PRINCIPLES OF OPERATION

1. The rules of laser displacement measurements

Displacement measurements with the use of laser allow obtaining the accuracy of 1ppm and bettering. The tool that allows such high accuracies is the interferometer, first built by A.A. Michelson in 1881. Its simplified schematic is shown on Fig. 1.

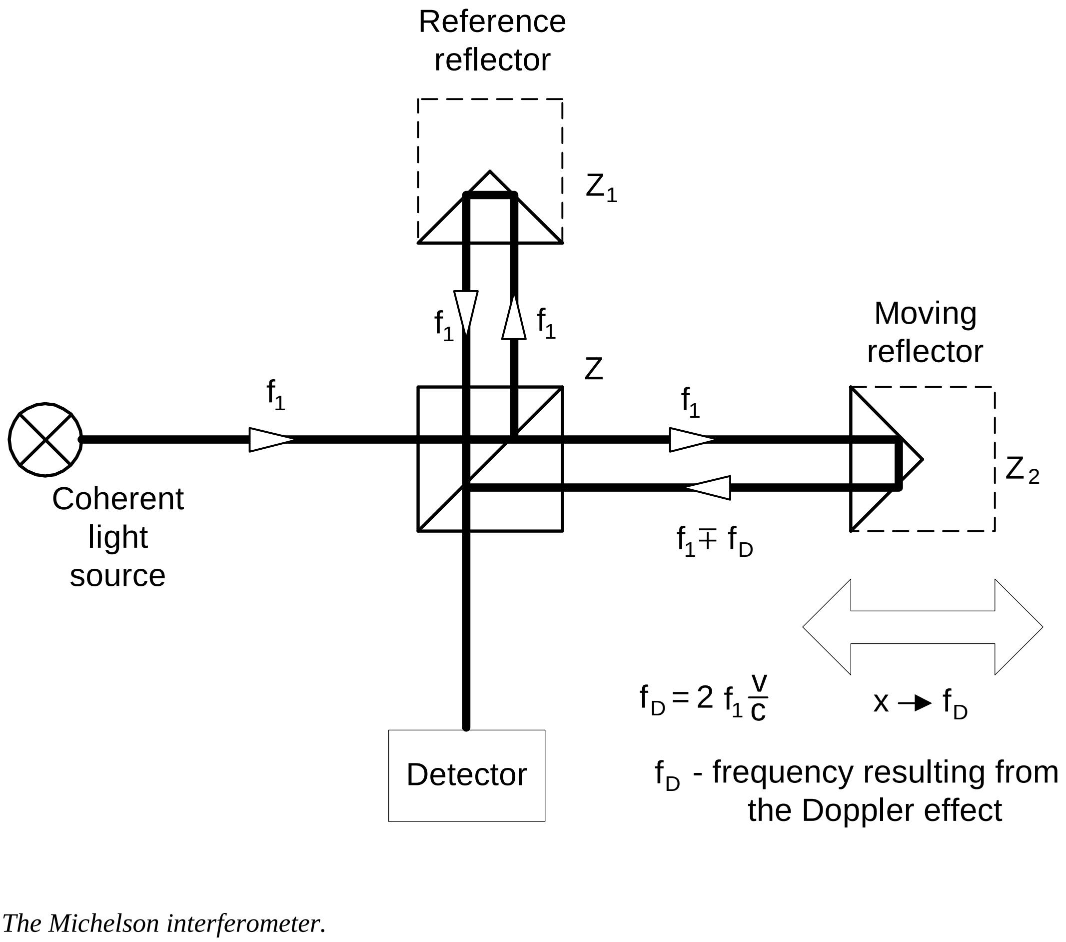

Fig. 1. *The Michelson interferometer.*

Coherent light beam fall on a self-transparent mirror. This mirror splits the light on two beams. The first goes to the reference arm and reflects from the reflector Z_1; the second goes to the measurement arm and reflects form the reflector Z_2. The reflected beams meet again on the detector. Because these beams come from the same, coherent, source, they will interfere.

When the moving reflector is being displaced, the frequency of the reflected beam in the measurement arm changes. The detector counts the frequency difference between reflected beams f_D (see Fig. 1). The measured value of displacement is obtained according to

$$L = f_D * \frac{\lambda}{2} = N * \frac{\lambda}{2} \tag{1}$$

Where: N – number of pulses,
λ - light wavelength.

The construction of real interferometers

The main disadvantage of Michelson interferometer results from the fact that the detector does not determine, whether f_D is negative or positive, thus from the measurements one obtain the displacement of the moving reflector without the sign. Currently there are widely used two methods that allow to get also the direction of the movement. Depending on the number of light frequencies (wavelengths) used in the interferometer, the first is called *homodyne* (one frequency) and the second *heterodyne* (two frequencies) method.

In the homodyne method, shown on Figure 2, as a coherent source of light is used linearly polarized laser. If it is two-mode laser (i.e. it generates two wavelengths) than one mode must be cut off with the use of a properly set polarizer. The polarising splitter splits the light beam from the laser on two beams polarized vertically (90^o) and horizontally (0^o). The former is directed to the measurement arm and the latter to the reference one. The frequency of the beam in the measurement arm changes with the movement of the moving reflector. The polarization of the reflected beams is changed to circular with the use of a $\lambda/4$ waveplate. Setting polarizers to angels 0° and 45° two signals shifted in phase are obtained. The phase shift is $+90^o$ when the measurement arm moves to and -90^o when it moves from the laser.

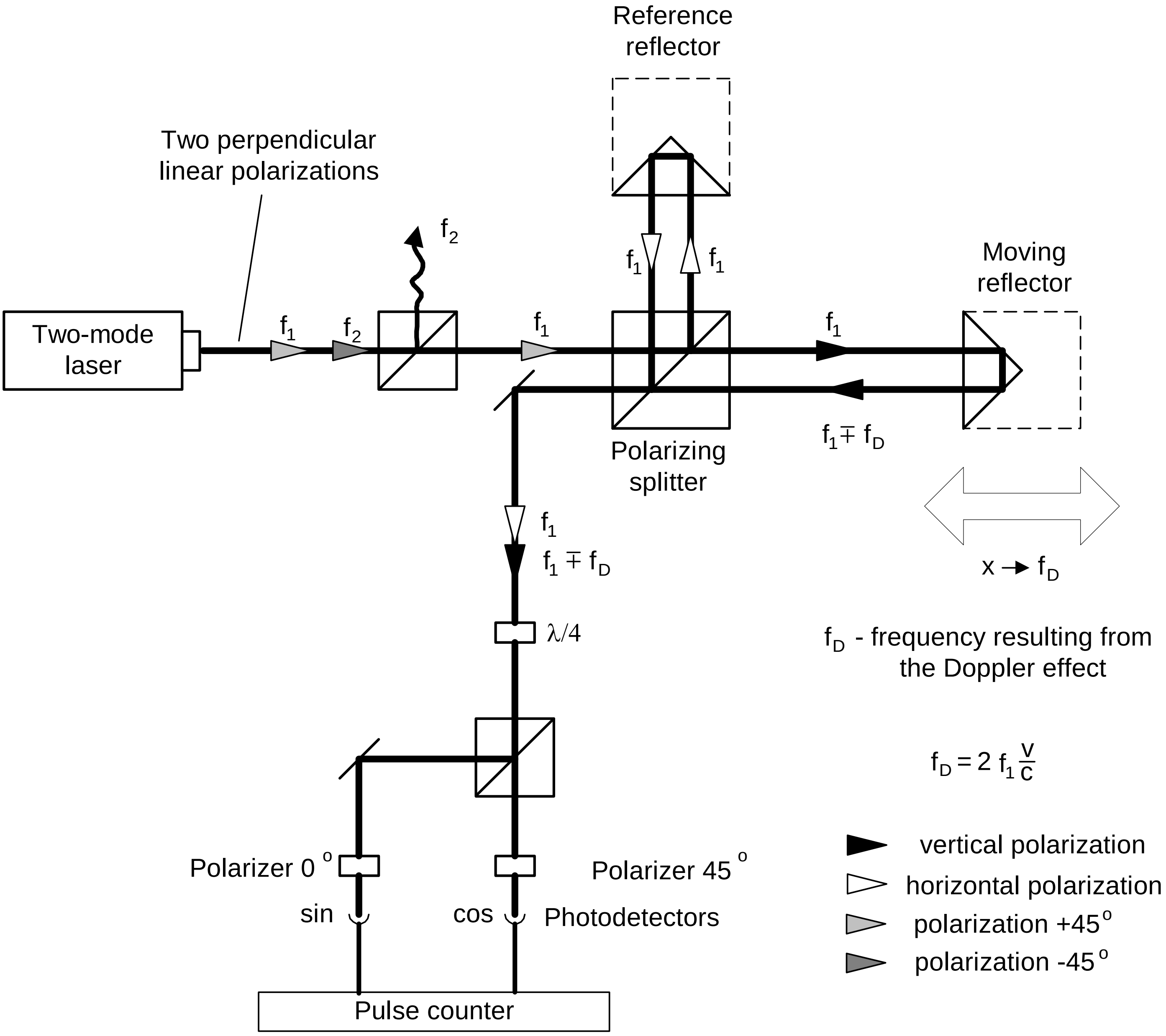

Fig. 2. *The block diagram of an interferometer working according to the homodyne method.*

In the heterodyne method, shown on Figure 3, two laser frequencies are used. Therefore a two-frequency laser is needed, e.g. a Zeeman laser. A two-mode laser is not suitable for heterodyne method interferometer, because the difference between f_1 and f_2 is usually too high for an electronic counter. The output beam of a Zeeman laser consists of two circularly polarized „subbeams", one polarized leftward and the second rightward. A λ/4 waveplate changes circular polarization to linear. The main difference between two described methods is that in the heterodyne one the beam frequency in reference arm differs from the beam frequency in the measuring arm. A detection path is also different – the measurement is done by subtracting differential frequencies of reference and measuring arms.

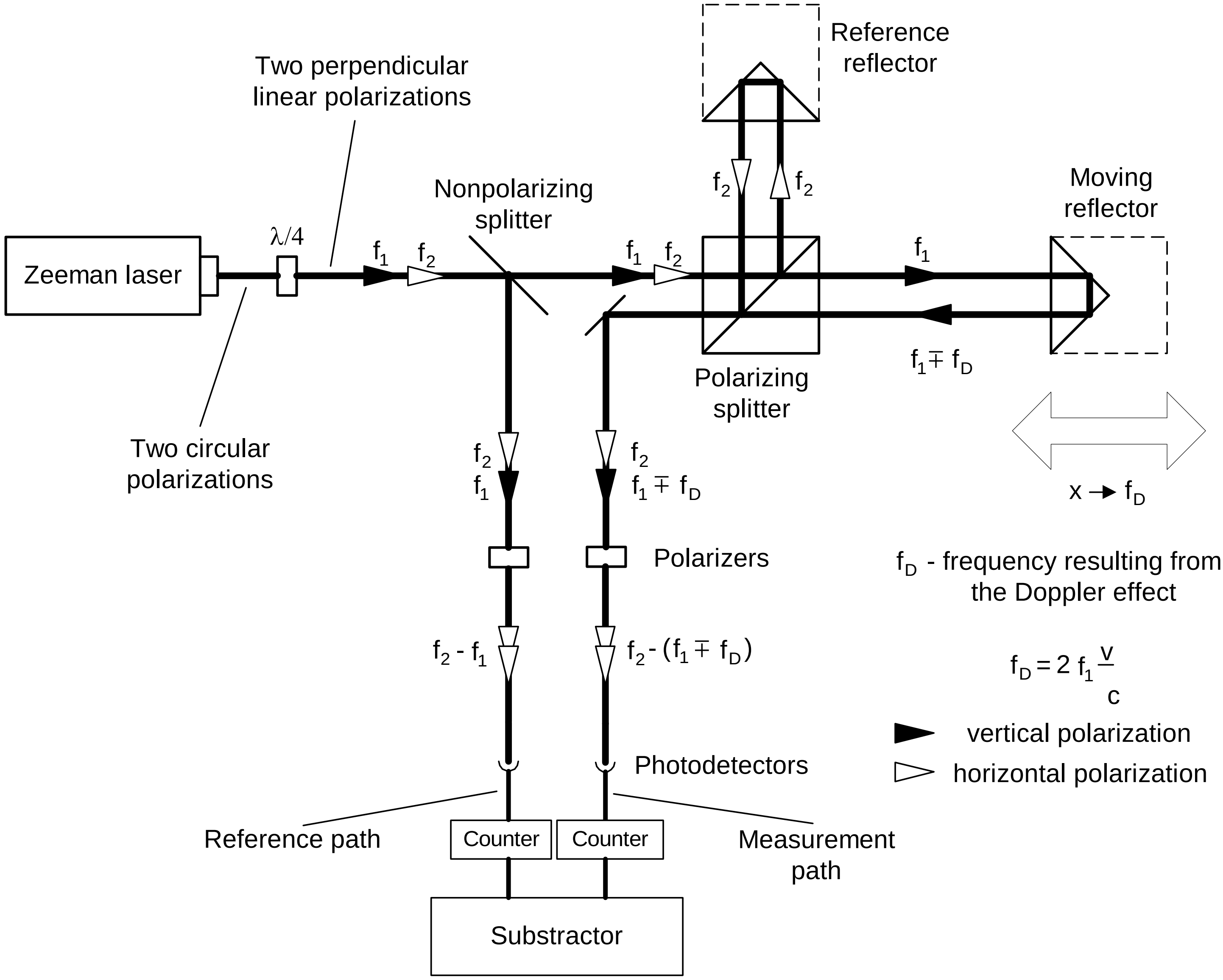

Fig. 3. *The block diagram of an interferometer, working according to the heterodyne method.*

The heterodyne method gives correct results only when f_D does not exceed the difference between the laser frequencies, i.e.: $f_2 – f_1$. In reality, that difference, resulting from the Zeeman effect, is about 1MHz. This limits the maximum available velocity of measuring arm, in one direction, to 0.3 m/s. The next disadvantage of the heterodyne method is, that two frequencies must be used for measurements, while in the homodyne method the second may be used for measuring e.g. a second axis.

The influence of the outside conditions on the measurement accuracy

According to equation (1) an interferometer’s unit of measure in length measurement is laser’s wavelength. From definition

$$\lambda = \frac{v}{f} \tag{2}$$

a wavelength depends on laser’s frequency f and the speed of light v in the measuring path. If the measurement is done in vacuum, than $\nu = c = 3*10^8$ m/s. The speed of light in a medium other than vacuum (e.g. air, water) is lower and is described as

$$v = \frac{c}{n} \tag{3}$$

Where: n – a refraction coefficient.

Normally the refraction coefficient n is a complex variable or even a tensor, but for less accurate calculations it is simplified to a constant. The air coefficient depends mostly on the pressure P, temperature T and humidity H. The dependence $n_{T,P,H}$, for the air was empirically determined by Edien and is described as

$$n_{T,P,H} - 1 = 2{,}8775*10^{-7}*P\frac{1+10^{-6}*P*(0{,}613-0{,}00997*T)}{1+0{,}003661*T}+\Delta n \tag{4}$$

$$\Delta n = -3{,}033*10^{-9}*H*e^{0{,}057627*T} \tag{5}$$

From the above equations one may obtain the refraction coefficient dependences on T, P and H in usual conditions (T=293K, P=1000hPa, H=50%):

$$\frac{\partial n}{\partial T} = -0{,}93*10^{-6}\left[\frac{1}{K}\right]$$

$$\frac{\partial n}{\partial P} = +0{,}27*10^{-6}\left[\frac{1}{hPa}\right]$$

$$\frac{\partial n}{\partial H} = -0{,}96*10^{-8}\left[\frac{1}{\%}\right]$$

It is worth to notice that the most critical parameter is the temperature, because its change influences the coefficient n more than changes in the pressure and much more than changes in the humidity.

2. The accuracy of laser interferometers

Errors caused by the environment

The most impotent source of errors in machine geometry measurements is the temperature (or more exactly, the change of the temperature) of the measured machine. For example, if the machine's base is made of steel, than the base's length increases 11.7μm when its temperature changes 1K. It shows how important it is for very precise measurements to measure the temperature of the controlled part of the machine and to use it in readout corrections. This is not a simple task for a few reasons, but the most important one is that, than when the machine operates, there are temperature gradients on it. That means that more than one temperature sensor is needed and that the more sensors are used the better accuracy can be achieved. Moreover the shape of the measured part of the machine may "absorb" a part of the expansion of the material or the part may be built of materials of different expandability.

As was mentioned in the previous chapter, the temperature influences the accuracy also as it changes the refraction coefficient of the medium the measurements are made in (usually it is air, but may be e.g. water). An Edien equation was presented, showing how the refraction coefficient of the air changes with the change of the air temperature, pressure and humidity. The errors caused by the change of the wavelength are less important than the mentioned above, but they cannot be abandoned. Roughly, a 1ppm error (i.e. 1μm/m) is caused by: the air temperature change of o 1K, the air pressure change of 4hPa and the air humidity change of 30%.

A dead path error

A dead path error is an error associated with the change in environmental parameters during a measurement. This error occurs when some part of the light path (a *dead path*) is not included in the temperature (both air and base), pressure and humidity compensation.

The *dead path* of the light path is a distance between the optical interferometer and the base (or the null point) of the measuring position (L_1 on Figure 4). Let the position of the interferometer and the retroreflector do not change. When there is a change in the air temperature, pressure or humidity, than the wavelength changes on the whole path length ($L_1 + L_2$). The path length changes also when the temperature of the base changes. But the correction system will use the correct wavelength only on the length L2 and will correct only this length. The correction will not be made on a dead path L_1. In this way, the laser system will “move” the base point.

A dead path error is the more severe the greater is the distance between the interferometer and the base point. This error is especially important in laser interferometers where the interferometer is build-up in a common casing with a laser head, because it is than very difficult to reduce a dead path.

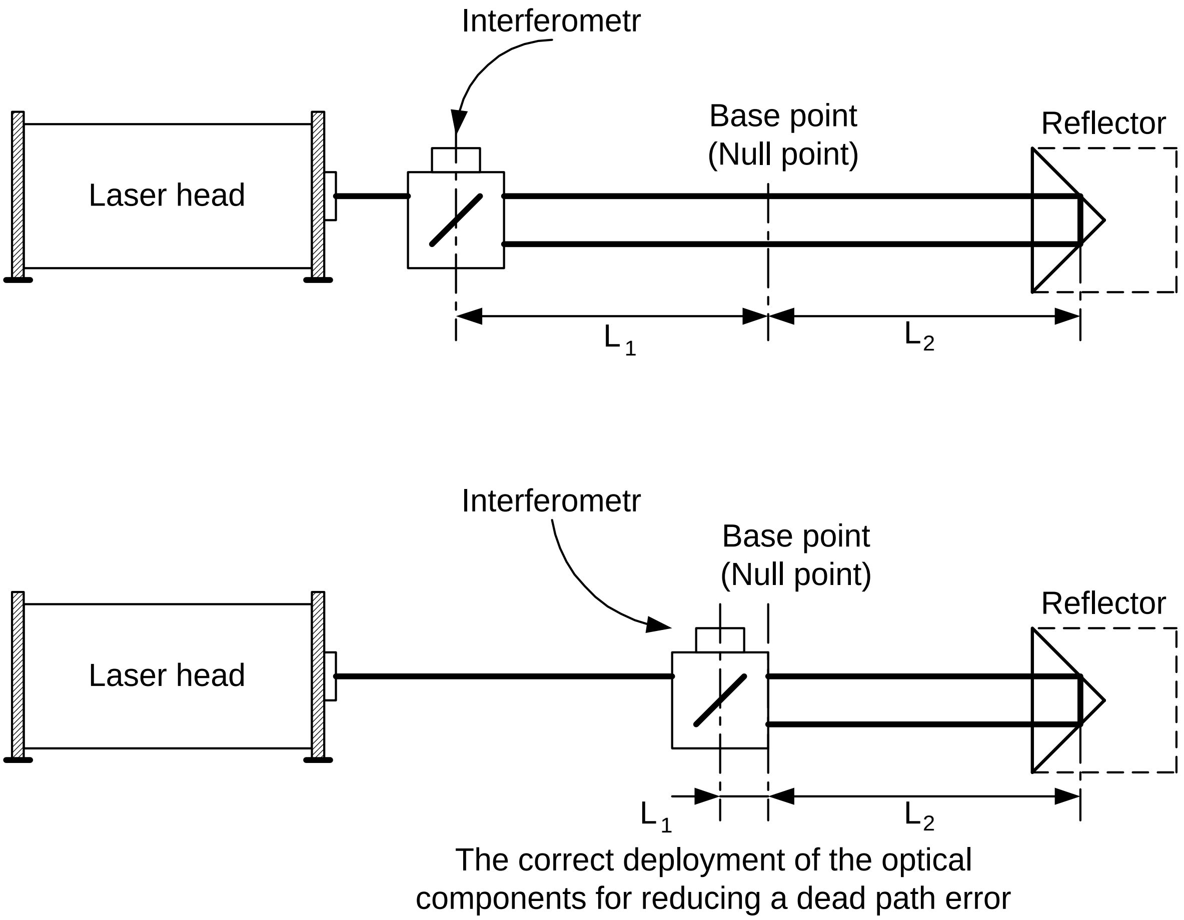

Fig. 4. *An illustration of a dead path error..*

A cosine error

If the laser beam is not parallel to a measured axis of a machine (i.e. the optical path is not properly adjusted) than a difference between the real distance and the measured distance occurs. This error of unadjustment is known as a cosine error, because its magnitude depends on the angle between the laser beam and the axis of the machine (Fig. 5).

If, as a reflector a flat mirror is used, than the beam must be perpendicular to it. If the machine changes its position form point A to point B, than the beam stays perpendicular to the mirror, but moves on its surface. The distance measured by the laser interferometer L_{LMS}, will be smaller, than the real distance L_M, according to

$$L_{LMS} = L_M * \cos\Theta \qquad (6)$$

The above equation is valid also when as a reflector a corn cube is used.

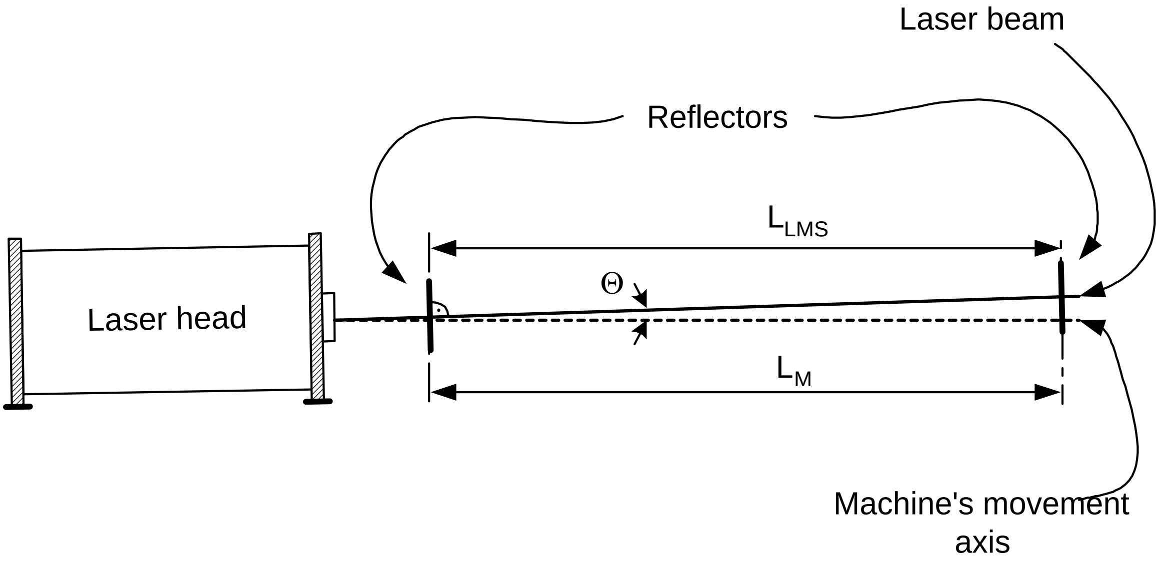

Fig. 5. *The beam unadjustment as a cause of a cosine error.*

The only method of eliminating the cosine error is a proper laser beam adjustment done before a measurement.

An Abbe error

An Abbe error occurs when, during measurements, the measured part does not move perfectly straight and there appear angular movements, which cause sloping of the retroreflector. The sloping of the reflector is the greater the longer is the distance between the axis of the measurement and the axis of movement. This distance is called *An Abbe offset*. Only the movements in the axis of the measurement are important (see Fig. 6). An Abbe error may be avoided only when there are no angular movements of the retroreflector in the axis of the measurements.

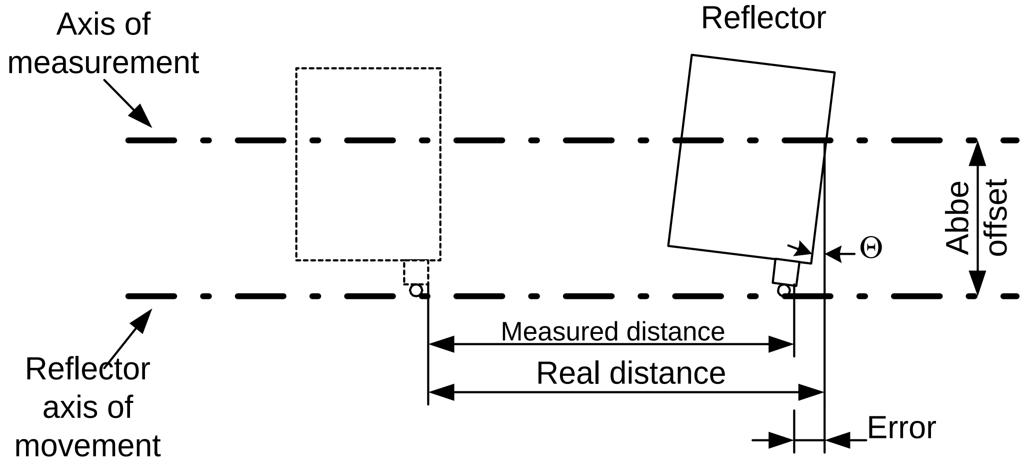

Fig. 6. *An illustration of an Abbe error.*

A laser stability error

As was already mentioned, in laser measurements the laser wavelength instability changes directly the readout from the interferometer, e.g. a relative instability of the laser in the range of 1ppm (10^{-6}), causes an error of 1μm on every 1m of a measured distance. Therefore the laser instability error is important mainly in measurements in vacuum (where a refraction coefficient is constant) and when a low stability laser is user (e.g. a semiconductor laser). The stability of usually used in laser measurement systems, HeNe gas lasers is 0.01 ppm, so the stability error may be neglected.

Other errors

In some conditions, a noticeable error may be caused by the electronic part of the interferometer. As the electronics is used mainly for counting, the errors may be associated either with miscounting (some pulses are not counted) or with miscalculating (the calculations are made with finite precision).

A summary of a laser measurement system errors

In order to show which of the errors influence the accuracy of a laser measurement system the most, an exemplary calculation of errors on a 1m long steel machine is shown on Figures 7 and 8. Different scales of the charts should be taken into account.

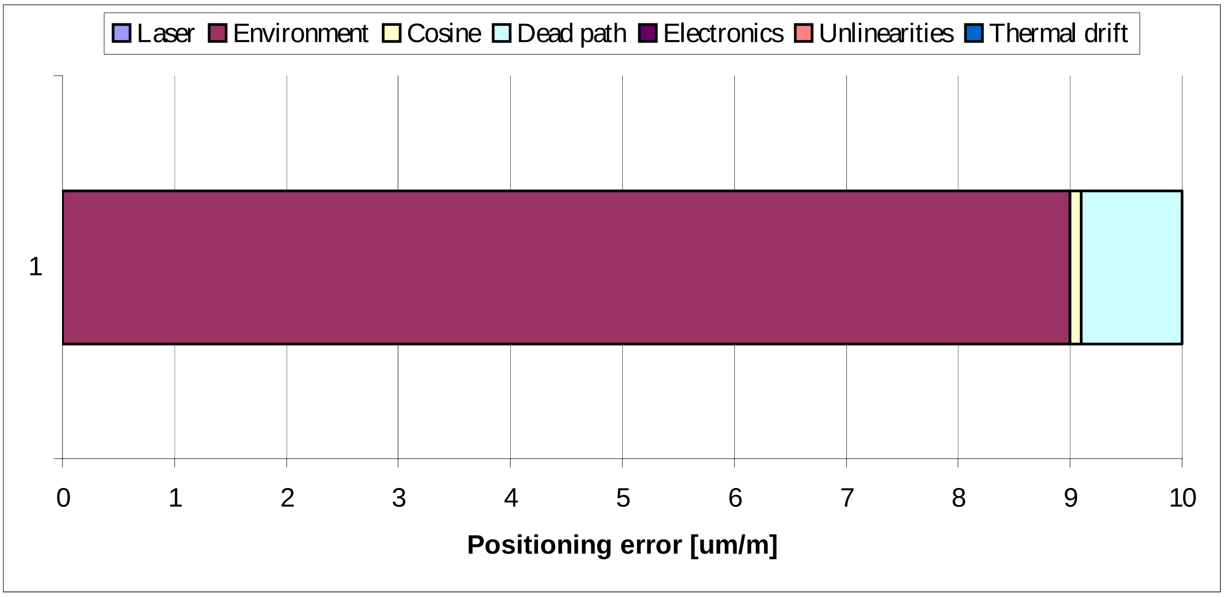

Fig. 7. *A calculation of errors for a laser measurement system* ***without the compensation*** *of the environment.*

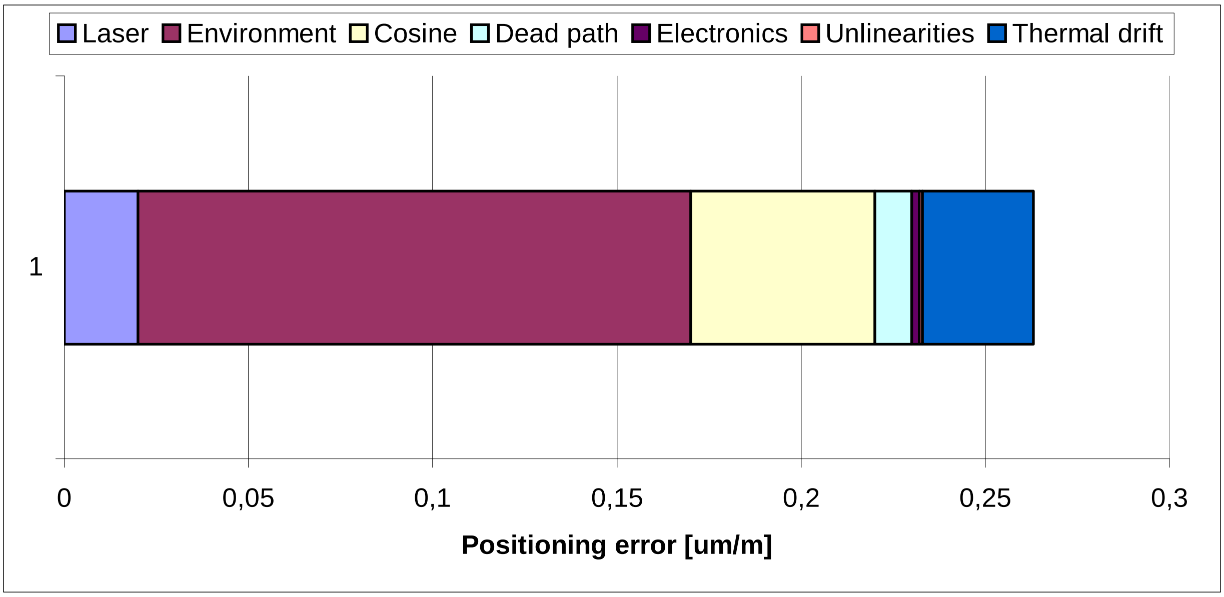

Fig. 7. *A calculation of errors for a laser measurement system* ***with the compensation*** *of the environment.*