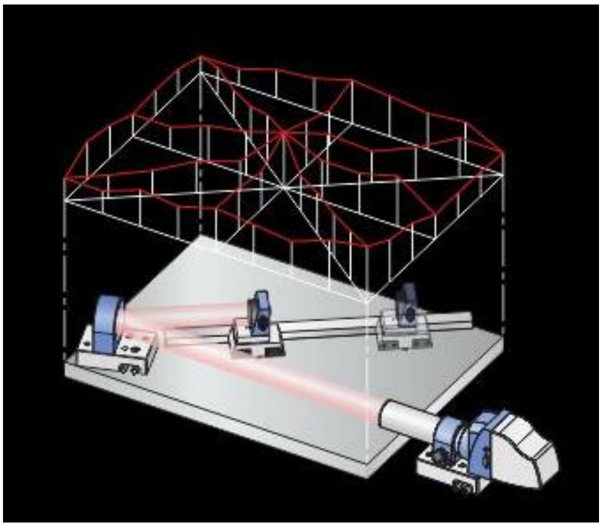
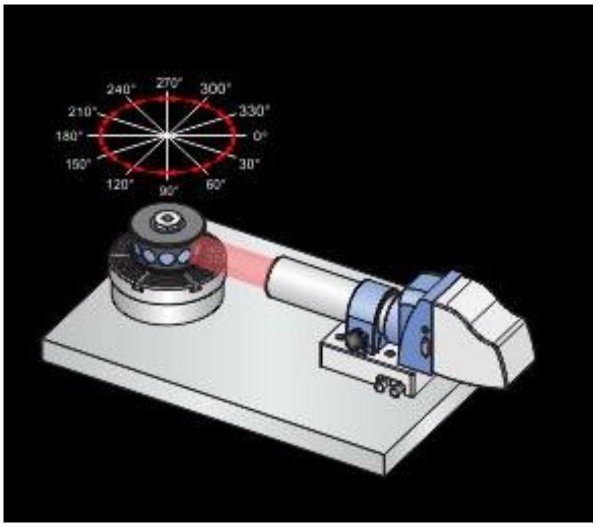
WHITEPAPER





Straightness and flatness measurement with electronic autocollimators

For precise measurement results:
Recognising and avoiding measurement errors.

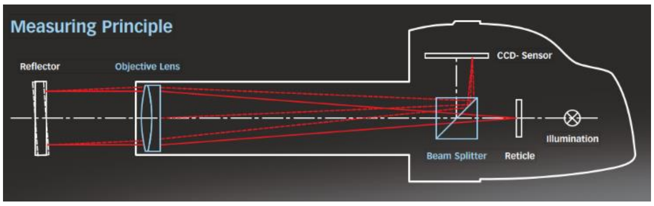
MÖLLER-WEDEL OPTICAL

Instruments You Can Trust

1. Autocollimation: How it works

An **autocollimator** emits a parallel, i.e. "collimated" beam of light, which is reflected back by a mirror.

If the mirror is perfectly aligned, the light beam falls back onto itself. If the angle of the mirror changes, the reflected light beam also changes its angle and the so-called autocollimation image appears shifted on the CCD detector in an electronic autocollimator.



Measuring range and measurement uncertainty

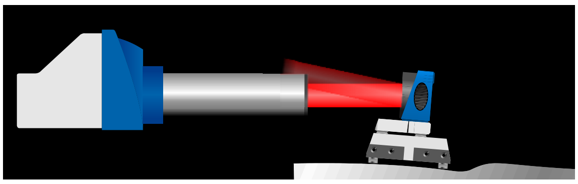
The focal length of an autocollimator determines the measuring range and the measurement uncertainty. The longer the focal length, the smaller the measurement uncertainty, colloquially speaking, the greater the measurement accuracy. This is accompanied by a reduction in the measuring range.

This principle can be compared to a camera shot: A panoramic shot - with a short focal length - shows a large area with few details. On the other hand, if you zoom in on an object for a portrait, you only see a small area of the image - at a long focal length - but with a lot of detail.

With electronic autocollimators, in addition to the focal length, the sensor size, pixel size, pixel sensitivity and the evaluation algorithms used are decisive for the measuring range and measurement uncertainty.

2. Vignetting, Measuring Range and Measuring Distance

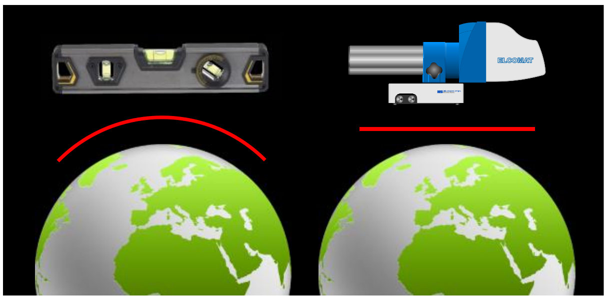
The positioning of the autocollimator relative to the mirror is similar to looking through a keyhole: the field of view of the observer changes with the distance and size of the aperture. If parts of the image are cut off or shadowed by the keyhole, this is called "vignetting" in optics.



Vignetting is the decisive factor that limits the maximum achievable measuring distance: If the angle is too large or the measuring distance too great, the reflected ray bundle aims past the free aperture of the autocollimator.

3. What are the advantages of the autocollimation principle?

- The image position is independent of the distance between the mirror and autocollimator.
- The image position does not change with parallel beam displacement.
- "Large-area measuring beam" - therefore the influence of optical noise is less than with laser systems, for example.
- In contrast to inclination measurement systems, the curvature of the earth has no influence on the measurement (see table on the right) as light travels in a straight line independent of center of gravity.
- Measuring distances of over 20 m are possible.



Measuring Distance	Height deviation due to earth curvature
20 m	7.8 µm
10 m	2.0 µm
5 m	0.5 µm
2.5 m	0.1 µm

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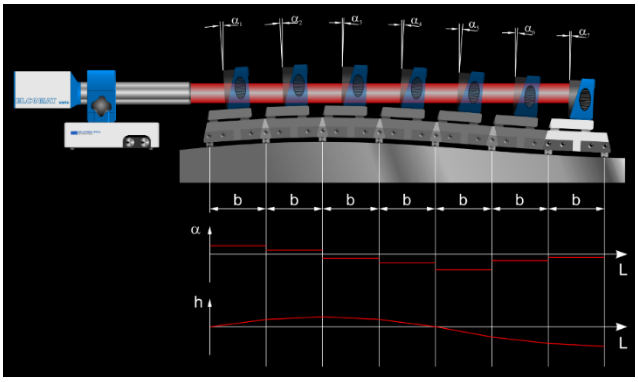
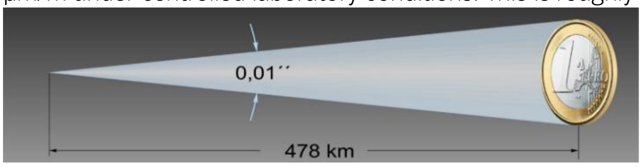
4. How do straightness measurements with autocollimators work?



In straightness measurement, a mirror with a defined base length b is moved step by step over the test piece. The height difference between the reference points is calculated from two individual measurements of the pitch angle, and the height profile of the test piece is reconstructed from the total number of individual measurements. If a mirror base with a lateral stop is used, the yaw angle can be measured simultaneously, and the height and lateral profile of the sample can be determined. With high quality and well aligned autocollimation systems, profile lengths in excess of 20 meters can be measured.

5. What accuracy can be achieved under industrial conditions?

Modern high-precision electronic autocollimators can measure smallest angles down to 0.01 angular seconds ≈ 0.05 µm/m under controlled laboratory conditions. This is roughly equivalent to the height of a euro coin in relation to the distance between Hamburg and Frankfurt (Main). Typical measurement applications in mechanical engineering use autocollimators with a measurement uncertainty of 0.5 µm/m to 5 µm/m.



The accuracy specification (accuracy class) should include the operating conditions defined by the manufacturer and the uncertainty of measurement guaranteed by the manufacturer over the entire measurement range (e.g., ±1.25 µm/m or ±0.25 arcsec). The measurement uncertainty should be stated for a confidence interval of 95% of the measured values (2σ).

When measuring straightness and flatness, in addition to the accuracy class of an autocollimator, the achievable repeatability (multiple measurements without changing the measurement setup) and reproducibility (multiple measurements after setup and dismantling) of the measurement results are critical.

If the error influences described in the following section are taken into account and in the case of a measuring track with a maximum unevenness of less than ±50 µm/m, height deviations from the actual profile can be determined under industrial conditions that are much smaller than the specified measuring accuracy class of the autocollimator used would suggest.

Achievable deviation in [µm] at 100 mm base length under industrial conditions with typical noise using the ELCOMAT® product range as an example

Measuring distance in [m]	ELCOMAT® vario N 140/40	200/40	300/65	500/65T	ELCOMAT® 5000
1.0	2.2	1.7	0.9	0.4	0.3
2.0	3.1	2.4	1.3	0.6	0.4
3.0	3.9	3.0	1.6	0.8	0.5
5.0		3.9	2.1	1.1	0.7
10.0			3.1	1.7	1.2
12.0				2.0	1.4
15.0					1.7
20.0					2.2

The adjacent table shows the maximum measuring deviations at various measuring lengths using a mirror with a base length of 100 mm, without taking into account any interfering environmental conditions, using some autocollimators from the ELCOMAT® product range as an example. Since the position of the maximum height deviation can be different for each measuring path, a direct conversion into a µm/m specification is not possible.

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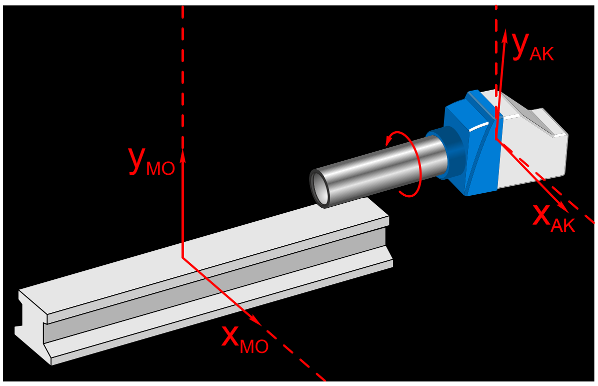
6. What to look out for when preparing and carrying out a Straightness/Flatness Measurement

Aligning the Autocollimator

Errection / Crosstalk:

If the measurement axes of the autocollimator do not match the axes of the target, there is an alignment error. In this case, the measured values of the axes influence each other and the measurement is subject to error.

Since the alignment angle between the coordinate axes is unknown, the measurement error of the x and y axes cannot be clearly separated from the measurement values. Therefore, it is important to check and correct the alignment of the autocollimator to the mirror/guideway coordinate system.



For lower accuracy requirements, this can easily be done using a spirit level or an alignment sensor built into the autocollimator.

If the measurement accuracy requirements are high, the movement or readings of the x-axis should also be observed by rotating the mirror around the y-axis. If the x-axis measurement error is less than 50 µm/m or 10 arcsec over the entire measurement range, the residual alignment error is negligible for applications in mechanical engineering.

For the above reasons, the alignment must be taken into account, especially when measuring flatness (levelling slabs, granite slabs, etc.), as errors can be propagated by the path calculation.

Errection and crosstalk from straightness to flatness

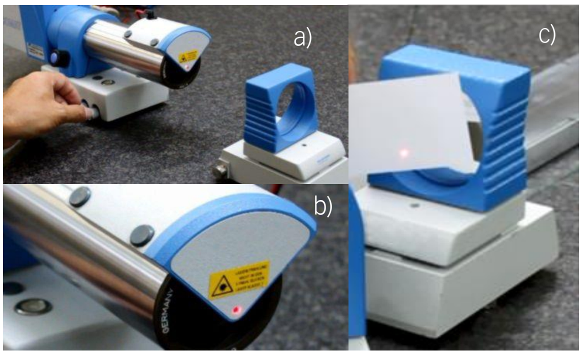
Errection	Crosstalk
5°	8.7%
2.5°	4.3%
1°	1.7%

Alignment:

A laser diode is typically used as an optical alignment aid.
This is aligned in an appropriate mechanical mount. Pre-adjustment and alignment is especially important when measuring long guideways.

There are two parameters to adjust:

1. Beam direction:
   a. The autocollimator must be adjusted using the adjustment knobs on the adjustable holder.
   b. The alignment laser beam must be reflected back onto itself.
2. Beam position:
   c. The laser beam should hit the center of the mirror. If this is not the case, the autocollimator must be moved parallel in height and side (step 1 may have to be repeated).



Alignment should be performed at the farthest measurement position (maximum autocollimator-to-mirror measurement distance). Then check that the laser beam hits the center of the mirror at the foremost measurement position and that a measurement signal is present.

The alignment aid should then be removed and the alignment fine-tuned using the adjustment screws of the autocollimator's adjustable holder, taking into account the angle display in absolute measurement mode. Ideally, the

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start and end values should be in the range of ±100 µm/m for a start and end point-based measurement with a correspondingly precise guideway.

Temperature control of the autocollimator

Early installation or storage of the autocollimator at the measurement station ensures that the measurement system assumes the temperature of the environment. This ensures that the optical and mechanical components do not drift during the measurement. The autocollimator should be switched on well before the start of the measurement (follow the manufacturer's instructions) so that the temperature inside the autocollimator stabilizes at a constant level.

Perpendicularity of the mirror (reflector) as part of the measurement alignment to the measurement path

A double-sided mirror with high plane parallelism (< 5 arcsec, approx. 25 µm/m) is recommended for straightness and flatness measurements. Due to the excellent plane parallelism, the perpendicularity of the mounted mirror to the plane formed by its support points (usually three points) can be checked.

If the perpendicularity of the mirror is not guaranteed and the mirror surface is therefore not perpendicular to the base (e.g. if the base feet are worn) or to the scanning direction, the autocollimator is aligned at an angle to the path. As a result, the measuring beam moves away from the center of the mirror as the mirror is moved along the measurement path, and vignetting limits the measuring range earlier. The requirements vary depending on the length of the measurement path. The following table provides guideline specifications for the perpendicularity to be achieved for a low measurement uncertainty. Perpendicularity can be checked by checking the mirror at both 180°-positions.

Perpendicularity of the measuring mirror to the scanning points / scanning direction of the base The requirement for perpendicularity is higher for parallelism and flatness measurements, so the values should be better by a factor of 2.		
Measuring Distance in [m]	Perpendicularity better than in [µm/m]	in [arcsec]
20	250	50
10	500	100
5	1000	200
2,5	2000	400

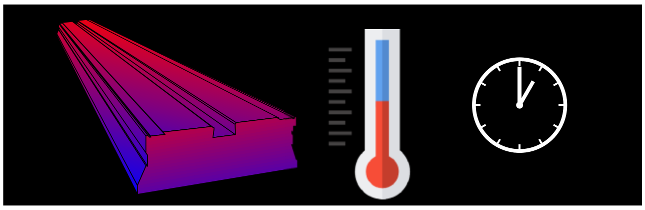
Environmental Influences

Errors caused by sensor movements:

If the autocollimator is unintentionally moved even slightly during a measurement, the measurement uncertainty will increase and the reference of measurement is lost. Therefore, contact with the cables or the autocollimator should be avoided during the measurement. When the autocollimator is mounted on a tripod, measurements should not be performed if cranes, pallet trucks, forklifts, etc. are moving in the vicinity of the measurement station. Machines that can transmit vibrations to the floor during the measurement should also be turned off if possible. Instead of using a tripod, it is recommended to mount the autocollimator directly on the measurement object using a mounting bracket with a stop bracket to minimize the influence of different vibrations on the measurement object and the autocollimator.

Minimize thermal gradients

Machining, transport, finishing (grinding, scraping, polishing), storage, or cleaning with liquids can cause the workpiece to have an inhomogeneous temperature distribution.



This leads to different local expansions and results in bending of the workpiece. Such effects occur especially when massive and long guideways are located in non-air-conditioned rooms and the temperature fluctuates greatly (day/night). This can lead to different measurement results during one or more measurements of the workpiece. This is not due to the measuring device, but to the local expansion of the workpiece (heating from the ends to the center, from the outside to the inside). It is therefore important to allow a few hours to elapse between machining and cleaning the workpiece and the subsequent accurate measurement, or to average several measurements taken at different times.

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Optical flicker/noise (air turbulence/flow):

Optical noise is caused by temperature differences that are generally present in the air. The refractive index of the air changes locally due to temperature differences. This can increase measurement uncertainty even for short distances. To minimize measurement uncertainty, all doors, windows, or other sources of drafts should be closed during the measurement. The temperature in the measurement room should also be approximately stable during the measurement. Avoid external heat sources in the vicinity of the test object, as these can heat the air and affect the measurement locally. Good alignment of the autocollimator to the mirror ensures that the full measurement beam is utilized, refractive index fluctuations are averaged over the measurement beam diameter used, and the vignetting effect is reduced as much as possible. This minimizes the influence of optical noise on the measurement. To minimize optical noise, the air in the measurement chamber between the autocollimator and the mirror can also be swirled so that the noise is virtually homogeneous in time and space.

Dust / Dirt

Dust and dirt on the track can also affect the measurement result. The measurement track should be cleaned prior to measurement. If wet cleaning is necessary, the measurement should be delayed until the measurement track is completely dry.

Extremely bright light sources / arc discharges (welding):

Electronic autocollimators are generally designed for industrial conditions and will operate properly in bright environments. However, direct exposure to sunlight or other bright light sources should be avoided, as this may overexpose the sensor and prevent the actual measurement signal from being analyzed.

Further Information:

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