

Length Metrology and Calibration Systems

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1. Introduction

Accurate length measurement plays a vital role in meeting the needs of industry and commerce for traceability to common national and international standards, especially in view of the common market and world trade. Such measurement needs arise across a wide applications base, from large-scale engineering projects such as dam construction, aerospace and shipbuilding, through automotive engineering and components manufacture, to precision engineering and nanotechnology (DTI/NMDS, 2002b).

The lowest uncertainty attained in dimensional measurements of a material object occurs in semiconductor industry and integrated circuit (IC) production. The dimensional feature of interest in a line scale is the critical dimension (CD). The CD corresponds to the width of the smallest line that can be produced on a wafer with an acceptable yield of manufactured devices; presently this parameter is less than 0.1 μm . Requirements in other areas, such as manufacture of precision instruments, large machines (e.g. planes), and others also rise fast. In all these areas the principle “to stop means to fall behind” is in force. Development of measurement systems is impelled by the augmentation of customer needs as well as by steadily evolving state-of-the-art measurement technologies (Bosse & Flügge, 2001).

Length metrology has a fundamental role to maintain the primary standard of length, the metre, and to provide the infrastructure to enable a wide range of dimensional and positional measurements to be made traceable to the metre. National metrology institutes (NMIs) in a number of countries and companies that produce precision high-tech products pay much attention to accuracy-related research with the aim to improve properties of length calibration systems and to specify their uncertainty budget. Metrological programmes in the area of length measurement are consistently carried out in the USA, Japan, UK, Germany (Bosse & Flügge, 2001; Beers & Penzes, 1999; Israel et al., 2003), and other countries. The programmes impel the creation of metrological infrastructure that increases industry competitiveness, supports industrial innovations, and improves control of manufacturing processes and quality. For example, systematic research of accuracy of vacuum nano-comparator, performed in German National Metrology Institute (PTB) in 2000 – 2006, resulted in reducing the measurement repeatability error from 14 nm down to 0.2 nm. NIST, the National Metrology Institute of the USA, is carrying out research on nm-accuracy one dimensional (1D) metrology with the development of components of next generation length scale interferometer. In conceptual design, the system would have a range for 1D measurements from 100 nm to 1 m with a target expanded uncertainty of from 1 nm to 10 nm.

One of the most sophisticated challenges for science and the high technologies engineering is the growing need to address real industrial problems rather than the ideal measurement situation and embed the traceable length metrology directly into technological processes by performing precise dynamic measurements in more demanding environments than those of calibration laboratories.

This chapter will present a synopsis and analysis of literature and existing scientific and technical solutions of precision length calibration. It covers analysis of laser interferometers, line detection systems, measurement signals and algorithms, as well as measurement capabilities of state-of-the art calibration systems worldwide. The contribution also addresses a thorny issue of achieving reliable measurements and meeting contradictory requirements of accuracy and productivity of line scale calibration in non-ideal environmental conditions, under the influence of many external influencing factors. The problems will be also upon the anvil of the development of an interferometer-controlled comparator that is operated in dynamic mode and enables to trace the calibration of line scale of up to $L \leq 3.5$ m long to the wavelength standard.

2. Length metrology

The basis of any dimensional measurement technique is found on the realization of the SI unit of length via frequency-stabilized lasers and displacement interferometry. The measurement technologies employed include laser-ranging devices, large-scale coordinate measuring machines (CMMs), optical- and ultraviolet-light microscopes, scanning electron microscopes (SEMs), atomic force microscopes (AFMs), and scanning tunneling microscopes (STMs).

Both direct and indirect high accuracy measurements of length, distance and displacement make use of wavelength or optical frequency sensing techniques. Direct measurement techniques include laser interferometer calibration of computer numerical controlled (CNC) machine tools and CMMs, and commercial laser-based instrumentation is widely used both nationally and internationally for this purpose, to measure displacements and distance from typically a hundred nanometers to tens of meters. Multiple wavelength instrumentation is used to extend accuracy within well-controlled environments, whilst modulated laser ranging techniques (electronic distance measurements) are now widely applied in surveying over distances up to a few kilometers with, in some cases, sub-millimeter precision. Such precision instrumentation comprises laser wavelength sources as measurement transducers of varying degrees of stability and accuracy.

Dimensional metrology covers measurement of dimensions and in principle also geometries based on distance measurements in a wide range of more specific measurements, targeted on from primary sources, i.e. lasers to geometrical measurement of complex profiles, which typically include:

- measurement of laser wavelength/frequency, stability, drift and line width of radiation sources that are used for interferometry and distance measurement;
- measurement of size or geometric features, like pitch, of 1D artifacts, for example end standards and linear scales or encoders;
- measurement of size and/or locations of features in 2D structures common in the semiconductor industry, such as in the complex patterns of integrated circuits
- measurement of size location and orientation of features in 3D patterns;

- measurement of deviations from ideal geometric forms, i.e. flatness, roundness, etc.;
- measurement of surface texture.

Calibration of a variety of parameters associated with the source, such as absolute wavelength or frequency, linewidth, stability or drift, are thus of primary importance to high precision length traceability. In parallel, techniques in wavelength metrology are targeted on other applications. These include spectral bandwidth characterization by wavelength division multiplexing (WDM) for optical communications, high resolution spectral analysis using Fabry-Perot standards, and high accuracy measurement of spectroscopic phenomena, which has strong input to scientific spectroscopy. Precision length metrology also plays a key role in the realization of derived units of pressure and current, for example. The highest wavelength/frequency accuracy and stability available contributes to the leading-edge determination of fundamental physical constants (DTI/NMDS, 2002a).

There are a number of sensor technologies and instruments with nanometer, or better, accuracy for measuring length that repeat well if used carefully, including the scanning probe and electron microscopes and some optical devices. However, universal measurement standards have not yet been established and even apparently sophisticated users of atomic force microscopes can produce large variations in their measurements of the same artifacts. Without agreed standards, tools or machines cannot be calibrated at the nanometer scale (Bureau International des Poids et Mesures, 2003).

Line graduated geometric bodies, with graduation spacings representing known distances, are the bases for all direct measurements of specific distances. It follows that instruments having line graduated elements as integral members may be considered the only mechanical means capable of carrying out direct measurements without complementary equipment or processes (Farago, F.T. & Curtis, 1994).

The need for reduced uncertainty in the “primary standard” aspect of length, i.e., in its definition and realization, and in the “secondary standard” aspect, i.e., in its transfer and dissemination through dimensional metrology, is linked strongly to tightening tolerances in industrial manufacturing.

2.1 Definition and realization of meter

The definition of the meter—whether in terms of a prototype meter bar, a wavelength of light, or the propagation of an electromagnetic wave in an interval of time—has provided the basis for the lowest-uncertainty realization of the unit.

In 1983, the meter was re-defined again to the one in effect today, namely: “The meter is the length of path traveled by light in vacuum during the interval of $1/299\,792\,458$ of a second”. At that time, the International Committee on Weights and Measures (CIPM) gave three basic methods for the practical realization of the meter: time-of-flight, using time intervals, and interferometry, using wavelengths or frequencies. CIPM gave five recommended radiations with assigned frequencies, wavelengths, and uncertainties (Quinn, 2003).

Of the recommended radiations, that of the iodine stabilized helium-neon (He-Ne) laser is the most widely used for practical realization of the meter. It has a wavelength of He-Ne = 632.991 398 22 nm, with a relative standard uncertainty u_r of 2.5×10^{-11} .

The effect of the re-definitions and advances in measurement of the frequencies of recommended radiations was to decrease the relative uncertainty attainable in realization of the meter by five orders of magnitude (Swyt, 2001).

Measurements of dimensions of material goods are most often referenced to the SI unit of length through material artifacts calibrated as dimensional standards. The meter, the basic unit for length, is usually transferred to measurement standards in the form of line scales or photoelectrical incremental encoders by length measuring machines that typically use a laser interferometer in air as reference measuring system. The measurement results are traceable to the meter due to the use of the wavelength of the laser interferometer.

2.2 Laser interferometry

Since practical realization of meter is closely related with the radiation of stabilized frequency lasers, laser interferometers are utilized for precise and traceable length measurements. Currently the detection principles of laser interferometer systems can be distinguished between homodyne and heterodyne techniques (Webb & Jones, 2004; Chapman, 2002). Homodyne interferometers utilize one frequency laser, and heterodyne two frequencies laser respectively. Heterodyne interferometry is inherently more resistant to noise due to its heterodyne frequency and the design of common-mode rejection which cancels out common noises coming from both reference and measurement signals, and though heterodyne techniques are susceptible to larger nonlinearity errors a large number of commercial systems uses namely this technique. Nevertheless the main parameters that determine the quality of laser interferometric systems are (Bobroff, 1993):

- resolution,
- measurement accuracy,
- repeatability of results,
- dynamic and measurement range,
- measurement speed.

A homodyne laser source is typically a He-Ne laser with a single frequency beam as output consisting of either a single polarization under 45° or a circularly polarized beam. The beam is split into the reference arm and measurement arm of the interferometer by a beam splitter. Following a reflection off their respective targets, the beams recombine in the beam splitter. In order to observe interference the two beams must have equal polarizations. This is accomplished using a linear polarizer oriented at 45° to the beam splitter. The photo detector signal is run through electronics which count the fringes of the interference signal. Every fringe corresponds to a path difference of half a wavelength. After superposition of measurement and reference beams a polarizing beam splitter is used to generate two 90° phase shifted signals. The direction of movement is determined at zero crossings of the interference signal using the other signal. Counting of the zero crossings of both interference signals provides a resolution of $\lambda / 8$ which is not sufficient for precision length measurements and therefore it has to be enhanced by interpolation techniques. In homodyne interferometers the amplitudes of the interference signals are used; the phase of the signal can be determined from intensities of perpendicular polarized signals. Manufacturers of homodyne interferometers are Renishaw, Heidenhain, Sios and recently Interferomet.

In heterodyne interferometers double frequency radiation source is required since the interfering measuring and reference beams must have slightly different frequencies and photo detectors detect the phase shift between these two beams, see Fig. 1.

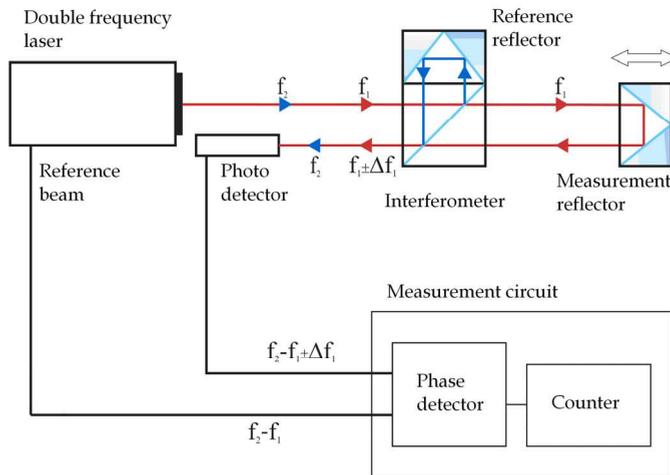


Fig. 1. Layout of heterodyne laser interferometer

Two frequencies are separated by their polarization state, so that a polarization beam splitter can generate a measurement beam with the frequency f_1 and a reference beam with f_2 . The movement of the measurement reflector with velocity v causes a frequency shift Δf in the measurement beam due to Doppler effect. This shift will increase or decrease depending on the movement direction of the measurement reflector. When counting the periods of reference and measurement signals simultaneously their difference is proportional to displacement. The direction of movement can be determined directly from the sign of this difference. Interpolation in heterodyne systems is equivalent to the measurement of the actual phase difference between fixed reference frequency and measurement frequency (Webb & Jones, 2004).

Heterodyne principle has a certain advantage, particularly for He-Ne lasers due to good signal to noise ratio enabling multi-axis measurement with high measurement speeds. In practice, the maximum speed of the laser interferometer will be limited by the primary beat frequency of a laser source, which is usually in the range of few MHz for Zeeman stabilization technique where high power magnetic field is required for separation of the laser frequencies, and 20 MHz for the acousto-optical modulators and from 600 to 1000 MHz for stabilized two-mode lasers that would correspond to more than 200 m/s speed to be measured. However, increase of the beat frequency will decrease the measurement resolution of the laser interferometer in return and therefore the bandwidth of phase detection is usually fixed in the absolute time scale in most phase measuring techniques (Yim et al., 2000).

The main advantage of heterodyne systems is that information about the measured displacement is obtained in form of variable signal and therefore measurement circuits are

not sensitive to variations of the measured signal level due to various disturbances. Since information about the displacement is gained from the signal frequency only one photo detector is necessary, and adjustment of optical elements becomes more simple, see comparison of both systems in Table 1.

	Homodyne	Heterodyne
Continous measurement	Yes	No
Sensing of moving direction	Quadrature	Always
Quadrature output signal	Yes	Yes
Error detection	not defined	Unambiguous
Sensitivity to radiation intensity	Yes	No
Sensitivity to enviromental irradiance	Yes	No
Frequency band of electronic circuit	$0 - 2v/\lambda$	$f_1 - f_2 \pm 2v/\lambda$
Signal to noise ratio	6 - 12 bit	2 - 3 bit
Multi-axis measurements	Limited	Yes
Photo detector	Complex	Simple
Adjustment simplicity	No	Yes

Table 1 Comparison of heterodyne and homodyne systems

Resolution of interferometers primarily depends on accuracy of phase detection of interference signal. Currently due to rapid development of information technologies and electronics it increased from $\lambda/8$ in 1965 up to $\lambda/2048$ (the wavelength of radiation source is divided into 2048 parts), and using traditional phase detection techniques the resolution of displacement interferometry amounts to about 0.1 – 10 nm.

Presently some commercially available phase detection systems allow digital signal processing and phase detection accuracy of 0.01° and which in combination with Michelson type heterodyne interferometer correspond to better than 10 pm system measurement accuracy.

The uncertainty sources in the laser interferometry can be grouped in three categories: setup dependent (cosine, Abbe, deadpath errors, mechanical stability), instrument dependent (stability of laser frequency, electronics, periodic deviations, etc.) and environment dependent (refractive index, turbulence, thermal sources) that are inherent in such systems and generally limit the relative uncertainty to 2×10^{-8} , resulting in an error of 20 nm per meter. For measurements over large displacements in air the last group is predominant in the uncertainty budget.

Thus linear measurement scale and accurate and adequate control and stabilization of environmental conditions are the main precision criteria for the modern interferometric displacement measurement systems. The use of digital data processing techniques enables to minimize nonlinearities of laser interferometers and increase the measurement resolution up to 10 pm (Webb & Jones, 2004). But in order to achieve the required relative length measurement uncertainty below 10^{-7} in practical applications, the measurement accuracy of air refractive index must be not less than 10^{-8} .

A good example for that is the comparison of static stability of He-Ne laser interferometer and linear encoder presented in Fig. 2. Experiments conducted have shown that users can expect fewer measurement fluctuations of the position display from linear encoders than from laser interferometers (Kaušinis et al., 2004).

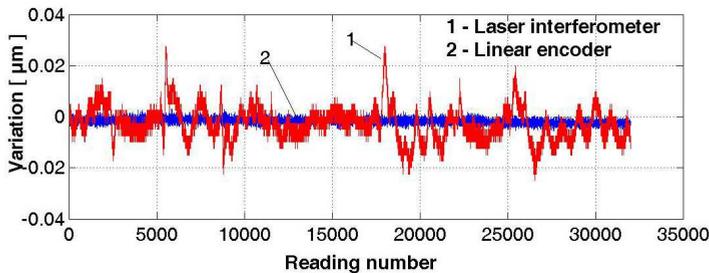


Fig. 2. Stability of laser interferometer and reference encoder

A long-term stability of the laser interferometer was mainly influenced by the temperature and refractive index. The refractive index of air was compensated by Edlen's formula. Both measurement systems were simultaneously read out in a static mode and actually, in comparatively good ambient conditions the interferometer has revealed clearly higher variances than the linear encoder. The temperature measurement system due to its data acquisition time and remoteness of the laser beam sensor is not able to compensate these variations.

The analysis of the dynamic mode of operation displayed results of the same order as variations of the laser interferometer measured in a static mode. Repeated measurements at different positions of the line scale displayed quite similar results. It is evident that, even in the finely air-conditioned laboratory environment, the low heat capacity of the air causes quick changes in temperature that can lead to relatively large fluctuations in measured values obtained from the laser interferometer. Comparatively short distances between encoder's scale and index grating minimize sensitivity to environmental factors.

2.3 Limits and challenges in length metrology

The future of length and dimensional metrology is being shaped by theoretical and practical limits to attainable uncertainties in measurement, by continuing trends in industry. There are two drivers that force the achievement of ever-smaller uncertainties in length and dimensional measurements. These are, first, the continuing industrial trend to tighter tolerances—represented in the microelectronics domain by Moore's Law—and, second, the continuing scientific trend to explore the limits of understanding through physical measurement.

The latter is bounded by a dimensional equivalent of Johnson, or thermal, noise that places an ultimate limit on the uncertainty of measurement of dimensional features. Thermal length fluctuations of a solid artifact, the spatial equivalent of electronic Johnson noise, are due to thermal agitation of the atoms of the material. In a measuring machine, such thermal noise places an ultimate limit on the ability to set the location of the origin of the axes of the

machine and, therefore, on the uncertainty of position measurements the machine can attain. Thermal noise similarly limits the uncertainty with which the length of an object can be measured. Therefore thermal fluctuation Δl in the length l of the side of the artifact is given:

$$\Delta l = \left(\frac{k \cdot T}{3} \cdot B \cdot l \right)^{1/2} \quad (1)$$

where k is the Boltzmann constant and T is the thermodynamic temperature, B is the bulk modulus of the material of the cube.

For example, for an object with a bulk modulus of that of fused silica, 3.5×10^{10} N/m², and a temperature of 300 K, the rms fluctuation in dimension of a 1 m cube is 0.2 fm (10^{-15} m) or, fractionally, 2×10^{-16} . Besides this factor is inversely proportional to the measured length and therefore by decreasing the geometrical dimensions of measured objects the length measurement uncertainty will increase proportionally (Swyt, 2001).

Generally the limit for length measurement uncertainty is firstly determined by realization capabilities of time unit (second) following the definition of the meter and which is in the uncertainty of second is in the order of 1.5×10^{-15} presently and, secondly, practical realization of temperature unit (Kelvin) as major disturbance parameter which influences the accuracy of dimensional measurements. However the actual precision of length measurements is limited by the other standard closely related with second that is the frequency standard - CH₄-stabilized He-Ne laser. Satisfying the requirements of International Committee for Weights and Measures and the most common realization of primary length standard is He-Ne laser with the wavelength of $\lambda = 632.99$ nm and relative standard uncertainty of 2.5×10^{-11} (Webb & Jones, 2004).

The bottleneck for calibration of material artifacts is determined by the capabilities of measurement systems to detect the boundaries/edges of geometrical features, requirements on environmental parameters as well as optical wave interferometry. In practice the lower limit for optical interferometry is in the range of 10^{-7} and mainly restrained by variations of air refractive index which in turn can be computed by Edlen's formula contributing to the length measurement error in amount of 5×10^{-8} and might be considered as ultimate limit for measurements in air. On the other hand, vacuum interferometry might be an option where currently achievable expanded measurement uncertainties are below 5 nm measuring high quality artifacts in lengths below 1 m (Köning et al., 2007).

Typically for calibration of precision line scales and traceability to length standard optical comparators are used where optical or X-ray interferometry is used and such systems enable calibration of length standards with uncertainties ranging from several nanometers up to some tenth of nanometers when measured length is significantly longer in comparison with the wavelength of radiation source. However when geometrical dimensions of the measured structures are of the order of the wavelength the use of such technologies becomes quite complicated and therefore comparative methods using X-ray diffraction or scanning microscopes are more common, particularly for investigation of micro electro-mechanical system (MEMS) structures, lithography and similarly (PTB, 2003; Swiss Federal Office of Metrology, 2004).

While comparing these different methods it is necessary to consider not only the measurement range and accuracy requirements but also effectiveness of such systems relating to metrological network and needs of particular country, design costs, etc.

Although different calibration methods and equipment, see in Table 2, for dimensional measurement of a material artifact are used, currently, optical comparators combining properties of laser interferometers and optical microscopes represent the lowest relative uncertainty (U/L) of dimensional measurements provided in a length calibration of a 1 m line scale, the relative expanded uncertainty (coverage factor $k = 2$) is 7×10^{-8} m at 1 m.

Length calibration method	Measurement range, μm		Uncertainty $U=[a^2+b^2]^{1/2}$	
	Lower limit	Upper limit	a, nm	b, nm
Calibrated atomic microscope (NIST)	0.1	10	3	$2 \cdot L, L=0.003 \div 0.02 \mu\text{m}$
Laser diffractometer (NPL)	2	$1 \cdot 10^6$	3	$0.1 \cdot L, L, \text{mm}$
Scanning electronic microscope and laser interferometer (NPL)	0.29	50	0.025	$0.19 \cdot L, L=0.06 \div 61 \mu\text{m}$
Optical microscope laser interferometer and video microscope with CCD (MIKES)	0.05	10	10	$0.001 \cdot L, L, \mu\text{m}$
Combined X-ray and laser interferometer (NPL, PTB)	0.001	$1 \cdot 10^3$		$0.03, L < 10 \mu\text{m}$ $0.04, L < 100 \mu\text{m}$ $0.17, L < 1 \text{mm}$

Table 2. Comparison of different length calibration techniques (PTB, 2003; Swiss Federal Office of Metrology, 2004)

3. Length calibration systems

Length calibration problems are inevitably connected with mastering and research of modern interferometric displacement measurement technologies, error compensation technique as well as digital microscopy achievements. These problems are often determined by the embedded metrology needs that can be met only by developing novel systems that absorb recent scientific and technical findings and optimally comply with specific calibration requirements as well as by improving existing calibration systems open to complying with fundamental principles of precision engineering. Satisfying more demanding requirements ultimately drives the demand to trace/validate the products on their manufacturing line as well as performing the graduation line detection and position measurements in a short time.

The ability to provide reference measurements at such levels of uncertainty requires developments beyond the current state of the art in each of three areas:

- the physical artifact to be calibrated;

- the measuring machine to do the calibration
- the theoretical model of the systematic errors in measurement results arising from the interaction of the artifact and the measuring machine in the calibration process.

In addition, the three developments need be tied together in a measurement procedure that includes innovative measurement algorithms and methods.

For high precision line scale calibration and traceability to primary length standard optical comparators with movable optical line detection system or movable line scale are used. The interferometer is the instrument that transfers international standard of length into physical measurements. Digital measurement microscopes enable to perform precise positioning of length calibration systems, to estimate quality of line edges and precise location of lines. The system is placed in an air-conditioned environment.

The interferential comparator presented in Figs. 3, 4 was developed to calibrate both line graduation scales up to 3.5 m long and incremental linear encoders.

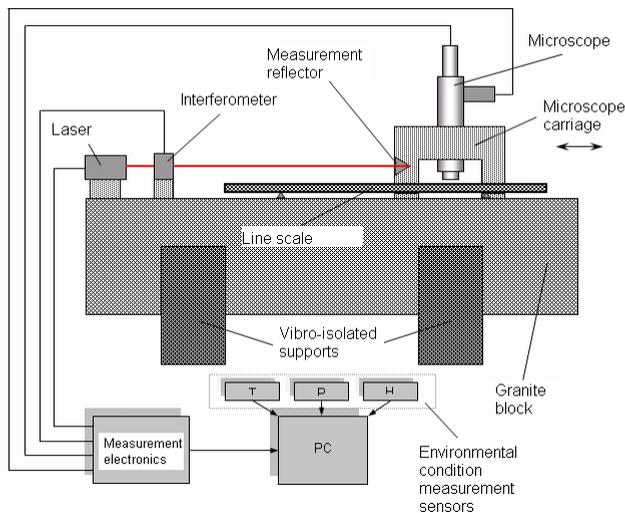


Fig. 3. Mechanical layout of the precision line scale comparator

The comparator consists of four main parts, namely the body of the machine, a laser interferometer, a translating system and a detecting apparatus. The body of the machine, which is made of granite surface plate, is used as the base of the machine and as a guide for the moving carriage. Measurement of the displacement of the carriage is realized by laser interferometer that consists of Zygo ZMI 2000 laser head and interferometer with the single-pass arrangement. The interferometer provides a resolution of 0.62 nm.

The comparator was designed to achieve expanded measurement uncertainties ($k = 2$) down to 7×10^{-7} m ($L = 1$ m) in dynamic regime. It enabled to trace the calibration of line scale of up to $L \leq 3.5$ m long to the wavelength standard. The magnification and numerical aperture of the NIKON objective lens used was $20\times$ and $50\times$, and numerical aperture - 0.4 and 0.55 respectively.

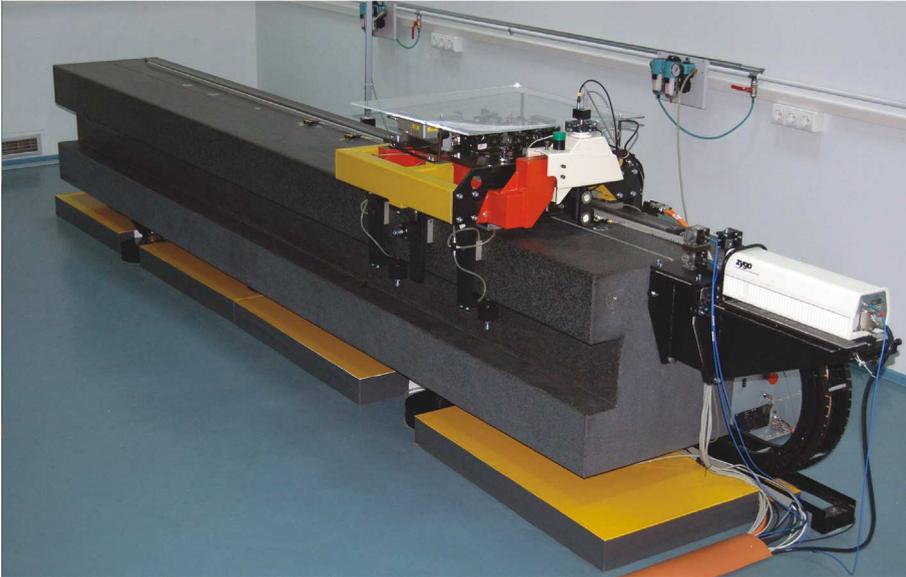


Fig. 4. Precision interferometer-controlled line scale comparator with charge-coupled device (CCD) microscope

A moving CCD microscope serves as structure localisation sensor for the measurements of line scales. The microscope on the carriage guided on aerostatic bearings is moved with a controlled velocity of 1–10 mm/s.

The graduation line distances are measured during continuous motion. Average profiles of the graduation lines are formed by summing picture element intensities of each row of the CCD. Line centre is calculated as weighted mean from intensity profile of a line.

Air pressure, temperature, humidity are on line accessed to determine the refraction index of the air by the Edlen's formula. The angular control loop - together with the numerical procedure - was applied to compensate and reduce the Abbe uncertainty contribution.

The whole calibration process and all operations of the system are controlled by the PC, which runs according to specific operation program that includes also the error compensation.

The measured performances confirm that investigated measurement system can operate reliable at velocities up to 6 mm/s without appreciable loss in measurement accuracy.

In order to examine the calibration process in real time, the experiments of the line scale calibration with a moving CCD microscope have been carried out in specific operating modes, and the accuracy of dynamic calibration was analysed.

3.1 Artifacts

Graduated length scales come in many forms, and are made in lengths from a few micrometers to over a several meters. Those longer than a meter or two are usually classified

as measuring tapes or rods. Many materials are used including steel, Invar, glass, glass-ceramics, silicon, and fused silica. Cross sectional shape can be rectangular, "H," modified "U" (flat bottom), or a modified "X" (Tresca). At present, the line scale interferometer is limited to graduation widths ranging from submicrometer to 100 mm, and spacings ranging from less than 1 mm up to 1025 mm. Spacings are generally measured from center to center of the graduations, but can also be measured from edge to edge.

Some devices that are not strictly linear scales are measured in the line scale interferometer. These include end standards in a size range (250 mm to 1000 mm) that can present measurement problems with laser interferometry.

Two dimensional patterns are measured by treating each row and column of graduations as an independent scale and, when possible, an estimate of orthogonality can be made by measuring the diagonals.

3.2 Error analysis of length calibration systems

Making measurements with nanoscale precision poses several major difficulties. Environmental fluctuations such as vibration or temperature change have a large effect at the nanoscale. For example, any external change to the large machines used in manufacturing microelectronics components will affect the creation of nanoscale features and their crucially important alignment to each other. The ability to measure these influences, and thereafter to minimize them, is therefore vital.

The error budget is an accuracy model of the machine in its environment expressed in terms of cause-and-effect relationships. It may involve random quantities such as seismic vibrations or deterministic quantities such as deflections due to gravity or weights of moving axes and payloads. The error budget helps identifying where to focus resources to improve the accuracy of an existing machine or one under development. It provides useful information for the specification of subsystem precision requirements to achieve an overall balance at the levels of difficulty.

The technical basis for the error budget rests on two assumptions:

- the total error in a given direction is the sum of all individual error components in that direction, and
- individual error components have physical causes that can be identified and quantified.

A practical difficulty arises because we generally cannot quantify the errors in complete detail especially at the design stage. Although an error may vary spatially and temporally, usually the only estimate will be a bounding envelope and perhaps an approximate frequency of variation.

In general, machine tools errors can be divided into two categories: systematic and random errors. Systematic errors can be described by deterministic mathematical and engineering models. Random errors are difficult to model and to compensate. In the calibration of line standards, several essential sources need to be identified and eliminated or corrected. The following error map, see Fig. 5, presented as cause and effect diagram, gives the sources of uncertainty classified by type and their origin (Jakštas, 2006).

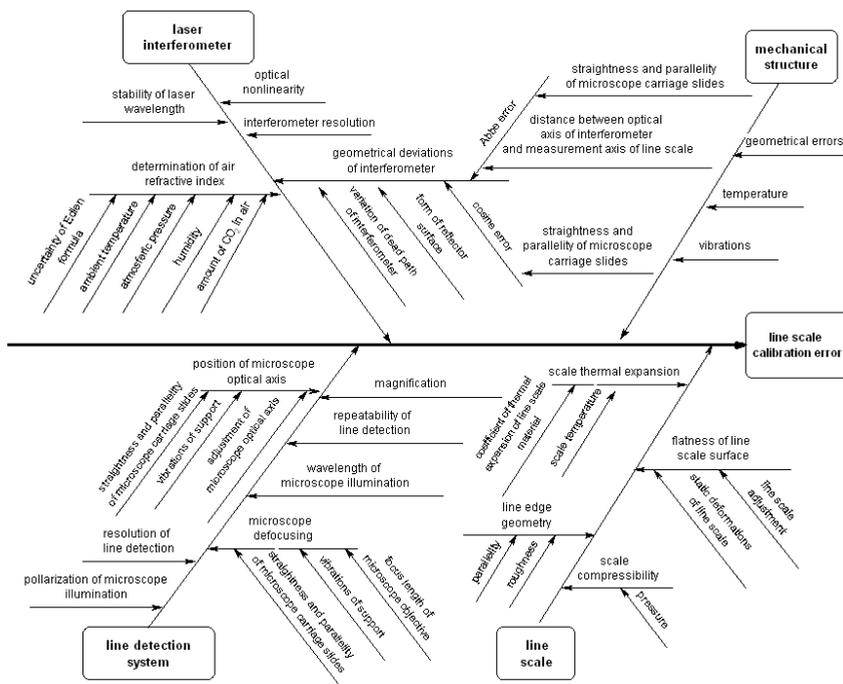


Fig. 5. Example of error model for line scale calibration system

Among the key factors that affect the accuracy of length calibration systems are geometric deviations and thermal effects on the comparator components and the scale. Mechanical limitations of calibration systems are featured by the whole complex of a mechanical system including error compensation circuits.

Thermally induced errors in measurement are an accuracy-limiting factor in the length metrology. Temperature, barometric pressure and humidity influence the refractive index of air and, thus, the wavelength of light; temperature also affects the length of the scale being measured. The philosophy of precise dimensional measurements is, therefore, to approximate thermal equilibrium near the reference temperature 20 °C for measurement condition. In order to calibrate especially long line scales some prerequisites have to be fulfilled as far as temperature influence is concerned:

- precise temperature measurements of scale and environment
- temperature stability over measurement time
- correction of small temperature drifts
- negligible thermal gradients
- temperatures close to reference temperature

Temperature problems are a widely assessed error source in precision measuring machines. While analyzing high precision calibration systems it is essential to evaluate an average volume temperature of some parts of a mechanical comparator as well as the temperature of the scale. Under real calibration conditions, temperature measurement is possible only at

certain points. The response time of temperature sensors is also rather long (from several seconds to several minutes). Therefore, fast temperature changes cannot be detected, and, consequently, the measurement uncertainty increases. The thermally induced errors in the long-stroke measuring machine are more significant because of their size and complexity. Due to high requirements for geometrical stability of calibration system, the temperature deformations caused by changes of several hundredth parts of Kelvin must be considered. The cause-and-effect relationships can be calculated in considerable detail using modern finite element (FE) analysis and empirical heat transfer formulas, but doing so requires considerable knowledge about the design and environment, see chapter 3.3.

The results of temperature measurements performed in the comparator laboratory (shown in Fig. 6) have revealed that maximum temperature deviations from the mean amount to about ± 0.25 K (during the whole period of system operation) and the main reasons that induce temperature gradients are laser source, computation and control unit, and thermally non-isolated part of the ground floor. The measurement of air temperature during the calibration procedure due to the introduced dynamic mode indicated much smaller temperature variances, and calculated standard deviation was 0.034 K. For precision calibration of the line scales not only the closeness of laboratory temperature to nominal 20 °C temperature is of crucial importance, but also temperature stability (deviations) during calibration procedure. Therefore, a period of temperature stabilization that can last for 10-14 hours is necessary in order to accomplish high precision calibration procedures.

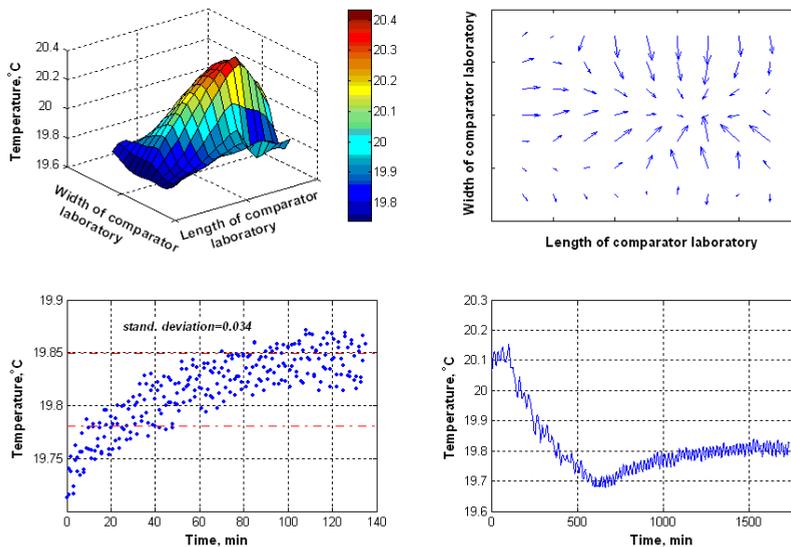


Fig. 6. Temperature measurements in the laboratory of length calibration system

3.3 Modeling

Error-related problems specific to length measurements are caused primarily by geometrical and thermal deviations of the comparator components and the scale. One of critical tasks in

the dynamic calibration of the scales is microscope image acquisition, i.e. bringing the specimen into focus before taking an image and measuring any feature. Due to imperfections of the stage, i.e. inaccuracy of the motion of the scanning mechanism and vibrations, the microscope slide is not perfectly perpendicular in regard to the optical axis of the imaging system. Measuring even a slightly vibrating structure with any degree of accuracy is prone to an error with an optical microscope. Any deviation in the distance of microscope lens with respect to the scale - for example, when the surface is in motion during the data acquisition process - introduces measurement errors. The magnitude of the resulting error can range from a few nm to several μm depending on the magnitude of such disturbances and the measurement setup. The most common error associated with small vibrations is the error in detection of the line scale graduation.

Structures of precision length measuring machines are often too sophisticated to be modelled precisely by applying simple methods. Therefore complex models as well as their analysis tools are needed in order to perform qualitative and quantitative description and analysis of determinants of the precision length calibration process.

In this work finite element method (FEM) techniques were used for behavior simulation of the comparator carriage, CCD microscope and calibrated line standard itself under the influence of dynamic and thermal factors, like variations of environmental temperature, vibrations in the structure caused by seismic excitation.

The state-of-the-art FE technique was applied in order to evaluate the possible influence of dynamic and thermal factors upon the inaccuracies of measurement. Two basic physical phenomena were of interest:

1. displacements of the structure as a consequence of applied dynamic excitations, as well as, non-homogeneities of the temperature field;
2. heat transfer inside of the structure caused by an external temperature field.

All necessary aspects of the dynamic behavior of the comparator can be investigated by employing small displacement elastic structural models as (Jakštas et al., 2006)

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{F(t) + Q(t)\} \quad (2)$$

$[K]$, $[M]$, $[C]$ are stiffness, mass and damping matrices of the structure; $\{F\}$ is nodal vector of external excitation forces; $Q(t)$ is nodal force vector caused by the temperature propagation effect; $\{U\}$, $\{\dot{U}\}$, $\{\ddot{U}\}$, are nodal displacement, velocity and acceleration vectors.

FE models enable us to simulate all 3D displacement or vibration patterns of the structure. Vertical vibrations of the microscope may lead to defocusing. Vibrations in the direction of motion may cause detection errors in determining positions of graduation lines.

In practice the excitation vectors $F(t)$ caused by external dynamic effects or by moving parts of the structure are not known explicitly, but often are subjected to external excitation propagating through the base and supports of the comparator structure. A spectrum analysis is one in which results of a modal analysis are used with a known spectrum to calculate displacements and stresses in the structure modeled. The model is capable of predicting the system's behavior under thermal load and enables us to investigate the

thermo-mechanical processes in the system, by taking into account both static and dynamic disturbances and parameter deviations.

The dynamic response of the comparator as a result of seismic excitation was investigated by employing small displacement elastic structural models (Jakštas, 2006; Jakštas et al. 2006). Modeling of seismic excitations in the comparator structure has shown that maximum displacements are expected at the bottom plane of the microscope objective and can amount more than 100 nm.

Modal analysis of the spatial carriage and microscope deviations induced by seismic excitations as well as those caused by operation of the carriage drive vibrations has shown that dynamic factors may contribute significantly to the calibration uncertainty budget. To minimize, in particular, the vibrations of the measurement reflector the construction of the carriage structure was optimized and drive-originated were vibrations reduced.

Extensive investigations were accomplished to both reduce the dynamically induced deviations originated by the dynamic excitations of the mechanical structure and optimize the comparator design. The precision measurements were performed in order to evaluate the impact of small vibration on performance of the line scale calibration process. The experimental results revealed, in particular, that the sample standard deviation of the drive-induced relative displacements between the moving reflector of the interferometer and the measurement point of the microscope may reach $0.662 \mu\text{m}$ (at calibration speed 3 mm/s); they were considerably reduced by optimization the carriage structure and elimination the undesirable modes of vibration.

Measurement results depicted in Fig. 7 show an improvement of systems stability using the optimized microscope carriage structure (blue line). The sample standard deviation of the drive-induced relative displacements of measurement mirror was reduced from $0.178 \mu\text{m}$ down to $0.054 \mu\text{m}$ (Kaušinis et al., 2009).

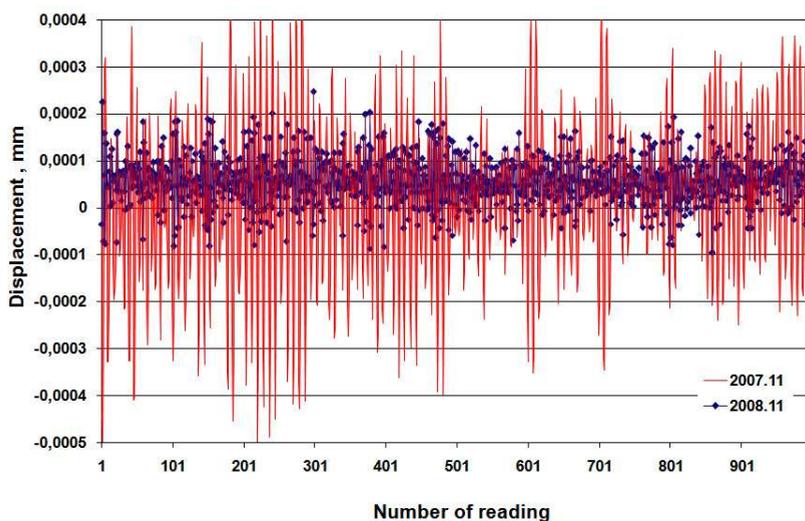


Fig. 7. Comparison of vibrations of the interferometer measurement mirror

Temperature problems are a widely assessed error source in precision measuring machines. While analyzing high precision calibration systems it is necessary to evaluate an average volume temperature of some parts of a mechanical comparator as well as the temperature of the scale. Under real calibration conditions, temperature measurement is possible only at certain points. The response time of temperature sensors is also rather long (from several seconds to several minutes). Therefore, fast temperature changes cannot be detected, and, consequently, the measurement uncertainty increases. The thermally induced errors in the long-stroke measuring machine are even more significant because of their size and complexity. Due to high requirements for geometrical stability of calibration system, the temperature deformations caused by changes of several hundredth parts of Kelvin must be considered.

The cause-and-effect relationships can be calculated in considerable detail using modern FE analysis and empirical heat transfer formulas, but doing so requires considerable knowledge about the design and environment.

The impact of temperature on the mechanical deformation of the line scale can be simulated in several ways:

1. temperature values at certain points of the construction can be detected experimentally and used for calculation;
2. temperature field can be calculated depending on the assigned non-homogeneity of the environment temperature by taking into account heat convection processes between the parts of the structure and its surrounding.

One of precarious temperature disturbances is the heat spread out by the CCD camera of the measuring microscope. As the steady-state temperature under the operating conditions is known, the thermal expansion process can be modeled by using the FE simulation, and the temperature values can be found at all points of the microscope structure. Having the temperature values obtained, the displacements due to thermal expansion can be calculated at any point of the structure.

The equation of the structure heat balance reads as follows:

$$[C]\{\dot{T}\} + [K_{Th}]\{T\} = \{S_{\infty}\} \quad (3)$$

where $[C]$ - matrix of thermal capacity, $[K_{Th}]$ - matrix of thermal conductivity, $\{S_{\infty}\}$ - nodal vector of heat sources of the element determined by the heat exchange over the surface of the body.

The solution presents the nodal temperature values, which are further used as loads in the problem of thermal expansion of the structure as:

$$[K]\{U\} = \{Q\} \quad (4)$$

where $[K]$ - stiffness matrix of the element; $\{Q\}$ - vector of nodal forces determined by temperature loads.

The FE computational model of the structure was set up, in which the temperatures of the structure and the ambient air could be calculated. The model is based on the coupling of the following physical phenomena:

1. Heat transfer by the ambient air due to its thermal conductivity;
2. Convective heat transfer (due to the motion of the air);
3. Heat exchange between the air and comparator structure;
4. Heat transfer by comparator structure due to its thermal conductivity;
5. Formation of deformations in comparator structure due to the non-homogenous thermal field generated in it.

In the computational model phenomena 1-4 have been described by means of ANSYS (FLOTTRAN) element FLUID142. The element can be used under two different conditions:

- liquid (gas) dynamics described by the continuity equation, the advection-diffusion equation and the ideal gas state equation;
- thermal conductivity in the solid described by the thermal conductivity equation.

The model is capable to predict the system's behavior under thermal load and enables us to investigate thermo-mechanical processes in the system and facilitates finding proper structural solutions to reduce the impact of thermal load on the calibration accuracy.

Displacements in the structure caused by the calculated temperatures field are depicted in Fig. 8.

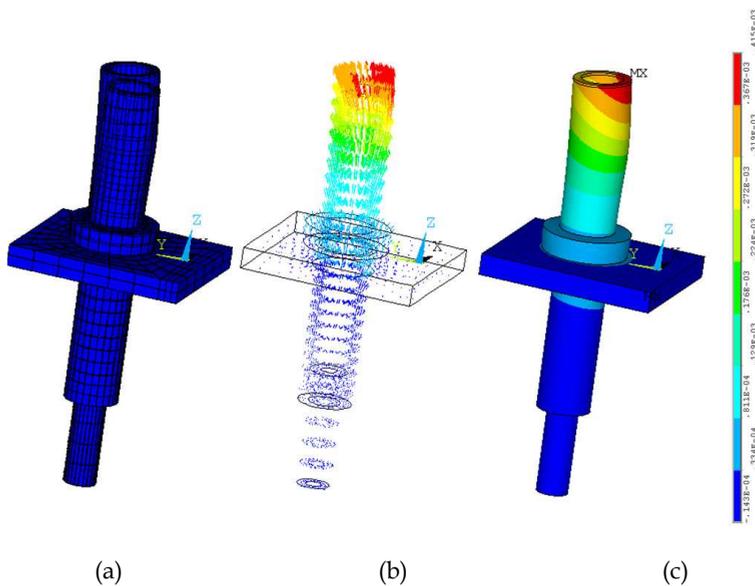


Fig. 8. Displacements in the structure caused by the calculated temperatures field; CCD camera is fixed to a side of the microscope: (a) deformation of the construction; (b) vectors of nodal displacements; (c) deformation of the structure

Vector $[Q]$ in equation (1) can be easily determined if the temperature field inside of the structure is known. If only the surrounding transient temperature field is known, the temperatures inside of the structure can be obtained by solving the thermal conductivity problem

$$[C_{th}]\{\dot{T}\} + [K_{th}]\{T\} = \{S_{\infty}\} + \{Q_{th}\} \quad (5)$$

where $[C_{th}]$, $[K_{th}]$ - thermal capacity and conductivity matrices of the structure, $\{S_{\infty}\}$ - nodal vector of heat sources determined by heat convection across the surface of the structure.

In order to determine distribution of the temperature fields around the CCD camera, temperature sensors were arranged, and temperature distribution measured at CCD cut-off, warming up, and steady operating conditions.

Calibration error caused by a thermal CCD camera impact under steady-state calibration conditions is of a random character and in real-time it cannot be compensated by mathematical methods. Within the experiments conducted an estimate of the variance of this error amounts to $\pm 0.23 \mu\text{m}$ at the 95% probability level (Barauskas et al., 2011).

3.4 Line scale calibrations

High-precision measurements of line scales basically apply two main modes of calibration: static and dynamic. Currently, static line detection systems are predominantly used in metrology institutes and calibration laboratories worldwide. The static method is potentially more accurate but somewhat slow, whereas the dynamic method offers taking advantages of scale calibration in terms of speed, accuracy and throughput. It also allows the construction simplification, because high-precision settling of the moving scale or microscope is unnecessary, and the measurement process is less influenced by ambient environmental conditions. On the other hand, the dynamic method encounters difficulties induced by measurement speed fluctuations, time delays, noise and vibrations especially during the graduation line detection. Mechanical limitations for the dynamic mode are featured by the whole complex of mechanical system including error compensation circuits.

As the dynamic calibration process is to be examined in real time, the experiments of the line scale calibration with both a slit and moving CCD microscope have been carried out in specific operating modes, and the dependence of the accuracy of dynamic calibration vs. speed has been studied.

The calibration experiments were performed that intended to document current capabilities to carry out line scale calibrations on high quality graduated scales made of low thermal expansion substrates. The line scale standard made of the glass ceramic Zerodur was available for calibration purpose from PTB. The dimensions of the scale are 230 mm in length, 25 mm in width and 14 mm in height. The graduation represents a total length of 200 mm and consists of line structures with 1 mm length and $2.5 \mu\text{m}$ width. The line structures are reflecting on transparent substrates. The measurand that was determined on the line scale standard is the deviations from the nominal lengths for 1 mm lines (1 mm pitch). Fig. 9 shows the deviations from the nominal positions for the weighted mean, calculated on the basis of the set of 6 independent measurement runs taken at the microscope carriage speed 3mm/s. The environmental chamber and scale temperatures were held within $\pm 0.05 \text{ }^{\circ}\text{C}$ during the measurements. The positions of the line are corrected for the influence of the temperature deviation from $20 \text{ }^{\circ}\text{C}$ and pressure deviations from 1013.25 hPa.

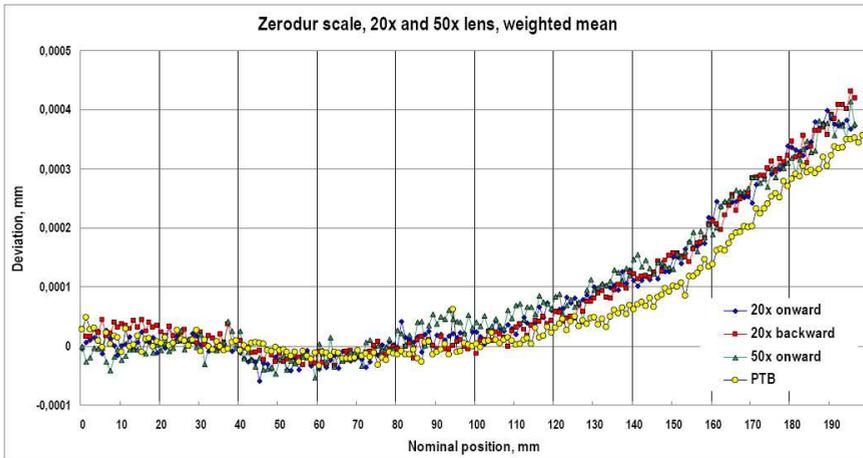


Fig. 9. Calibration results on Zerodur scale, 200 mm graduation, 1 mm step.

It has been demonstrated that the capabilities of a newly developed comparator are close to the calibration capabilities of analogous long scale calibration systems in the other countries, available from BIPM key comparison database, see Fig. 10, and still can be improved first of all by embedding an automatic line focusing system and tightening tolerances of ambient conditions in the laboratory.

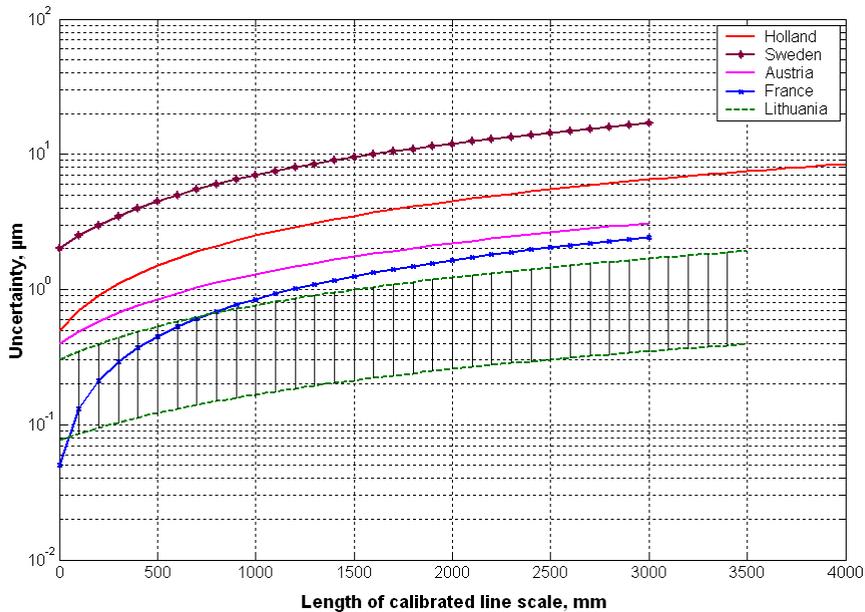


Fig. 10. Comparison of long line scale calibration capabilities

4. Conclusions

Precision measurements based on the length standard are very important, and their significance is growing with the advancement of science and industrial technology. Particularly important is product quality improvement in production processes. The development of metrology standards follows the needs of technology.

Diversity of tools and measurement techniques in dimensional metrology require significantly more mature set of standards for characterization of the measurement process used to obtain measurement data, e.g. what sampling strategy was used, what filtering was applied and what measurands definition was applied. It will also expect more know-how on the user level of the metrology involved in operating modern measurement equipment.

In industrial metrology, several issues beyond accuracy constrain the usability of metrology methods. These include, among other factors, the speed with which measurements can be accomplished on parts or surfaces in the process of manufacturing, and the ability of the measurement system to operate reliably in a manufacturing plant environment considering temperature, vibration, dust, and a host of other potential hostile factors.

The relevance and necessity of addressing the problem of precision and high-speed line scale calibration is primarily driven by the rapid increase of demands on calibration efficiency of precision scales. Considerably higher precision and efficiency requirements are set for new systems, besides, it is aimed at traceability of precision line scale parameters during manufacturing process in the technological line, and calibration process should be as short as possible.

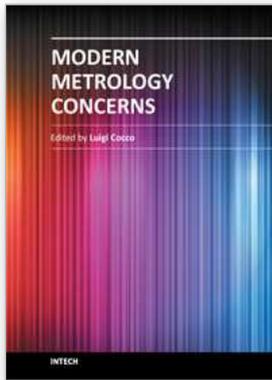
This chapter comprehends a synopsis and analysis of literature and existing scientific and technical solutions of precision 1D length calibration. It addresses also the problems of the research and development of an interferometer-controlled comparator that is operated in non-ideal environmental conditions and enables to trace the calibration of line scale of up to $L \leq 3.5$ m long to the wavelength standard.

The analysis and research results represent both systematic methodology and knowledge base for evaluation the length calibration accuracy that involve current and new technologies, and can be applied gradually in various precision machinery and instrumentation.

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