resulting in  $4.85 / \sqrt{3} = 2.8 \mu\text{m}$  uncertainty contribution with rectangular distribution.

### The accuracy of optical probing:

It was determined that the maximum optical probing accuracy obtained was  $20 \mu\text{m}$ , resulting  $20 / \sqrt{3} = 11.54 \mu\text{m}$  uncertainty contribution with rectangular distribution.



**The standard deviation of the mean value:**

The standard deviation of the mean value of typically 3 series of repeat measurements is better than 5  $\mu\text{m}$  for the optical probing test. Uncertainty contribution is estimated as  $5 / \sqrt{3} = 2.89 \mu\text{m}$ .

**Uncertainty contribution from Cosine error:**

The laser is adjusted parallel to the measurement axis better than 2 mm lateral shift in 10 m length. This results in a cosine error of  $2 \times 10^{-7} \times L$  resulting in  $(2 \times 10^{-7} \times L) / \sqrt{3} = 1.16 \times 10^{-7} \times L$  with rectangular distribution.

**Uncertainty contribution from coefficient of thermal expansion (CTE) corrections;**

No CTE correction is made for calibration of steel tapes and rules. However, uncertainty contribution is taken into account due to possible differences in CTE values. CTE of steel ruler or tape is known within  $\pm 1$  ppm and maximum temperature deviation from  $20^\circ\text{C}$  is less than  $0.5^\circ\text{C}$ . Uncertainty contribution due to CTE correction can be calculated by  $0.5^\circ\text{C} \times 1 \times 10^{-6} \times L$  resulting in  $0.5 \times 10^{-6} \times L$ . Considering this value as rectangular distribution, uncertainty contribution is estimated as  $(0.5 \times 10^{-6} \times L) / \sqrt{3} = 0.29 \times 10^{-6} \times L$ .

**Uncertainty contribution from Temperature measurements:**

No temperature measurement correction is performed. The uncertainty of temperature measurement for line scale used in 10m-Bench using material sensors is better than  $0.25^\circ\text{C}$ . Uncertainty contribution can be calculated as  $0.25^\circ\text{C} \times 11.5 \times 10^{-6} \times L$ . Uncertainty contribution is estimated as  $(0.25^\circ\text{C} \times 11.5 \times 10^{-6} \times L) / \sqrt{3} = 1.66 \times 10^{-6} \times L$  with rectangular distribution.

**Uncertainty contribution from Measurement force (tension load):**

Measurement forces, i.e. tension loads are applied during calibration of tapes according to manufacturer specifications. Uncertainty contribution arises due to length variations when there is the difference between applied force and specified force. The correction for different tension from specified can be estimated by Hooke's law;

$$\Delta L_F = \frac{(F - F_0)L}{AE} \quad (\text{N})$$

where  $\Delta L_F$  is a deviation in length due to applied force  $F$ ,  $E$  is the modulus of elasticity and  $L$  is the length. The term  $(L/EA)$  is the sensitivity coefficient used to make the connection between measurement force and deviation in length and  $u(F)$  is the uncertainty of applied force and  $u(\Delta L_F)$  is a deviation in length due to the uncertainty of applied force where  $F_0$  is tape tension at calibration (N),  $F$  is tape tension (N),  $L$  is the distance measured (mm),  $E$  is Young's elastic modulus ( $\text{N}/\text{mm}^2$ ) and  $A$  is cross-sectional area of the tape ( $\text{mm}^2$ ). The following numerical values for  $A$  and  $E$  are given by the manufacturer.

$$(F - F_0) = 0.5 \text{ N (Estimated)}, A = 2,4 \text{ mm}^2 \text{ and } E = 20.7 \times 10^4 \text{ N}/\text{mm}^2$$

Manufacturers give specifications and even correction values due to the difference in the applied and specified force (tensioning loads). The numerical values obtained from literature is rectangular distribution, the standard uncertainty contribution is calculated as

$$u(\Delta L_F) = \frac{(1.0 \times 10^{-6} \times L)}{\sqrt{3}} = 5.81 \times 10^{-7} \times L$$

The expanded uncertainty value;  $U_{k=2} = \sqrt{(80)^2 + (4.1 \times L)^2} \mu\text{m} : (L = \text{m})$  is valid for the length measurements up to 5 m.

## Conclusion

Steel Tape and Steel Ruler measuring system can be used for calibrating meters up to 5m (and up to 10 by stitching method) using a laser interferometer. Estimated uncertainty value for calibrations made using a laser interferometer

$$U_{k=2} = \sqrt{(80)^2 + (4.1xL)^2} \text{ } \mu\text{m, (L = m)}$$

## Acknowledgments

The authors would like to thank to Emre SONOLUK and Özkan KARABAS from TÜBİTAK UME and SASO-NMCC Dimensional lab. staff and their valuable help and support.

## References

- [1] OIML R 35-1 – EN, “Material measures of length for general use”, International Organization of Legal Metrology 1985, <http://www.oiml.org/>
- [2] 73/362/EEC, “Material measures of length.”, European standards and directives, 1973.
- [3] Euramet Length website, <http://www.npl.co.uk/euromet/length/projects/forms/677-progress.pdf>
- [4] BIPM website, <http://kcdb.bipm.fr/appendixC/search.asp?met=L>
- [5] Guide to the expression of uncertainty in measurement, International Organization for Standardization (ISO), Geneva, 1993:
- [6] 5529A Dynamic Calibration System, Agilent Technologies, 2013.  
<<http://www.home.agilent.com/en/pd-1000001491%3Aeps%3Apro-pn-5529A/dynamic-calibration-system?&cc=TR&lc=eng>>.
- [7] “A motorized 5m Tape Comparator for Traceable Measurements of tapes and rules”, Tanfer YANDAYAN, Bülent ÖZGÜR, Elsevier, Measurement 49(2014) 113-125