Scales vs. Laser Interferometers
Performance and Comparison of Two Measuring Systems

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Scales and laser interferometers both are linear displacement measuring systems (LDMS). It is the performance of the LDMS that limits the accuracy of servo-positioning machine tools and/or measuring instruments. The traditional systems for this purpose (besides lead-screws) have been graduated scales. Since the invention of the He-Ne gaslaser laserinterferometry has been an attractive alternative to scales. The performance of both systems are partially very similar, partially very different. In this paper metrology relevant capabilities of both systems are described and compared.

KEYWORDS: Accuracy; Displacement measurements; Gratings; Laser interferometers

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Further valuable information were received or given by comments by: K. Blaedel - LLNL, N. Bobroff - IBM, J.B. Byrd III and L. Chaloux - Rank Pneumo, A. Ernst and W. Miller - Heidenhain, C. Evans - NIST, M. Imai - SONY, T. Jinguja - Canon, P. Morantz - Cranfield Precision, G. Wyntjes - OPTRA, K. Zhao - NIM

1. Introduction

Scales and laser interferometers are linear displacement measurement systems (LDMS). The primary objective of such displacement measurement systems is to perform accurate measurements of movements along linear axes.
Accuracy in this context is a matter of different parameters like stability, repeatability, resolution etc..

The accuracy level of interest in this paper
is

- a part in 10^6 or even 10^7

for

- measurement ranges up to 1 m,

and

- a resolution of the order of nanometers.

The paper will deal exclusively with optical grating scales and He-Ne-Gaslasers (λ = 633 nm).

2. Historical background
2.1 Graduated Scales

Until 1960 line scales have been used world wide to define and to realize the unit of length as well as for practical application in trade and manufacturing technology.

J. Pettavel (SIP-CH) mentiones:
Line scales were already used in antique civilizations. Very old standards of length can be seen in the Egyptian Museum of Torino which owns five "cubits". Three of them are made of wood, one being gold covered, one is made of bronze and the last one in basalt. One of the wooden scales is specially interesting in the sense that it is an end standard of the "royal cubit" (length 526,6 mm) and a line standard divided in 28 digits (mean length 18,7mm). Furthermore, 15 of the "digits" are subdivided in 1/2, 1/3, 1/4, ..., 1/16 of a digit. The reading of the hieroglyphs has shown that this line scale was made during the reign of Pharaon Horanheb, that is to say 1300 years B.C. (**Figure 1**).

Figure 1 Egyptian line scale, total length/"royal cubit" divided in 28 "digits", about 1300 years B.C. (Egyptian Museum of Torino)

In the ancient China of approximately the same time many different line scales were used.
But in the context of this paper two other information, given by Zhao Kegong (NIM-China) are interesting to mention: "From the Han-Dynasty (220 - 206 B.C.) on there has been a continous discussion how to define a (national) standard. Finally it was decided to define the length of a tube-bell from brass, that produces a certain audio frequency (pitch) to realize the unit of length! This definition connected with some instruction for practical application was valid for more than 1000 years until Quing-Dynasty (1662 - 1722)."
An astonishing modern definition - in principle - and realization by means of a frequency resp. wavelength, however an acoustic one. Secondary standards were derived from this national standard, mostly line scales.
For practical dimensional measurements in engineering of that times, an other Chinese measuring instrument is interesting to mention. **Figure 2** shows a vernier calliper from Xing-Mang-times (9 A.C.), most probably the first measuring instrument of this type world wide. The reference is a graduated scale.

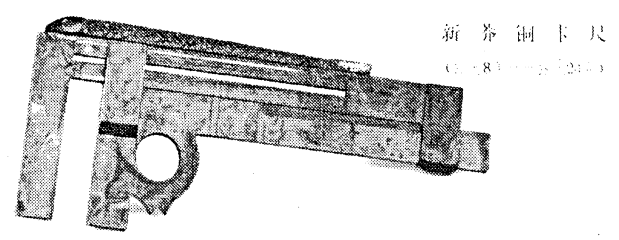

Figure 2 A vernier calliper from ancient China (Xing-Mang-Time, 9 A.C.)

These graduated scales were observed firstly by unweaponed eyes, later by using visual microscopes.
The first photoelectric microscope was developed in the late 40s of this century. Thanks to a magnification of 60000, which later became digital with a resolution of 10 nm, errors of the order of 10 nm could be measured (J. Pettavel).
The improvement of accuracy of the realization of the national and international units of length was analyzed by Petley (NPL-U.K.) and is shown in **Figure 3** /1/.

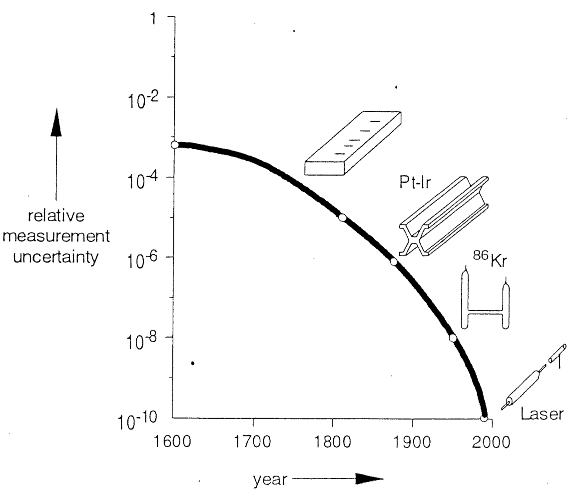

Figure 3 Improvement of accuracy for the realization of the unit of length

Until 1960 definition and realization of the unit of length was based on line scales. The latest version has been the well known Pt-Ir-Prototypes of the BIPM in Paris. In October 1960, the 11th "Conférence Générale des Poids et Mesures" decided to define the meter with a specified radiation of the orange light emitted by Krypton 86.
The role of line scales as length standard was finished, but their industrial use went on.

Scales of nowadays technology are incremental displacement measurement systems (**Figure 4**). These exist of

- an Optical Grating Scale,
- an Opto-Electronic Reading Head, and
- electronics for Data-Aquisition and -Counting.

The relative movement between the scale and reading head is the measurement of interest.

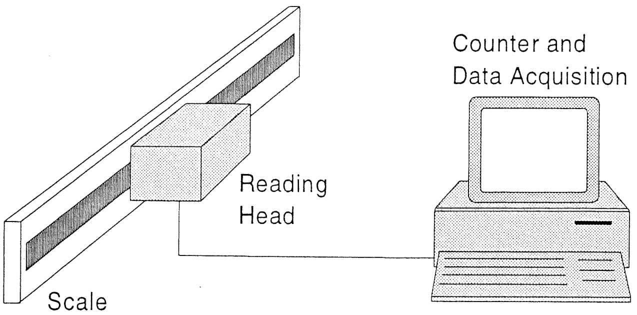

Figure 4 Scheme of an incremental linear displacement measurement system by means of optical grating scale

2.2 Laser Interferometer

The history of laser interferometers is very short compared with that of scales.

Its roots go back to interferometry by using conventional light sources. The first scientist who did interferometry displacement measurements for the purpose of dimensional measurements was A.A. Michelson; about 100 years ago. He was it, who in collaboration with Benoit from the International Bureau for Weights and Measures (BIPM) compared the wavelength of Cadmium Isotope lamps with length standards. **Figure 5** shows the principle of a Michelson Interferometer.
It was only possible to count directly the number of fringes for very small displacement of the movable mirror for length. The reasons were the limited coherence length of the light sources of that time, the very limited light intensity, the lack of photodetectors and electronics of today. Nevertheless they were able to determine the wavelengths of three cadmium lines by indirect comparison with the meter /2/.

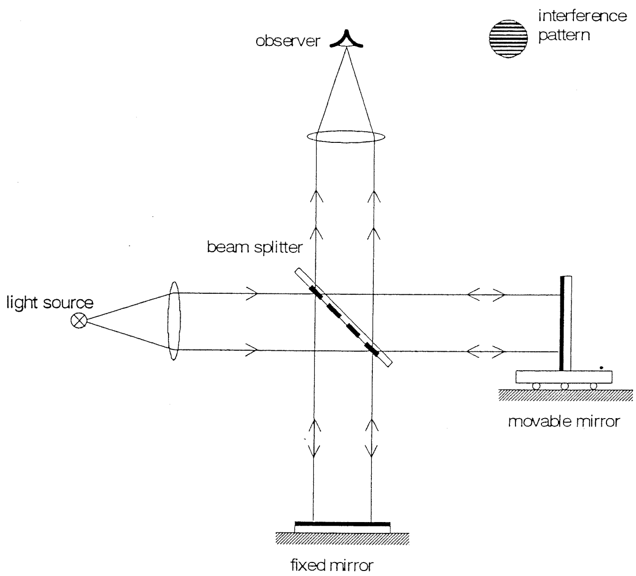

Figure 5 Michelson-Interferometer (Principle)

In 1961 the He-Ne-Laserinterferometry started with the invention of the He-Ne-Gaslaser and first experiments in scientific laboratories and very soon in industrial laboratories as well.
Interferometry itself was not new for the physicist and engineers. But what they had done until 1961 was very similar to what Michelson and Benoit had done several decades before.

The laser changed the technology completely. This light source was superior over all known conventional light sources by a factor of 10^8 with respect to coherence length and light intensity /3/.

These features were and are still today important for the application in engineering dimensional metrology. But frequency stabilized He-Ne-lasers are also the scientific base for the new meter-definition from 1983.
Laser interferometers of todays technology are incremental displacement measuring systems (**Figure 6**), existing of:

- a frequency stabilized He-Ne-Gaslaser,
- an interferometer with several optical components,
- optoelectronic detectors, and
- electronics, i.e. counter and data aquisition.

The linear movement of the reflector is measured.

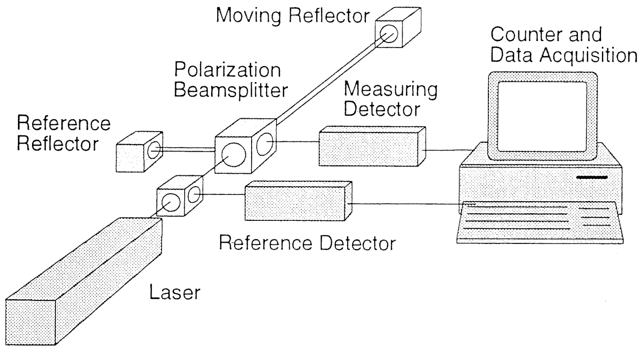

Figure 6 Scheme of a Heterodyne He-Ne laser interferometer

3 Physical principles of operation

Linear Displacement Measuring Systems by means of Optical Grating Scales or He-Ne-Laser interferometers exist in different versions.
It is not the intension of this paper to give preference to any mentioned system compared to others, not explicitly mentioned in the paper.

3.1 Scales

Scales for application in Precision Engineering as a possible alternative to laser interferometers are so-called interferential scales.
The physical principle of the "Canon Laser Linear Encoder" will be described as an example. As shown in **Figure 7a** light beam emitted by a laserdiode is directed onto the optical grating scale through a beam splitter.
The resulting first order diffraction pattern is reflected from the grating to a mirror, which reflects it back to the grating. A new pair of ± first order beams are then created and return along the same light paths. Due to a half-mirror, the ± first order diffracted beams interfere via the beam splitter and enter a photo detector. As the scale is displaced by one pitch, the phase of the ± first order diffracted light is displaced by $\pm 2\pi$ each. As the light enters the grating twice, the total phase displacement is $\pm 4\pi$/pitch. As a result, a signal with four sinewave periods per pitch, can be obtained from the photo detector.
The Canon L-104 Laser Linear Encoder has a grating pitch of 1.6 µm and outputs a sinewave signal having a period of 0.4 µm from the detector head. The signal is processed further to divide the signal 40 times and thereby achieve a resolution of 0.01 µm /4/.

The principle of the Heidenhain system is described in /5/.
The scanning signals are produced in a scanning head which contains a transmitted-light phase grating (index grating) with the same grating period as the scale, an LED as light source, a condensor and three solar cells (**Figure 7b**, left). The optical configuration of the grating interferometer is depicted in Figure 7b, right, greatly simplified but with the beam paths "unfolded".
The index grating $G_1 = G_3$ (**Figure 7b**, right) which is identical with the phase grating P of Figure 7b, left, is used as an optical beam splitter (G_1) and analyser (G_3) with equivalent functions as optical half-mirrors have in conventional interferometers.

General to all different interference scales is that the interference phenomenon is only used to generate sinusoidal opto electronic signals, independent of the wavelength of the light source, which is a function of the relative linear displacement between the scale and the reading head. With some electronic signal processing the final measure of displacement is:

$$d = \frac{i}{k \cdot f} g \qquad (1)$$

d = linear displacement
g = grating constant, pitch of scale
f = optical multiplication factor
k = electronic interpolation factor
i = number of counts

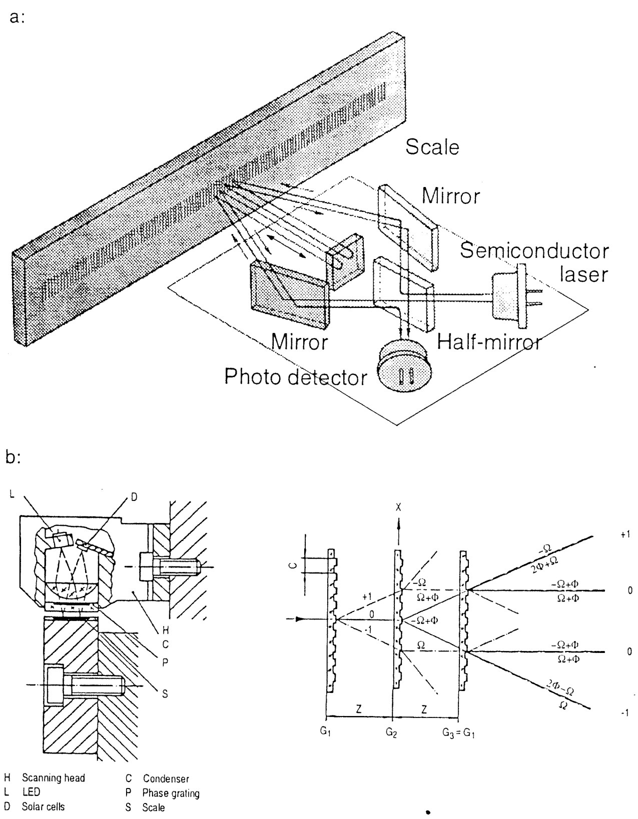

Figure 7 Principle of two versions of scanning signal generation from optical grating scales
a: Canon Laser Linear Encoder /4/
b: Heidenhain Linear Encoder LIP 101 /5/
left: design scheme
right: operating scheme

3.2 Interferometers

The basis of nearly all interferometric linear displacement measurements is the Michelson interferometer as sketched in Figure 5 and its variants /6/. **Figure 8** shows the principle of an He-Ne-Laser interferometer for displacement measurements of highest accuracy. In an interferometer, the ability of light waves to interfere is made use of. This property can be observed when light from the laser reaches a target via two different paths.
When the light reaches the target, it becomes more intensive or extinguishes, depending on whether the difference between the two paths - referred to as optical path difference - is a multiple of the wavelength or an odd-numbered multiple of half the wavelength. When the path difference in an interferometer changes with time or place, the intensification and extinction of the light changes accordingly. This light modulation is photoelectrically determined. In the most simple case, the changes between brightness and darkness - the interference orders - are counted.

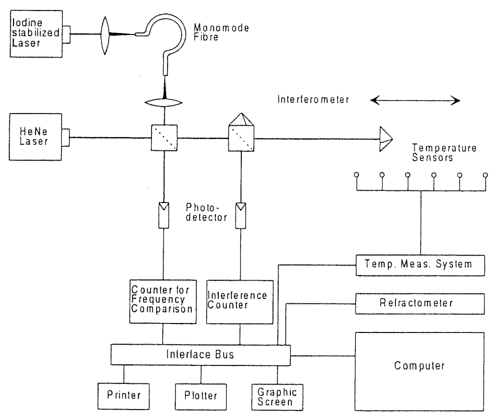

Figure 8 Principle of optimized laser interferometer system for displacement measurements of highest accuracy. Setup includes traceability to Iodine stabilized He-Ne-laser, refractometry and temperature measurements

Expressed in units of the wavelength of light, the displacement length d then is

$$d = \frac{i}{k \cdot f} \lambda \qquad (2)$$

λ = wavelength of the laser
d = linear displacement
f = optical multiplication factor
k = electronic interpolation factor
i = number of counts

3.3 What is common, what is different?

Common is:

- Scales and laser interferometers, in the sense of this article, are both measuring systems to measure displacements between the positions of moving parts.
- These measurements are done incrementally in both cases.
- Both systems exist of mechanical, optical, opto-electronical, and data processing components.

Different is:

- The reference
  for scales: optical grating on material
  for laser interferometers: laserwavelength, e.g. in air

The discussion of the performance of both systems must therefore be concentrated on these mentioned properties, in particular on the consequences of the differences between them.
This will be done under different aspects in the next chapters.

4. Physical limitations of accuracy

Limitations of accuracy of any system are set by two main aspects of equivalent importance, i.e.:

- the physical principles, chosen to solve a problem
- the technical perfection to realize the physical principle.

This chapter deals with physical principles which set the ultimate limitations under all circumstances for linear displacement measurements, starting with the definition of the term accuracy.

4.1 Accuracy

The "International Vocabulary of General Terms in Metrology" defines accuracy (of measurement) to be:
"The closeness of the agreement between the result of a measurement and the (conventional) true value of the measurand", and states in a additional note, the use of the term "precision" for accuracy should be avoided.
The Oxford Dictionary explains accuracy in short as the "exact conformity with a standard or with truth".

4.2 Definition and Realization of the unit of length

The ultimate standards with which conformity is required are the international agreements concerning definition and realizations of the unit of length. Since 1983, a speed-of-light definition has been introduced for the meter, i.e.:

> The meter is the length of the path travelled by light in vacuum during a time interval of 1/29972458 of a second.

This definition is a consequence of the development of the laserfrequency stabilization technology and is based on the fundamental equation

$$\lambda_0 \cdot f = c_0$$

where λ_0 = wavelength in vacuum
f = frequency of the same light source
c_0 = velocity of light in vacuum

By international agreement, the fundamental constant c_0 has since then be assigned the uncertainty "zero" by definition.
The vacuum wavelength λ_0 of a laser can thus be determined from the corresponding frequency f by calculation, the accuracy corresponding to that of the frequency. In several metrological state laboratories (NIST-USA, NPL-UK, PTB-DE) so-called frequency chains based on different

technologies have been established by means of which the frequency of a iodine-stabilized He-Ne gaslaser was linked up with the frequency of Cs atomic clocks.
An accuracy of a few parts in 10^{10} has been reached for the frequency and/or wavelength in vacuum of these gas lasers /7/.

Figure 9 shows the results of an international comparison of different iodine-stabilized He-Ne lasers. Metrology state laboratories from all over the world participated /8/. All the different frequencies and therefore vacuum wavelengths are in agreement within a bandwidth of less than 2 parts in 10^{10}.

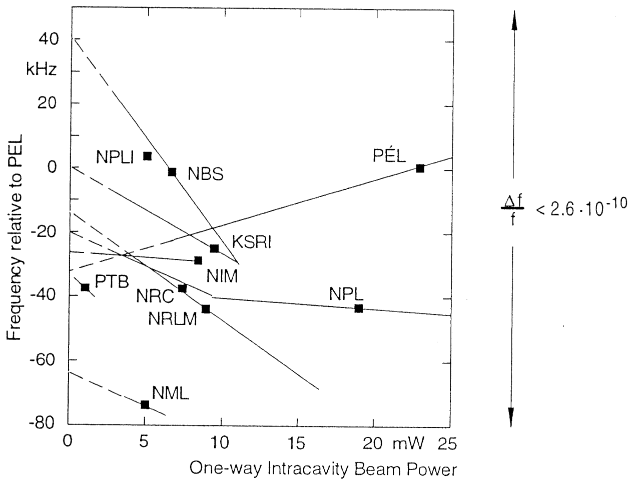

Figure 9 Degree of accordance between different iodine stabilized He-Ne lasers (λ = 0.633 μm). Source: R.B. Hurst et. al /8/

The radiation of the He-Ne laser (λ = 0.633 μm) stabilized with the absorbing molecule iodine is given in **Table 1**:

Name of laser	He-Ne laser (λ = 0.633 μm)
Absorbing molecule	$^{127}J_2$
Transition Component	11-5, R(127), i
Frequency f (MHz) Wavelength in vacuum λ_0 (μm)	f = 473 612 214,8 λ_0 = 0.632 992 398 1
Uncertainty (3σ)	± 10^{-9}
Conditions in using laser and absorbing cell	An iodine cell inside of the laser: Cold-finger temperature: 15°C ± 1°C Cell-wall temperature: between 16°C and 50°C Mean axial standing-wave power: 15 mW ± 5 mW Modulation amplitude (p-p): 6 MHz ± 1 MHz

Table 1 Operation instruction for He-Ne lasers stabilized with saturated iodine

4.3 Ultimate limits for establishing a metric

When ultimate limitations of accuracy is the matter of concern, it is a logical consequence of above facts, that the application of He-Ne lasers have the highest potential capability for ultimate accuracy.

Hence, C. Teague (NIST-USA) presented in his Key-note talk at the Stanford CIRP-General Assembly a graph showing the ultimate limits to realizing a metric for linear displacement measurements, shown in **Figure 10**.

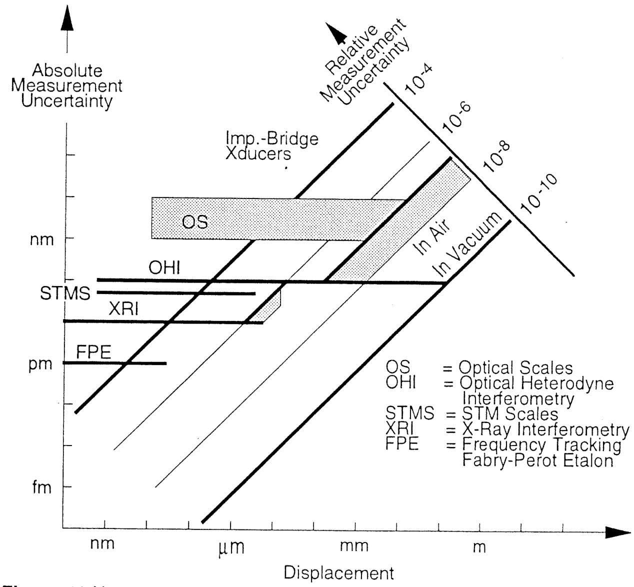

Figure 10 Nanometrology: Limits to Realizing a Metric (C. Teague; NIST-USA)

Figure 10 shows accuracy limits for different physical principles. The curves for Optical Scales and Optical Heterodyne Interferometry are of particular interest in the context of this paper /9/.
The figure also indicates implicitly, that an alternative between scales and interferometers exists for those accuracies larger than the indicated limits. It should be noted, that other features than the ultimate limits of accuracy are very often relevant and must be taken into account. Performance for technical applications in Precision Engineering are connected with those terms like resolution, linearity, robustness (or sensitivity against changes of working conditions, stability, e.t.c.) with which this paper will deal in the next chapters.

5. Technical limits of accuracy

This chapter deals with the performance of scales and interferometers given in **Table 2**:

Laser interferometer	Scale
Traceability to the SI	Traceability to the SI
Stability of λ_0, f	Stability of scale material
Linearity	Linearity
Resolution	Resolution
Refractive index n	Thermal coefficient of expansion α

Table 2 Equivalent features of laser interferometers and scales

5.1 Traceability to the metric system (SI)

5.11 Laser interferometers

Commercial He-Ne laser interferometers (λ = 0.633 μm) do not have laser sources with frequency stabilization to an absorption line.

Since 1976 by far the most people are convinced, that He-Ne laser interferometers are "a priori" traceable to the international and national standards and that no calibration by a national measurement institute is required. This was stated in a worldwide known letter, written by J.A. Simpson (NIST-USA) on behalf of the NBS to Mr. Herreman of Hewlett-Packard at that time. Simpson wrote:"....The physical principles of laser action preclude any He-Ne laser from producing light of a wavelength which differs from the accepted value of 632991.399 x 10^{-12} m by more than 1 part in 10^6. .....Modern stabilization techniques can and, when functioning, do reduce this uncertainty to perhaps 1 part in 10^9, they cannot by misfunction degrade the performance below the 10^{-6} level. ......"
The statements are in principle correct, but unfortunately it was not mentioned, that above value for the wavelength is the one of the iodine absorption line (see **Table 1**).

Commercial sytems emit laser light with reference of the emission line of the Ne-isotope of the laser, for which the centre is slightly different. **Figure 11** shows λ_0 measurement results of different laser sources calibrated by the PTB in recent years. All λ_0 measurements are within a bandwidth of 4 parts in 10^8, but the mean of all differs from the iodine absorption line about 1 part in 10^7.

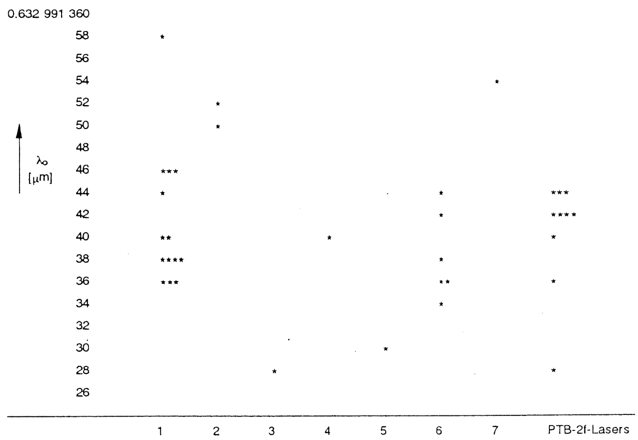

Figure 11 Results of λ_0 measurements of He-Ne lasers manufactured by 7 producers and PTB-2f-lasers

M. Sawabe (Mitutoyo-JPN) reported similar results /10/, in two cases even larger deviations were measured. These experiences were confirmed by representatives from other European national state laboratories and from manufacturers recently /11/.
As conclusion should be stated, that calibration of λ_0 of commercial systems is necessary as soon as an accuracy better than 10^{-6} is required to establish traceability.

5.12 Scales

It has never been a matter of discussion whether or not scales must be calibrated to establish traceability. They have to be calibrated!
For scales of highest accuracy calibration is offered by national measurement institutes world wide. They maintain interference comparatores for that purpose. The manufacturers have also those interference comparators for calibration of their master scales as well as for regular final inspection of their products.
Figure 12 shows measurement results of an international comparison of line scale calibration, organized by the International Bureau for Weights and Measures (BIPM).
All measurement results are within a bandwidth of ± 0.5 μm for a 1-m-steel scale. That is equivalent to a relative measurement uncertainty of 5 parts in 10^7.

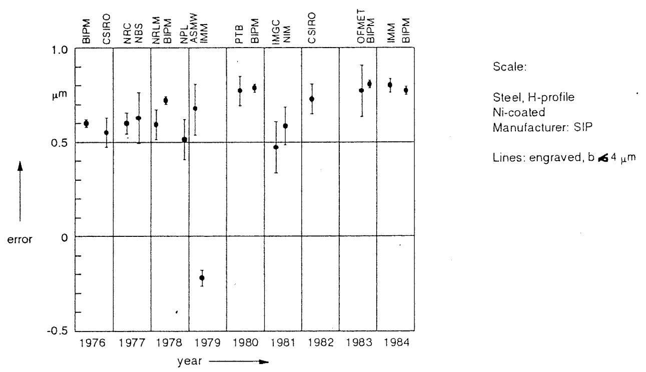

Figure 12 Results of an international comparison of a 1000 mm-line scale calibration

More recently intercomparisons of line scales with evaporated lines on quartz and Zerodur was performed between NPL-UK and PTB-DE. **Figure 13** shows the measurement results over a length of 200 mm. **Figure 14** shows the differences of calibration results between both institutes, which is within a range of ± 50 nm. For the total length the mean factor agrees within an uncertainty of 1 part in 10^7.

As a conclusion of this chapter should be stated:

- Scales need to be calibrated to establish traceability
- Calibration is provided with a best measurement uncertainty in the order of 1 part in 10^7 or 10 ... 50 nm, depending on the quality of the scale.

Deviations from linearity of the scale will be discussed in chapter 5.32.

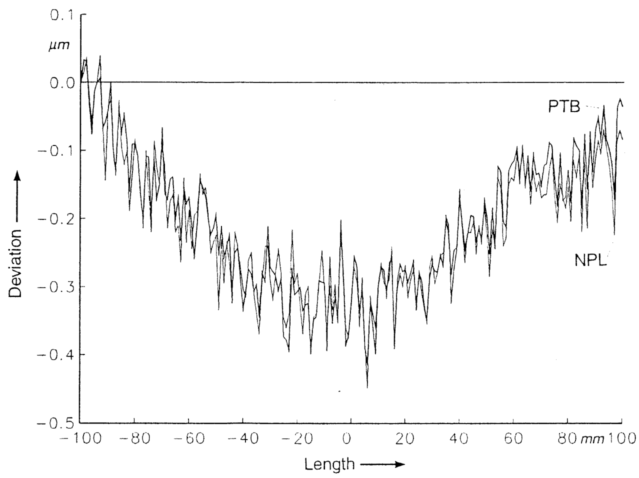

Figure 13 Calibration results of a Zerodur line scale (NPL and PTB)

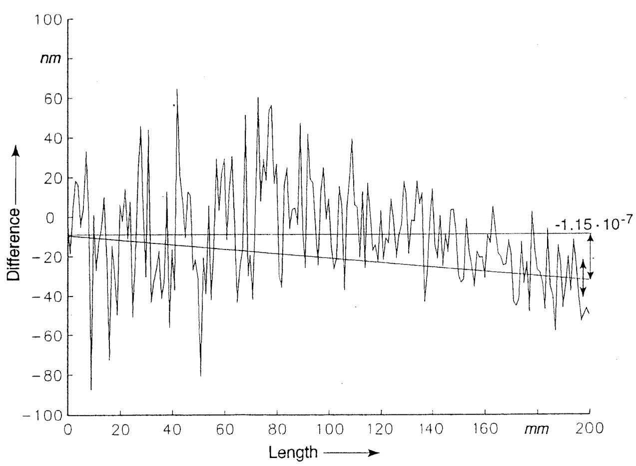

Figure 14 Differences between NPL and PTB calibrations of a Zerodur line scale

5.2 Stability

5.21 Stability of λ_0, f, of He-Ne lasers

Stability of λ_0 has two aspects:

- short term behaviour
- long term behaviour

Figure 15 shows the typical run-in effects of two laser sources (hp 5500c) as reported by A. Sacconi (IMGC-IT) during an EUROMET workshop in 1992 and confirmed by many others /11/.
The frequencies change their values over the first couple of hours in the order of 10 ... 50 MHz, which is the equivalent of a relative change of the vacuum wavelength of 0.2 ... 1 parts in 10^7 or 20 ... 100 nm over 1 m.

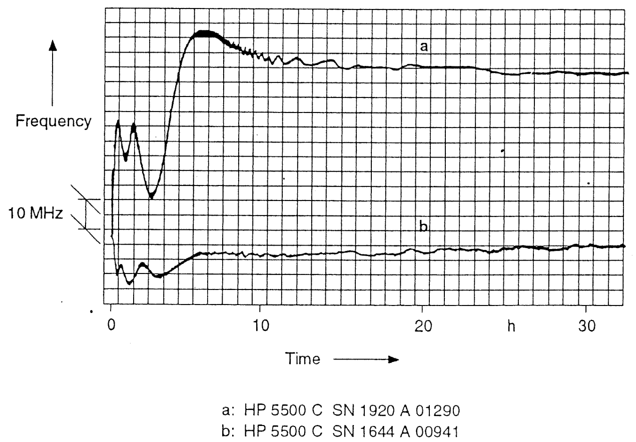

Figure 15 Frequency changes of two He-Ne lasers during warm-up time /11/

N. Bobroff (IBM-USA) contributed to this paper some information concerning long term stability of laser frequencies. **Figure 16** shows changes of different laser frequencies within a period of years. The reported frequency drifts can go up to 5 MHz/yr which is equivalent to 1 part in 10^8 (10 nm/year) /12/. Further references are given in /12/.

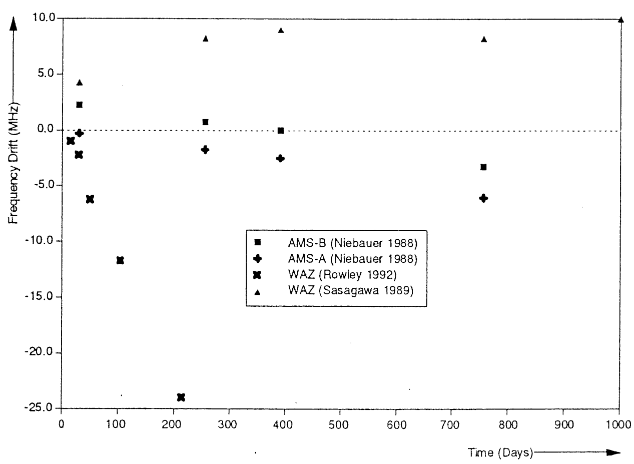

Figure 16 Long term stability of He-Ne laser frequency (N. Bobroff /12/)

As a conclusion to laser wavelength stability (λ_0, f) should be stated, that changes have to be expected when an accuracy better than 1 part in 10^7 is the target. It is very much recommendable, not to switch off and on the laser system but to keep the laser source switched on all time.

5.22 Stability of Scales

The stability of scales is directly dependent on the dimensional stability of the scale material.
Line scales of the past and today as well as optical grating scales are made from steel, glass and Zerodur.
Short term instabilities were not reported besides some changes of Invar scales in the past. This material does not play a remarkable roll for scales today because of these instabilities /51/.

J. Pettavel (SIP-CH) gave information about two line scales. The first one is made of mild steel, properly stabilized showing a mean lengthening of 13 nm/yr for 1 m over a period of 9 years.

Another line scale made of steel with 58 % of nickel, having the same thermal coefficient as steel and is stainless, showed a mean shortening of 0.23 µm/yr over a period of 22 years.
The PTB experience confirms this information from J. Pettavel. Concerning scales of differnt materials, some typical measurements are given in **Figure 17**.
In conclusion it can be said that no material is absolutely stable over time. Mild steel has a very high stability, glass and Zerodur are reasonable stable, but for highest accuracy recalibration must be recommended in any case.

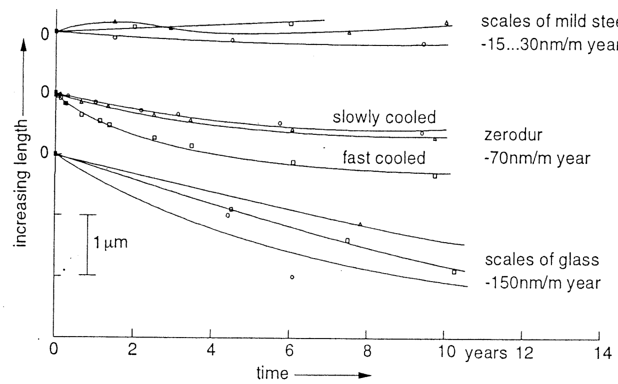

Figure 17 Long term stability of scales made from different materials

5.3 Linearity

5.31 He-Ne laserinterferomters

The wavelength of lasers in vacuum (λ_0) is a constant quantity up to our physical knowledge.
Under constant and homogenious environmental conditions (n = const. over time and space) this is as well so. The influence of ambient working conditions is discussed in Chapter 5.5 and Chapter 7.1.
This means that increments of the same optical and the same electrical phase are equidistant along a linear displacement measurement. The influence of optical and electronic interpolation is discussed in chapter 5.4.

In short can be stated, that the linearity of a laserinterferometer under constant and homogenious ambient working conditions and in constant incremental steps, i.e. same optical and electrical phase, is practically perfect.

5.32 Scales

The optical grating process is a technical one with some inherent imperfections.

To produce optical grating scales to highest linearity is the most difficult job of the scale manufacturers. The state-of-the-art should be given by some figures, provided for publication in this paper.

- Jinguja (Canon-JPN) provided a sketch (**Figure 18**) of their evaluation system to determine linearity of their short "linear encoder scales" (**Figure 19**). The evaluation system is simply a small He-Ne laserinterference comparator. Other manufacturers do the same work for improving linearity of their scales.

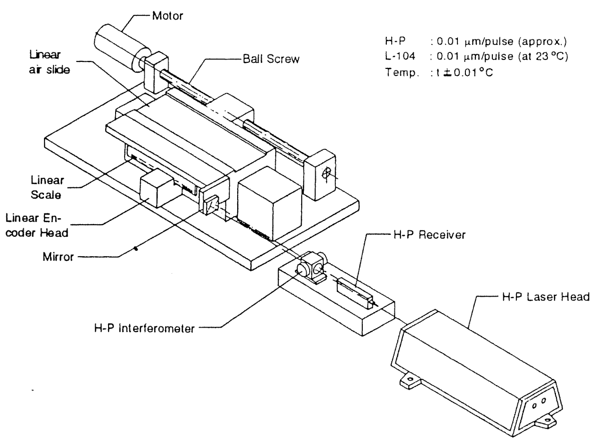

Figure 18 System of Canon for evaluation of linearity (after T. Jinguja)

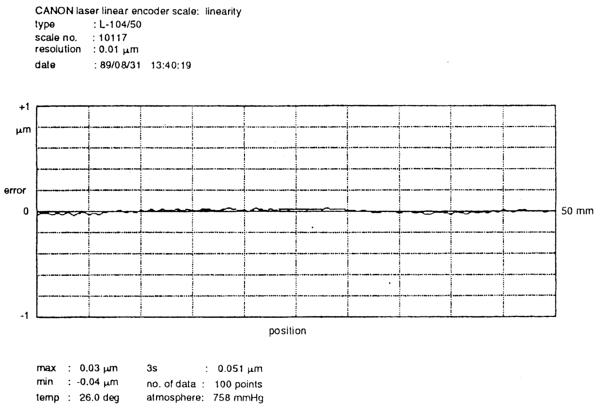

Figure 19 A "Canon laser linear encoder scale" measurement of linearity (after T. Jinguja)

- A. Ernst (Heidenhain-DE) provided some copies of calibration charts. **Figure 20** shows the results of a grating scale of 420 mm length of steel. The deviation of total length (20°C) is about 300 nm. The range of maximum deviation from linearity is about ± 50 nm over the full range with parts of the scale, where this range is much more smaller. Heidenhain has established three dividing machines and a laserinterference comparator for scale calibration in which the laser interferometer beams are operating in vacuum.

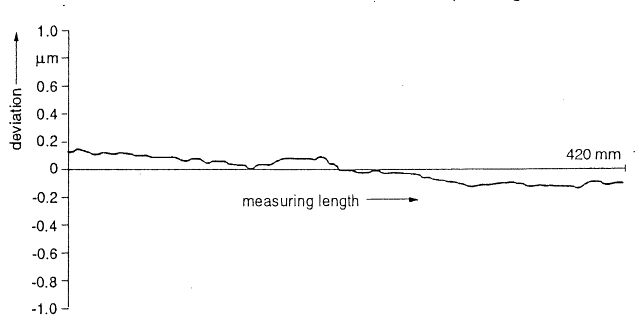

Figure 20 Calibration chart of an interferential linear encoder (Heidenhain)
Reference: laser interferometer in vacuum

Concerning linearity of scales the state-of-the-art can be stated:

- for lengths up to about 200 mm:
  maximum deviations can be brought down to appr. 20 ... 30 nm
- for lengths over 200 mm up to 1000 mm
  maximum deviations can be brought down to appr. 100 nm

These systematic deviations from linearity can be made subject of calibration procedures, mapped and then corrected by numerical error compensation down to an accuracy level of 5 ... 20 nm, dependent on the calibration capability.

5.4 Resolution, Interpolation

The resolution of displacement measurement systems is sometimes one of the most important features for the selection of a particular system. From Eq (1) and Eq (2) can be derived, that the smallest detectable step size is dependent

- on λ for interferometers, g for scales,
- and in both cases in the same way on the product of optical multiplication and electronic interpolation factors f and k.

Laser interferometers and scales available on the market have a resolution in the range of 1 nm ... 10 nm. The question is about the accuracy of the interpolation.

5.41 Laser interferometers

The optics of laser interferometers are very often arranged in such a way, that changes in the optical path are a multiple of the geometrical linear displacement of the reflector moved along a guideway /48/. There is a wide variety of different arrangements, called mostly "plane mirror interferometers" or similar. **Figure 21** shows the whole laser interferometer system of that type applied in CUPE'S NANOCENTRE, given by P. McKeown (CUPE-UK), and having a resolution of 1.25 nm /13/.

N. Bobroff (IBM-USA) stated in agreement with many others, that error sources inherent to the interferometer optics system are the reason for nonlinearities between the phase of an interference pattern and the displacement. This error has a period of one fringe and a typical magnitude of 5-10 nm in commercial heterodyne interferometers /12, 14/.

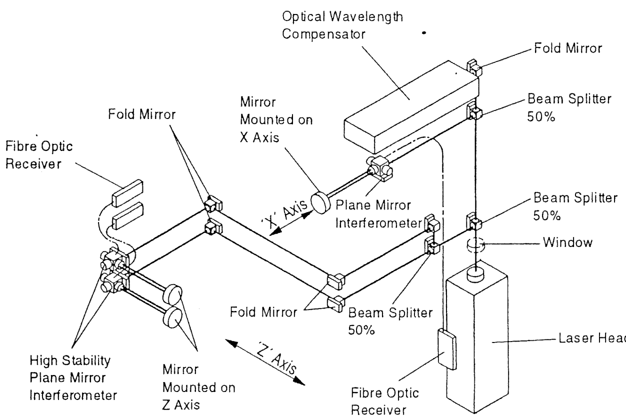

Figure 21 Interferometer system of the CUPE-NANOCENTRE

It is our experience at the PTB that those interpolation errors can go up to some ten nanometers, and that these errors are correlated with the quality of the optical components.

Figure 22 (a) shows the measured nonlinearities, having a period of $\lambda/2 \sim 0.316\ \mu m$ and an amplitude of about 6 nm. **Figure 22** (b) shows the same measurement with improved optical quality of the polarizing beam splitter and hence improved accuracy.

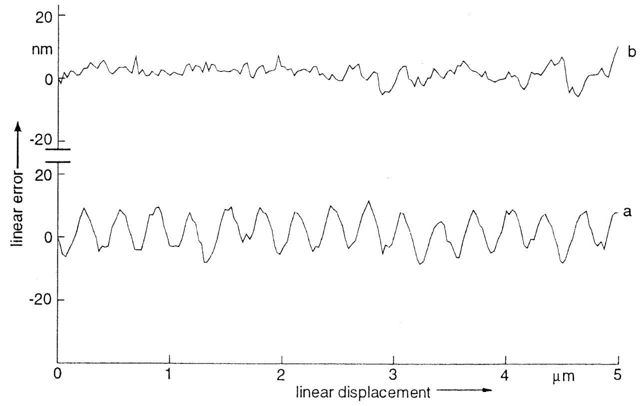

Figure 22 Measured nonlinearities of a heterodyne laser interferometer (Zygo-Axiom)
a) regular optical quality of the polarizing beam splitter
b) improved optical quality

In conclusion:
Figure 22 is a clear indication that resolution of commercial systems down to about 1 nm and even smaller values is possible.
Special care has to be taken into account to reduce interpolation errors into the same level, to earn benefit from high resolution.

5.42 Scales

There has been continuous discussions about what might be the ultimate limit of resolution of optical grating scale systems. The classical domain for this type of linear displacement systems has been the smallest step size larger 10 nm. But first scale systems are commercially available having a resolution in the 1nm domain.

Figure 23 shows results from PTB-investigations equivalent to the heterodyne laser interferometer.

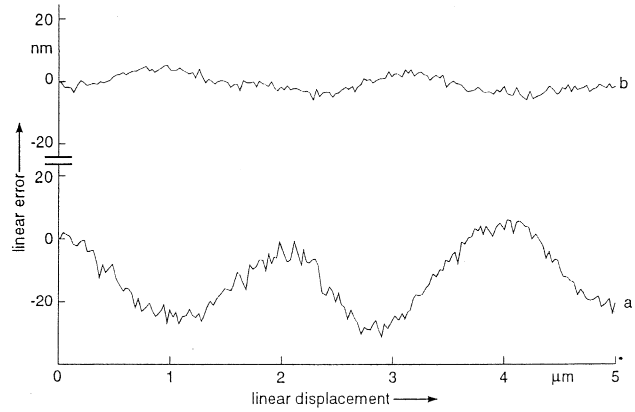

Figure 23 Measured nonlinearities of an optical grating scale system (Heidenhain LIP 101)
a) standard version
b) standard version with on-line interpolation error correction

Our results at the PTB confirm that scales of nowadays technologies can be used for linear displacement measurements with a resolution in the 1 nm regime even when the pitch of the scale is 8 µm. On-line corrections of interpolation errors have to be taken into account. Those means are available meanwhile /15,16,17/.

5.5 Influence of temperature, refractive index of air

5.51 Laser interferometers

The length scale of an interferometer is the wavelength λ. By far the most He-Ne laser interferometers are operating in air.

Four cases are known to us where this is not so:

1. The laser interferometersystem of the LODTM of Lawrence Livermore National Laboratory, where the interferometer beams are in vacuum /18/.
2. The laser interferometer of a diamond turning machine of a company in California, where the interferometer beams are in a Helium atmosphere /19/.
3. The laser interferometers of three deviding machines and the measuring machine of Heidenhain in Germany /20/.
4. The recently established vacuum laser interference comparator system of the PTB-division for Precision Engineering for studying the performance of scales and interferometers /21/.

It is very likely that some more systems are existing, but firms are not very much interested in report about their experiences and to give information to their competitors. This has to be respected. And by the way: the intension of this paper is to describe and to characterize the state-of-the-art for the standard situation and that is interferometry in air.

The wavelength in air is given by:

$$\lambda_{air} = \lambda_0 / n_{air} \qquad (3)$$

where λ_0 = wavelength in vacuum
n_{air} = refractive index of air

The refractive index of air is a well-known function of atmospheric pressure P, air temperature *T*, water vapor partial pressure p or relative humidity H, and carbon dioxide concentration by volume y.
For a number of years an empirical equation due to Edlén has been generally used in metrology /22,23/. This equation, which assumes a constant composition of air has recently been evaluated and a modified version has been shown to be more accurate (Birch, K.P. and Downs, M.J. NPL-UK, /24/).

Its value for standard conditions is

$$n_{air} \approx 1 + 2{,}7 \cdot 10^{-4} \qquad (4)$$

Changes of the thermodynamic status of the air result in changes of the refractive index as follows:

Temperature	$\frac{\Delta n}{\Delta T} \approx -1 \cdot 10^{-6}\,{}^{\circ}C^{-1}$
Pressure	$\frac{\Delta n}{\Delta P} \approx 2{,}7 \cdot 10^{-9}\,Pa^{-1}$
H_2O-content	$\frac{\Delta n}{\Delta p} \approx -3{,}5 \cdot 10^{-10}\,Pa^{-1}$
	$\frac{\Delta n}{\Delta H} \approx -10^{-8}(\%H)^{-1}$
CO_2-content	$\frac{\Delta n}{\Delta y} \approx 1{,}5 \cdot 10^{-10}\,ppm^{-1}$ (5)

T. Estler (NIST-USA) did a very detailed analysis with following conclusion /6/:
"......... we simply add the systematic errors due to the environmental parameters to the absolute uncertainty given by (an improved) Edlén. The result is

$$\frac{\Delta n_{air}}{n_{air}}(total) = \pm 8.5 \cdot 10^{-8} \qquad (6)$$

We believe that equation (6) represents a realistic limit on the possible accuracy of optical interferometric displacement measurements in air."
This analysis was done before and during field tests of the kinematic positioning accuracy of the LODTM, which is shown in **Figure 24.** While the linear axes of the LODTM are controlled by laser interferometers within flexible evacuated bellows, the field test laser interferometry must of necessity operate in the open air of the machine enclosure.

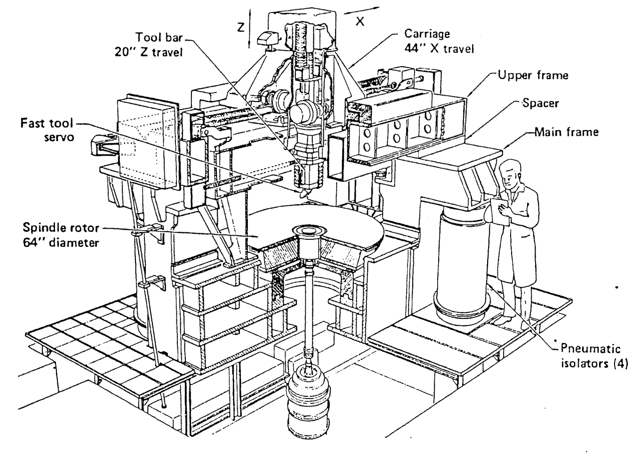

Figure 24 LODTM of the LLNL

At this point it must be mentioned that extremely well calibrated instruments are required for the measurement of

- air temperatures along the optical paths (as near as possible to the laser beam, distance between adjacent sensors smaller than 50 cm(!), accuracy level: 0.02°C)
- air pressure, accuracy level: 2 ... 5 Pa
- air humidity, accuracy level: 3 ... 6 %
- CO_2-content, accuracy level: 50 ... 100 ppm

When these conditions are fulfilled - and only then - and the working conditions are constant and homogenious, one can expect an accuracy demonstrated by Estler in some figures showing the linear displacement errors of LODTM axes (see **Figure 25**).

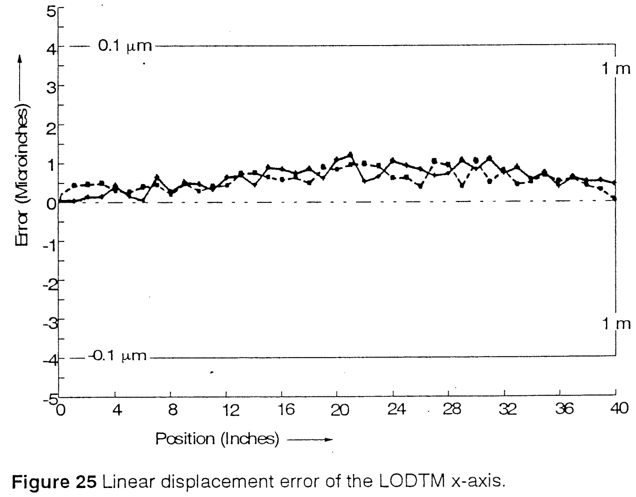

Figure 25 Linear displacement error of the LODTM x-axis.

The accordance between the vacuum laser interferometer of the LODTM and the NBS interferometer (now NIST) is within 1 part in 10^7 (after T. Estler /6/)

It is our experience and the experience of many other national metrology institutes that the status of calibration of sensor systems of compensation units is much worse. **Figure 26** shows the errors of refractivity, measured in different laboratories and workshops in the UK and Germany /25/. The results in most cases are more in the 10^{-6} then 10^{-7} domain. The results represent mean values of measurements. Because of the very large time constants of the sensor systems compared to the possible fast changes of refractivity, single measurements might be more worse. This matter is of particular importance for interferometry under workshop conditions and control systems in ultraprecision machine tools.

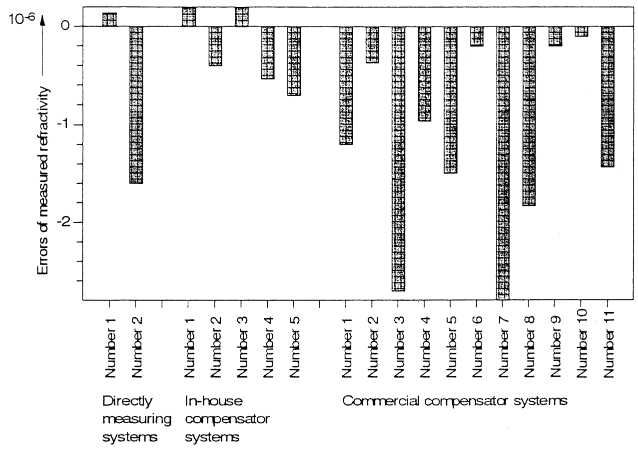

Figure 26 Errors of measured refractivity at different places in laboratories and workshops /25/

One would expect major improvements by the application of refractometers. Two types are existing:

- tracking refractometers
- absolute refractometers

Tracking refractometers measure only changes of refractivity, and only at the places where they are mounted. They have to be initiated to set the reference. All this can lead to problems as shown in **Figure 27**. Absolute refractometers have at least to be tested, better to be calibrated to guarantee proper functioning /11/.

Figure 27 (top) shows the measurement of refractivity over a time period of appr. 10 minutes at 20°C, using the improved Edlén-Formula and calibrated sensors of high accuracy. After initiating the tracking refractometer both measurements are in accordance within 1 part in 10^7 and in agreement with absolute refractometry.

Figure 27 (bottom) is taken at a temperature of 23°C in the same laboratory. Due to increase of air turbulence we recognize

- a higher noise level of refractivity measurements by refractometry
- a systematic offset due to improper initialization, i.e. zero set.

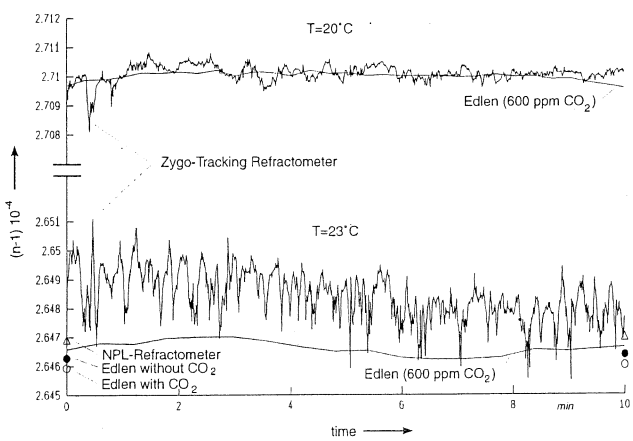

Figure 27 Results of refractivity measurements at two different temperatures

An absolute measuring refractometer can be assumed to be the ultimate solution for interferometry in air. That is true when it is done correctly. Correctly means:

- The instrument is proven to function correctly.
- It is applied in such a way, that the measured results are representative for the refractivity of the air, where the optical beams are of the laser interferometer.

In other cases results may be worse, what was recognized during our work at PTB and was confirmed by one colleague who did not want that this information is referred to him.

In conclusion:
Refractivity of the air places a fundamental limitation on the accuracy of laser interferometers. This limitations depend on the accuracy either of the measurement of the air parameters or the direct measure by refractometry /49/.

5.52 Scales

Optical grating scales are made from steel, glass or Zerodur. Their coefficients α of thermal expension (~ 20 °C), their uncertainty and order of time constant T_C is given in **Table 3**

Material	α in 10^{-6} K^{-1}	u_α in 10^{-6} K^{-1}	T_C (minutes)
Steel	10 ... 12	0.05 ... 0.1	>10 min
Glass	6 ... 10	0.05 ... 0.1	>>10 min
Zerodur	± 0.01	0.01	--
Laser Interferometer	~ 0.93	0.01	0

Table 3 Coefficients of thermal expansion and time constant for different scale materials; for the laser interferometer the equivalent thermal expansivity is given for comparison

To refer linear displacement measurements to the agreed international reference temperature 20°C it is necessary to know the thermal coefficient α of the individual scale and to measure the actual temperature of that scale.
Temperature measurements can be done with an accuracy of about 0.01 ... 0.05 °C, sometimes even better by calibrated contact sensors. Care has to be taken to detect gradients in the scale which might arise from heat sources. The state-of-the-art of dilatometry for the calibration of the coefficients of thermal expansion of scales and material of parts, important for application in precision engineering, needs to be improved.

The accuracy level of α for steel- and glass-scales in the order of 5 ... 10 % is not sufficient and is only acceptable when the actual temperature is near to the reference temperature being 20 °C. Zerodur seems to provide a performance superior to all other materials and this is correct as along as thermal behaviour of scales for linear displacement measurements is the target. It must be stated at this point, that the application of materials with a very small α requires very accurate temperature metrology at other parts, when dimensional accuracy is required (see Chapter 7.2).

In conclusion:
Scales are quite stable against short term temperature changes of the environmental working conditions. The coefficient α of thermal expansion places a fundamental limitation on the accuracy of linear displacement measurements. This limitations depend on the accuracy by which α is known and of the measurement of the scale temperature.

6. Performance for integration into machine structures

The field of application of linear displacement measurement systems (LDMS) is to establish the measurement reference of machine tools and of measuring instruments. Machine tools and measuring instruments, CMMs in particular, are made to produce or to measure workpieces to a specified accuracy.
P. McKeown (CUPE-UK) states that the workpiece accuracy is affected by many differenct factors and the application of some principles and/or techniques of application /26,50/. This is confirmed by S. Sartori (IMGC-IT) and his collaborators /27/.
Table 4 is a selection of only those factors, principles, and techniques affecting workpiece accuracy, which are relevant for the discussion of scales and laser interferometers in this paper:

Factor	Principle/Technique
Machine Design	Scale or Laser interferometers Abbe principle or options Metrology frames Error compensation Thermal properties
Environment	Temperature Humidity Pressure
Workpiece	Thermal properties

Table 4 Scales or laser interferometers - Relevant factors, principles and/or techniques for workpiece accuracy (after P.A. McKeown /50/)

It is the interaction of all factors and their principles/techniques, that lead to the accuracy of the manufactured or measured workpiece/part.

6.1 Abbe principle

What is nowadays described as Abbe's principle has its roots in a talk on "Measurement Instruments for Physicists", given by E. Abbe in 1890 /28/.

He described his design principles of instruments then manufactured by Carl Zeiss Jena. **Figure 28** shows the thickness measuring instrument of Abbe 1890.
The design principles he stated are:
1. The measurement - visual or by contact - is exclusively to be based on a longitudinal graduated scale with which the length to be measured is directly compared.
2. The measurement instrument is always designed so that the length to be measured is in a straight line continuation of the scale.

The basic intension to postulate this design principles was to minimize possible errors of measurements resulting from angular errors of the guideways in such instruments.

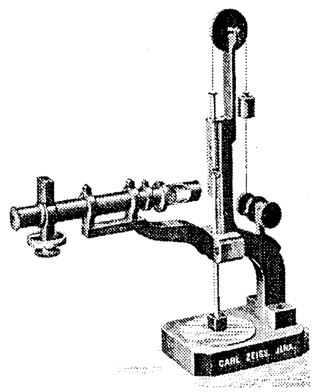

Figure 28 Thickness measuring instrument of E. Abbe, 1890

E. Abbe mentioned in the same paper:

- That the systematic errors of scales can be determined (- in our words: by calibration)
- That the length variations of the scales due to temperature variation can be calculated (- in our words: corrected).

Meanwhile Abbe's principle was studied in detail and partially modified by J. Bryan (LLNL-USA) and G.X. Zhang (Tianjing Univ. - CHINA) for a wider understanding /29,30/, what is not the matter of this paper.
But the most important consequence of this new understanding is that measuring angular errors and correcting the resulting systematic errors of misalignment is equivalent to minimizing those unknown systematic errors by optimizing mechanical adjustments.

This conclusion is relevant for discussion concerning scales and laser interferometers as alternatives. Machine tools and measuring machines are mostly working in more than one axis. Whether or not Abbe´s principle can be applied in the traditional meaning or Bryans interpretation indicated in **Table 5**.

LDMS	Abbe Principle					
	traditional			Bryans interpretation		
	1D	2D	3D	1D	2D	3D
Laser interferometers	X	X	X	X	X	X
Scales	X	-	-	X	X	X

Table 5 Abbe Principle - Application of laser interferometers and scales

Laser interferometers can be modified in their optical setup to realize the traditional Abbe principle with some restrictions even in 2D- and 3D-measuring machines. Plane mirror laser interferometry is the technology of today.

Figure 29 shows a sketch of a 3D-CMM of very high accuracy with multiple plane mirror laser interferometers in all three axis /32/. The Abbe principle is fulfilled in its traditional expression. K. Becker and E. Hey-

nacher (C.Zeiss - DE) stated: "The fundamental idea of the high resolution measuring system bases on the 3D-expansion of the old "masterpiece concept" (i.e. Abbe-principle). ...... This idea has been applied to measurements in space in the following manner:

- A configuration of three high quality flat mirrors oriented orthogonally to each other was built up, representing a space normal for the laser interferometrical measurement.
- A probe head contacting the workpiece mechanically was constructed (optically as future option).
- The position of the probe head relative to the reference mirrors is detected by means of an interferometrical laser measuring system.

In order to eliminate Abbe-errors resulting from tilts of the probe head, two laser axes are used for the x- and z-coordinates (see **Figure 29**), thus allowing to remove such errors by recalculating the exact position by software operations off line.

The measuring system itself uses a He-Ne laser emitting two frequencies separated by 1,75 MHz and polarized orthogonally to each other. The primary beam is splitted into five separate position measuring axes and one reference axis which allows to monitor the environmental conditions regarding air temperature, humidity etc."

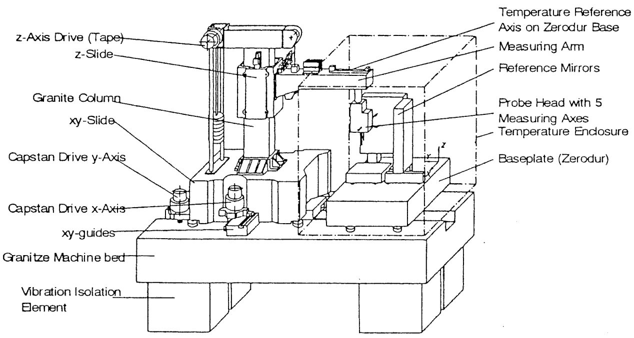

Figure 29 High Resolution CMM of Carl Zeiss - Sketch (after K. Becker and E. Heynacher)

An equivalent solution is not possible for machine tools and by application of scales.
But it should be mentioned that the CMM of **Figure 29** is an extremely expensive solution for measurement problems requiring highest accuracy of special parts, i.e. x-ray mirrors or equivalent workpieces.

The advanced technology of today and the future, with respect to Abbe principle, is:

- to design and manufacture the mechanical structure of machines to high accuracy, in particular to high stability and repeatability,
- to measure the remaining systematic errors, and
- to apply numerical error correction for further improvement of accuracy.

This "advanced Abbe principle" has demonstrated its capability in CMM applications to a high level of accuracy independent on whether laser interferometers or scales are applied /38/.

6.2 Metrology frame

The CMM of **Figure 29** and the LODTM of **Figure 24** are machines using a "metrology frame" structure /26/.
K. Becker and E. Heynacher express this simply:" The measuring system is separated from the machine control system." S.R. Patterson (LLNL-USA) described: "The LODTM uses a "metrology frame" structure, separate from the structural support for the slides and spindle, as a reference for the tool position measurements used in the control system. As it is not required to carry any load other than its own weight, this metrology frame may be designed wholly for thermal and temporal stability." /18,33/
E. Abbe described it in 1890 this way: "The scales are fasted at one end only so that they can expand freely."
The basic background for the implementation of a metrology frame into a machine structure is to protect the linear displacement measuring systems against mismeasurements resulting from any expansion of the mechanical structure.

K.H. Breyer and H.G. Pressel (C. Zeiss - DE) described the mounting technique of Zerodur scales to their CMM guideways consisting of aluminium alloy. "By fixing them (i.e. the scales) in one point only and " float supporting" the rest of the scale , it is guaranteed that no forces are transmitted to the Zerodur scale if the carrier material is subject to changes in length." /34/ (see **Figure 30**)

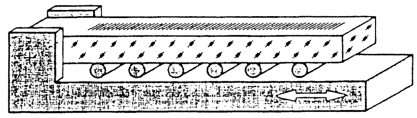

Figure 30 Principle of mounting a Zerodur scale (after K.H. Breyer and H.G. Pressel, C. Zeiss)

The necessity to realize a metrology frame grows with increasing differences of coefficients of thermal expansion between the LDMS, machine structure, workpiece material, and increasing demand for accuracy. All classical comparators, line scale comparators and interference comparators, have the metrology frame structure /35,36,37/.
As a conclusion can be stated that machine structures having a metrology frame are possible for the application of scales as well as laser interferometers. It is very expensive to realize those machines.

Manufacturers of scales, machine tools, and CMMs prefer often to align and to fasten the scales on specially prepared reference planes within the machine structures. They argue that this improves the total accuracy of the machines because of reduction of thermal errors would be more effective than the possible gain by realization of a not perfectly established metrology frame.
It is very obvious that the characteristics of those fastened scales is different from those supported in a metrology frame structure. The final performance of the whole machine is dependent on the individual assembly situation.
For precision machine tools and CMMs the calibration of their displacement measuring capability along specified functional lines /30/ must be done /31/.

7. Comparison of performances for application

In by far the most cases appliers of machine tools and measuring machines are not interested in the performance of a certain subsystem of their machines.
They need to know the performance of the whole to solve their problem: The problem might be either to machine or to measure a workpiece within prescribed or desired tolerances concerning surface roughness, form, dimension and/or a combination of these features. Complex workpieces exist of a variety of several elements to be machined or measured in sequence. Important side conditions influence directly or indirectly accuracy:

- The materials of these workpieces are mostly different one from another, with different coefficients of thermal expansion.
- changes of the ambient working conditions. Even in an air-conditioned environment temperature changes have to be taken into account resulting from internal and external heat sources.

Under those circumstances we have to deal with the performance of LDMS:

- for positioning accuracy of machines, and
- dimensional accuracy of workpieces

7.1 Performance of laser interferometers and scales for positioning accuracy of machines

Positioning accuracy of machine tools and measuring machines depend in principle on all discussed attributes of the LDMS, their integration into the machine system, and their interaction as far as scales and laser interferometers are concerned.
In a lot of cases in precision engineering manufacturers and appliers of machine tools, diamond turning machines in particular are nearly exclusively interested in the manufacture parts to very smooth surfaces and to a high degree of perfectness in form rather than dimension.

This case will be discussed in this chapter. The relevant attributes of the LDMS are

- resolution
- linearity coarse errors
  interpolation errors
- sensitivity against turbulences of the air and
  temperature variations

Finally some remarks will be given concerning

- alignment effects

Resolution of laser interferometers and scales of nowadays technologies are more or less in the same domain (1 nm ... 10 nm) with some minor advantages of laser interferometers. (see Chapter 5.4).

Linearity has two aspects: coarse errors and interpolation errors. Laser interferometers do not have coarse errors, scales have those errors of linearity. The differences can be reduced by application of calibrated scales and on-line error correction.

Interpolation errors of laser interferometers are in the range of 5 nm ... 20 nm and of scales in the range of 20 nm ... 50 nm. By on-line error correction these fine cycle errors can be reduced to the 1 nm level in both cases.

Sensitivity against environmental working conditions must be treated in more detail.

In addition to what was already mentioned in Chapter 5.5, A. Sacconi (IMGC-IT) reported, as many others too, about thermal sensitivity of heterodyne laser interferometers /39/. **Figure 31** shows detected displacement measurements although both reflectors were fasted to the beam splitter and adjusted near to zero order interference. Well known are dead path errors of laser interferometers /40/ which show similar effects but are dependent on the optical path difference for which the interferometer is set at its zero position /40,41/. Those effects were never reported for scales.

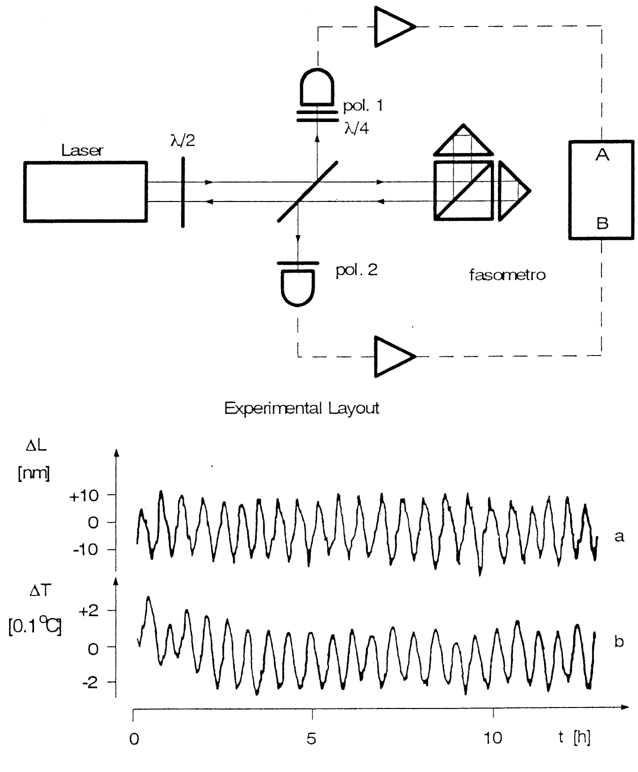

Figure 31 Zero point changes of a laser interferometer with temperature changes reported by A. Sacconi /39/
Top: experimental lay-out
Bottom: typical behaviour

At the PTB we studied sensitivity against thermal fluctuations by direct comparison of laser interferometers and scales with a vacuum laser interferometer as common reference.

Figure 32 shows results of those measurements for a specific position as a function of time. The variations of the interferometric measurement is larger than the variations of the scale measurements.

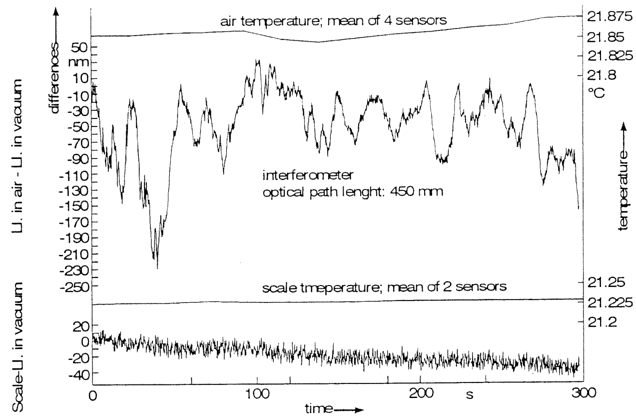

Figure 32 Sensitivity against fluctuations in the environment
Top: measured air temperature, changes of the differences between LI in air and LI in vacuum (reference)
Bottom: measured scale temperature, changes of the differences between scale and LI in vacuum (reference)

In **Figure 33** the standard deviation of those measurements at different positions are plotted (T ~ 21.4 °C).
There is a nearly linear increase of the short term variation (standard deviation) of the laser interferometric measurements from 5 nm for an optical path in air of a few mm to 80 nm for an optical path in air of appr. 800 mm. At the same time the standard deviation of the measurements of a scale is in the range of 10 nm to 15 nm and nearly independent on position.
It should be mentioned at this point, that the short term sensitivity of laser interferomters increases with increasing temperature-level (increasing level of turbulences). It can be reduced by shielding the optical paths using metallic tubes. But tubes do not reduce turbulences a lot. A factor of two or so was reported by somebody who do not want to be nominated. That agrees with our findings.

These short term variations of laser interferometer measurements cannot be reduced by application of refractometers. They can even make these things worse, because of their own variations of the same level in the same frequency bandwidth. This experience was also confirmed by others. Further improvements might be possible by two colour laserinterferometry as reported by H. Matsumoto and H. Honda /42/.

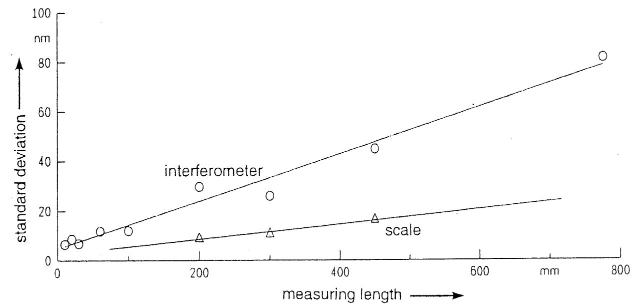

Figure 33 Short term variations of measurements at different optical path lengths of a laser interferometer and of a scale; common reference is a vacuum laser interferometer

Electrical filtering of the interferometer signal is more effective and is mostly done to reduce this type of this short term fluctuations. For short term positioning accuracy or repeatability above results show the performance of scales superior to laser interferometers.
This statement holds as long as no special case is taken into account to keep the ambient conditions for the laser interferometer extremely stable either by vacuum or very stable other atmospheric conditions.

Alignment accuracy can be a problem, when plane mirror interferometers are used /12/. The laser beam, the plane surfaces of the mirrors and the direction of linear motion have to be adjusted to be parallel or perpendicular. For 2D or 3D this is extremely difficult. For 2D- and 3D-application

misalignment can lead to different "scale factors" for the different axis and deviation from orthogonality between the axis /43/.

Alignment of scales parallel to the axis of movement need also care and experience. With some auxiliary measurement equipment this problem can be solved to a high degree of perfection. Scale support and fixture to the mechanical system has to be designed and constructed very carefully (see also Chapter 6.2).

Concluding the alignment effects:
The difficulties of proper alignment of laser interferometers and scales are more or less equivalent. The same is the case for consequences of misalignment.

In **Table 6** all accuracy levels relevant for the comparison of scales and laser interferometers concerning position accuracy of machines are given.

Attribute	Laser Interferometer		Scale
	t < 0.1 sec	t > 10 min	Zerodur, Glass, Steel
Linearity			
Coarse	--	--	5 ... 50 nm
fine cycle	1 ... 5 nm	1 ... 5 nm	1 ... 10 nm
Resolution	1 nm	1 nm	1 ... 20 nm
Sensitivity air turbulence t ≈ 20 °C	~ 10^{-7}	--	--
Zero-point (Δt = 0.1 °C) death path	--	~ 10 nm	--
thermal expansion (Δt = 0.1 °C)	10^{-7}	10^{-7}	10^{-8} $7 \cdot 10^{-7}$ 10^{-6}

Table 6 Accuracy levels of scales and laser interferometers relevant for positioning accuracy of machines

For a very rough conclusion for the overall performances of scales and laser interferometers it seems adequate simply to add the figures of

Table 6. This results in performance levels for positioning accuracy dependent on the available time for positioning as given in **Table 7**.

	Performance for positioning	
LDMS	t ≤ 0.1 sec (ΔT → 0 °C)	t ≥ 10 min (ΔT ≤ 0.1 °C)
Laser interferometer	~ (2 ... 5) nm + 10^{-7}	(10 ... 15) nm + 10^{-7}
Scale		
Zerodur	(5 ... 50) nm	(5 ... 50) nm+10^{-8}
Glass	(5 ... 50) nm	(5 ... 50) nm+$6 \cdot 10^{-7}$
Steel	(5 ... 50) nm	(5 ... 50) nm+10^{-6}

Table 7 Performance of laser interferometers and scales of different material for positioning accuracy of machines.

7.2 Performance for dimensional accuracy of parts

As soon as the manufacture or measurement of parts and workpieces to specified dimensional accuracy is concerned, the following attributes of LDMS have additionally to be taken into account to those dealt with for positioning accuracy:

- traceability
- stability
- refractivity, thermal expansivity of the LDMS
- thermal expansivity of the workpiece
- temperature (absolute) and temperature stability
- accuracy of temperature measurements

Traceability of the wavelength of lasers and scales are discussed in Chapter 5.1. Their stability is described in Chapter 5.2, and their refractivity and thermal expansion are described in Chapter 5.5.
The remaining points deal with the thermal influence of the environment on the whole process and the dimensional behaviour of the workpieces. There is a number of scientific and technical papers published, even written standards /44,45/.
J.B. Bryan gave a CIRP-keynote paper /46/ in 1990 and many more contributions to the discussion on thermal effects in precision engineering, manufacturing technology and dimensional metrology.

All available information and own experience condensed to the relevance of this paper shows that the highest level of dimensional accuracy of parts is achieved:

- when the actual temperature of the part and the LDMS both is 20 °C
- when the thermal expansivity of the part and the LDMS approaches equality

The more general case should be discussed by means of **Figure 34,** which is a transfer chart for estimating the attainable dimensional accuracy level, expressed in dimensional uncertainty, depending on the uncertainty of the 20 °C-temperature and the thermal expansions of workpieces /47/ and LDMS.
One important fact must be mentioned, that is that the dominating influencing factor besides temperature is the difference of thermal expansivity between the part and the LDMS.

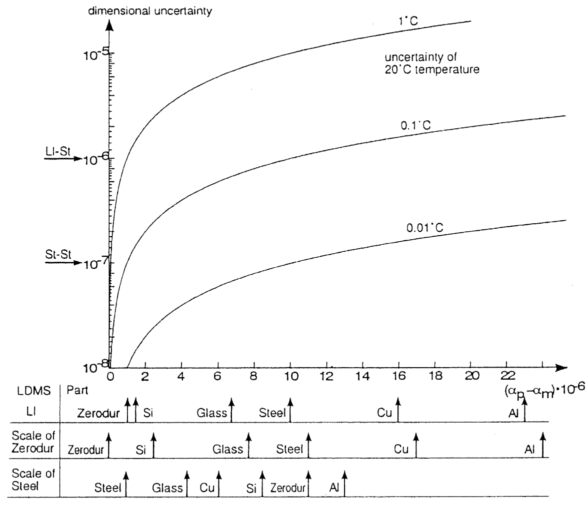

Figure 34 Transfer chart for estimating the attainable dimensional accuracy level (dim. uncertainty) depending on the uncertainty of 20°C-temperature and the thermal expansions of workpieces and LDMS

Figure 34 indicates very clearly the necessity of very stable and accurate thermal conditions, when dimensional accuracy of parts is the target. It also confirms the experience of practioneers, that the thermal behaviour of workpiece material should have the same or at least very similar thermal behaviour as the reference, to minimize temperature effects.
Two examples are given to demonstrate the application of this chart, i.e.:

- workpiece of steel and laser interferometer, accuracy level is ~ 10^{-6} for U_{20} = 0.1°C
- workpiece and scale of steel, having both an uncertainty of $u_{\alpha} \approx 10^{-6}$ K^{-1}, accuracy level is ~ 10^{-7} for u_{20} = 0.1 °C

The general case of arbitrary spatial and temporal temperatures and their variation are not discussed in this paper. In general can be said:
The general case of arbitrary spatial and temporal temperatures and their variation are not discussed in this paper. In general it can be said:

- dimensional accuracy is directly proportional
  : to temperature measurement accuracy
  : to the accuracy by which thermal expansivity of the part and LDMS is known.

In conclusion:
The performance of scales and interferometers for dimensional accuracy of parts is dominantly dependent on temperature related attributes of the workpieces and the LDMS.
Even when traceability and stability of the LDMS are in the order of parts in 10^7 or even 10^8, these levels of dimensional accuracy cannot be attained under normal and even reasonable good working conditions.

As soon as
- the actual temperatures differ more than 0.3 °C from 20 °C
- the uncertainty of temperature measurements is larger than 0.1 °C
- the difference between thermal expansivity of workpiece and LDMS is larger than $1 \cdot 10^{-6}$ K^{-1},

the dimensional uncertainty - after compensation of systematic thermal expansion - is worse than 5 parts in 10^7 /45/.
This accuracy level is independent on whether scales or laser interferometers are used for displacement measurements. Different time depends on reactions on temperatur changes make things worse.

8. Comparison of Scales and laser interferometers

The characteristics of scales and laser interferometers for concluding comparison of their performances are given in **Table 8**.

	optical grating scales	laser interferometers
Accuracy	dependent on accuracy of calibration and on-line error compensation	vacuum interferometry sets the ultimate limit in open air dependent on accuracy of refractometry
Linearity	dependent on calibration of coarse erros and on-line fine cycle error compensation	linearity is in very high fine cycle error compensation is necessary
Resolution	≥ 1 nm	≥ 1 nm
Measuring range	≤ 1500 mm	≤ 30 m
Reproducibility, Precision	limited by thermal characteristics with t_c > 10 min	limited by atmospheric fluctuations: $t_c = 0$ length dependent Zero-point stability death path minimization
Integration into machines	- traditional Abbe-principle only for 1 D - metrology frame structure : is possible : scale fixture easy : two parts (small): scale and reading head	- traditional Abbe-principle for 1D for 2D and 3D with minor restrictions - metrology frame structure : is possible : adjustment of optical components need care and experience

Table 8 Synopsis for comparison of performances of scales and laser interferometers

In general it can be stated:

- for ultimate accuracy in dimensional metrology and highest precision engineering the best choice is:
  - vacuumlaserinterferometry or
  - laser interferometry under extremely constant environmental conditions absolute refractometry etc., combined
  - with very accurate temperature measurements
- for high accuracy (10^{-7} ... 10^{-6}; 10 ... 100 nm)
  - scales and interferometers are more or less equivalent, when the accuracy limiting components are calibrated (in both cases)
- for accuracy (10^{-6} ... 10^{-5}; 0.1 ... 10 µm)
  - scales are mostly more reasonable than interferometers for integration into machine tools and CMMs
  - scales must be calibrated before application but scales of steel in particular need less care of thermal effects during application
  - laser interferometers need not to be calibrated, but their compensators need very much.

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