**MÖLLER-WEDEL OPTICAL**
INTERNATIONAL
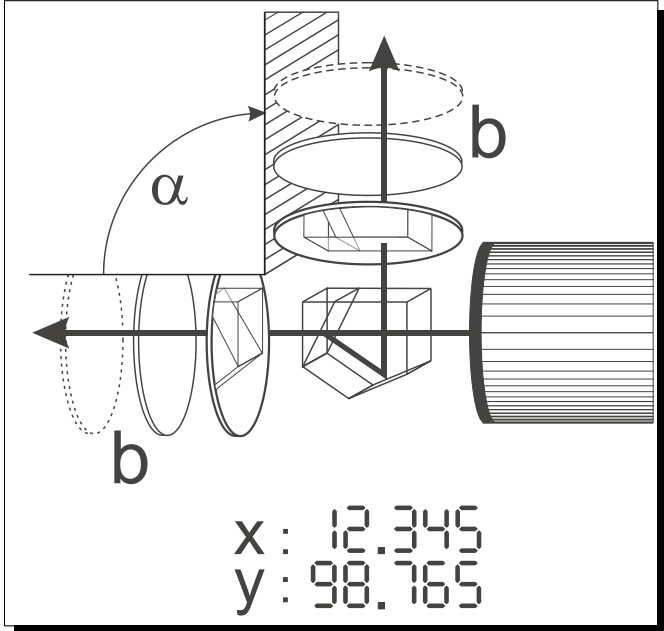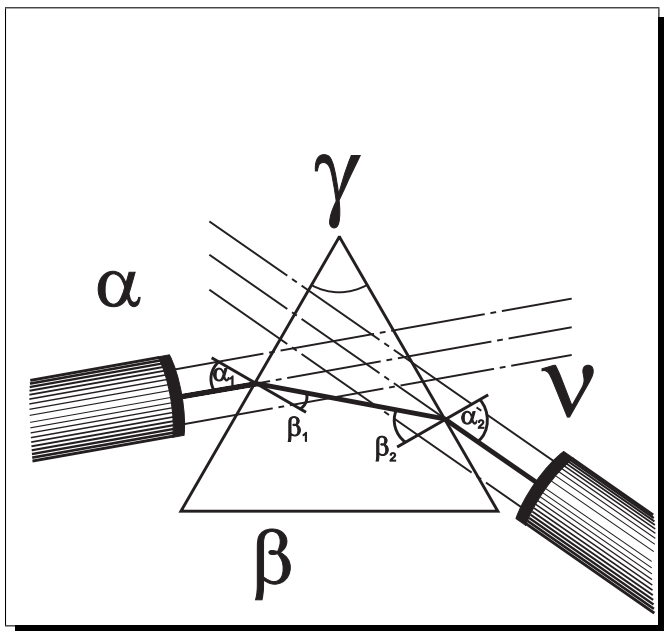
**Examples for Applications
of collimators, telescopes,
visual and electronic
autocollimators**

# Contents

# 1 Introduction

Autocollimators are high-precision instruments for measurement of angular settings. Principal field of application are calibration and measurement tasks in optical and mechanical engineering.

In the following a selection of examples from the wealth of applications is presented. The applications are roughly divided in two areas - optical and mechanical engineering. With this collection of examples we would like to give you an idea for the solution of your specific measurement problem.

The description of the measurement tasks are made for visual autocollimators. Nevertheless in most cases a computer aided evaluation by attaching a CCD-camera or with an electronic autocollimator ELCOMAT is possible, too. This kind of evaluation offers the advantage of enhanced accuracy with even shorter measurement time.

## 1.1 List of symbols

| | | |
|---|---|---|
| $f'$ | : | focal length |
| $n$ | : | refractive index of a medium |
| $x', y'$ | : | coordinates in the image plane |
| $\Delta x', \Delta y'$ | : | distance in the image plane |
| $\alpha, \beta$ | : | wedge angle, angle between two surfaces, tilting angle |
| $\delta$ | : | deviation angle, angle between two beams |
| $\sigma$ | : | angle between a beam and an axis |
| $\varepsilon$ | : | angle of incidence |
| $\theta_x, \theta_y$ | : | angle reading of telescopes or autocollimators |
| $\Delta\theta_x, \Delta\theta_y$ | : | angular difference reading of telescopes or autocollimators |

## 1.2 Used Units

Unless otherwise noted in the equations given in this document, distances have to be inserted as millimeters and angles in seconds of the arc. The factors [·206265 arcsec] and [·3438.8 arcmin] included in the formulas convert the values to seconds of the arc and minutes of the arc, respectively.

## 1.3   How autocollimation works

The autocollimator projects the image of a reticle pattern in collimated beam path to infinity. A mirror in the optical path reflects the beam back into the autocollimator. The reflected beam generates the autocollimation image.

When the mirror is perpendicular to the optical axis, the beam is reflected into itself. When the mirror is tilted with an angle $\alpha$, the incident angle of the beam on the mirror is $\varepsilon = \alpha$. After reflection the beam enters the objective obliquely with an angle of $\sigma = 2\varepsilon$. Depending on the angle of the ray bundle to the optical axis, the autocollimation image is shifted from the centre.

The shift of the autocollimation image from the centre in both $x'$ and $y'$ directions is a measure for the tilt of the mirror. Autocollimators that are calibrated to tilting angle show half the angle of the reflected beam to the optical axis on their reading and therefore directly the tilting angle $\alpha$ of the mirror. Under the assumption that the tilt occurs only in $y'$-direction, the angular reading $\Delta\theta_y$ on the reticle is equal to $\sigma/2$:

$$\alpha = \frac{\sigma}{2} = \Delta\theta_y.$$

The tilting angle can also be calculated directly from the shift of the reticle image $\Delta y'$:

$$\alpha = \frac{\sigma}{2} = \frac{\Delta y'}{2f'}.$$

In the general case of a tilt in both $x'$ and $y'$ directions the tilting angle can be calculated by using the theorem of Pythagoras:

$$\alpha = \frac{\sigma}{2} = \sqrt{\Delta\theta_x^2 + \Delta\theta_y^2} = \frac{\sqrt{\Delta x'^2 + \Delta y'^2}}{2f'}[\cdot 206265 \, \text{arcsec}].$$

Where:
$\alpha$            : tilting angle of the mirror
$\sigma$            : angle of the beam with respect to the optical axis of the autocollimator
$\Delta x'$, $\Delta y'$ : shift of the reticle image
$f'$            : focal length of the autocollimator
$\Delta\theta_x$, $\Delta\theta_y$: angular reading of angle calibrated autocollimators

The shift of the reticle image can be measured e.g. with a reticle with millimeter scaling or an eyepiece with double micrometer.
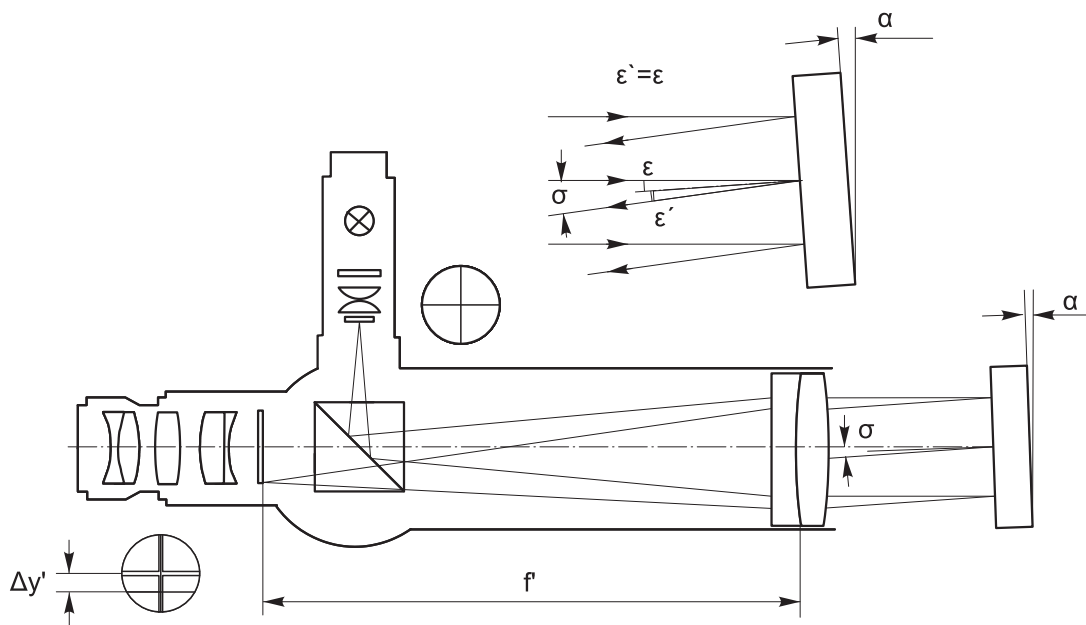
# 2 Applications in Optical Industry

## 2.1 Testing of Parallelism With Collimator And Autocollimator

**Set-up:**

- Collimator with reticle S115 (single crossline)
- Autocollimator with reticle S127 (double crossline) and double micrometer
- Index table or Goniometer
- Adjustable holders

**Measurement**

At first the angle $\varepsilon$ between the optical axis of the autocollimator and the surface normal is determined. Two images of the collimator reticle can be observed with the autocollimator: one from the front and one from the rear surface. If both images coincide, then the front and rear surface are parallel to each other. If the images are separated by a distance $\Delta y'$ from each other, then the surfaces are not parallel. The distance $\Delta y'$ is measured with the aid of the double micrometer:

$$\alpha = \frac{\Delta y' \cos \varepsilon}{2f' \sqrt{n^2 - \sin^2 \varepsilon}} [\cdot 206265 \, \text{arcsec}]$$
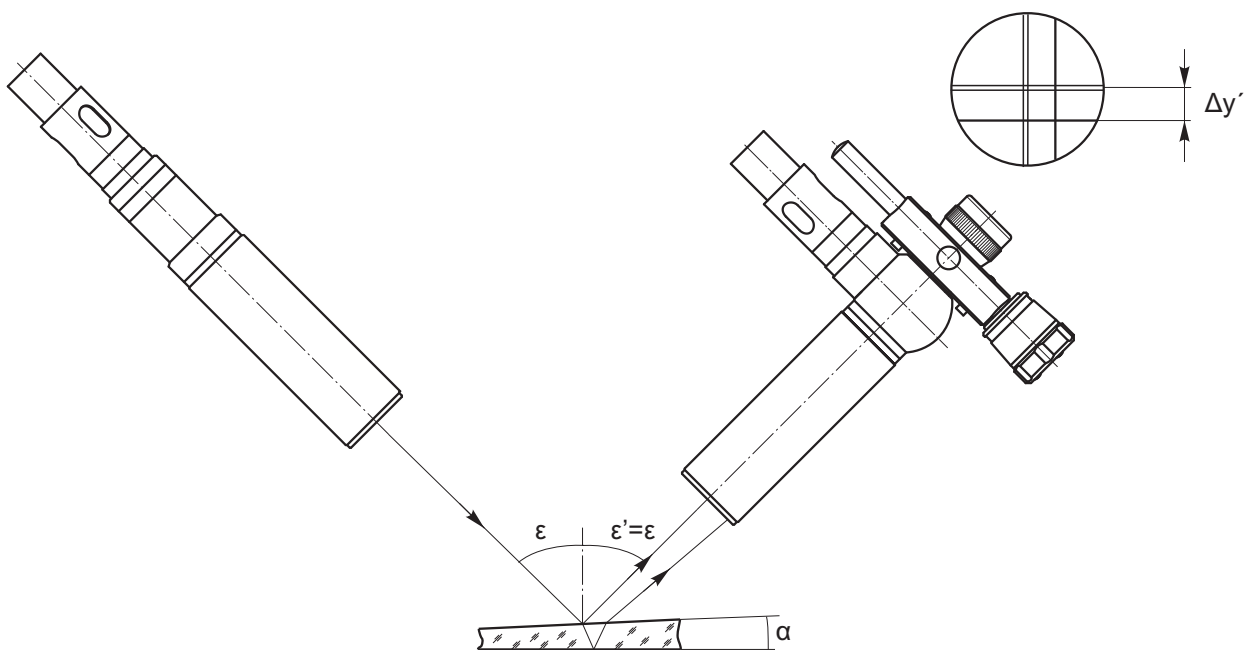
Where:
- $\alpha$ : wedge angle
- $\Delta y'$ : distance between the collimation images
- $n$ : refractive index of the specimen
- $f'$ : focal length of the telescope
- $\varepsilon$ : angle of incidence on the specimen — angle between optical axis of the autocollimator (or collimator) and surface normal of the specimen

## 2.2   Testing of Opaque Wedges and Plane Parallel Plates

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator), ELCOMAT 3000 or ELCOMAT vario

or

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401…S431 (reticle with graduation)

and

- Supporting table with plane parallel (optionally mirror coated) surface
- Vertical stand
- Plane-parallel mirror

With the ELCOMAT direct, ELCOMAT 3000 or ELCOMAT vario the measurement is more precise and the measurement time is reduced.

**Measurement**

Put the plane-parallel plate on the supporting table. Adjust the supporting table to the autocollimator, such that the autocollimation image is centered in the eyepiece reticle (a). Remove the mirror and put on the test specimen. Put the mirror on top of the test piece.

Rotate the specimen in such a manner that the read out of the $x$-direction is zero (b). Read out the deviation $\Delta y'$. The deviation from parallelism $\alpha$ is determined for $\alpha < 5°$ by:

$$\alpha = \Delta\theta_y = \frac{\sigma}{2}.$$

or by

$$\alpha = \frac{\Delta y'}{2f'}[\cdot 206265 \text{ arcsec}] = \frac{\sigma}{2}.$$

Where:
$\alpha$  :  deviation of parallelism
$\sigma$  :  angle to autocollimator axis
$\Delta y'$ :  distance in the autocollimation image plane
$f'$  :  focal length of the autocollimator
$\Delta\theta_y$:  angular reading of autocollimators with angular graduation



a)                                         b)
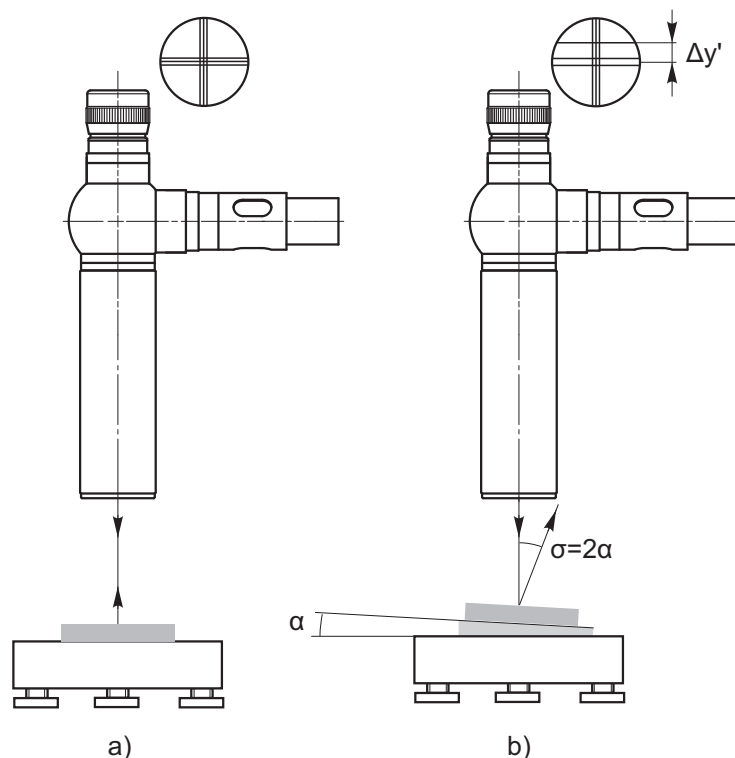
## 2.3   Testing of Transparent Wedges — Evaluation by Double Cross

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator)

or

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401...S431 (reticle with graduation)

With ELCOMAT direct the measurement is more precise and the measurement time is reduced.

**Measurement**

Adjust specimen to autocollimator in such a way, that one image of the collimator reticle is centered in the eyepiece reticle.

Rotate the specimen so that the angular deviation of the other reticle image is zero in *x*-direction. After reading the $\Delta y'$ respective $\Delta\theta_y$, the angular deviation $\alpha$ can be calculated by ($\alpha < 5°$):

$$\alpha = \frac{\Delta\theta_y}{n} = \frac{\sigma}{2n}.$$

or

$$\alpha = \frac{\Delta y'}{2nf'}[\cdot 206265 \text{ arcsec}] = \frac{\sigma}{2n}.$$

Where:
- $\alpha$   :   Wedge angle
- $n$   :   Refractive index of the specimen
- $\sigma$   :   Angle to autocollimator axis
- $\Delta y'$ :   Distances in the autocollimation image plane
- $f'$   :   Focal length of the autocollimator
- $\Delta\theta_y$:   Angular reading of autocollimators with angular graduation
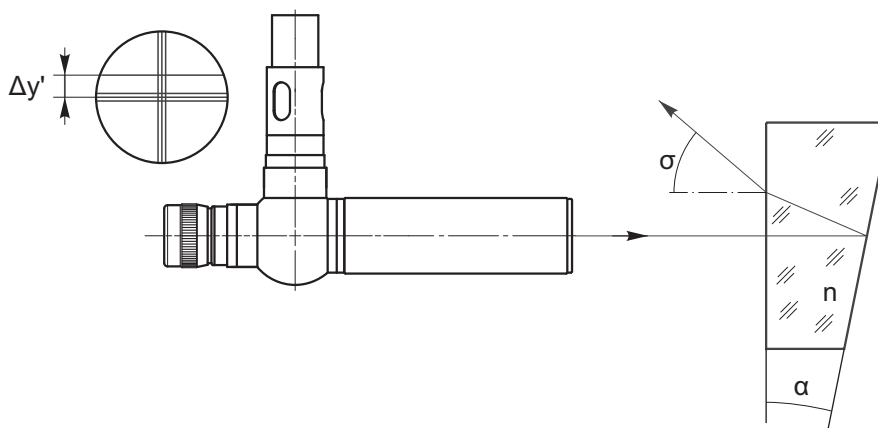
## 2.4 Testing of Transparent Wedges — Evaluation by Reference Mirror

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator), ELCOMAT 3000 or ELCOMAT vario

or

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401…S431 (reticle with graduation)

and

- flat mirror

With the ELCOMAT direct, ELCOMAT 3000 or ELCOMAT vario the measurement is more precise and the measurement time is reduced.

**Measurement**

Adjust the reference mirror to the autocollimator in such a way, that the image of the collimator reticle (single cross) is in the centre of the eyepiece reticle.

Insert the specimen and adjust the angle to the optical axis of the autocollimator so, that it is smaller than approx. $\pm 5°$. Rotate the specimen such that the angular deviation is zero in x-direction. After reading the $\Delta y'$ respective $\Delta\theta_y$, the angular deviation $\alpha$ can be calculated by ($\alpha < 5°$):

$$\alpha = \frac{\Delta\theta_y}{n-1} = \frac{\sigma}{2(n-1)}$$

or

$$\alpha = \frac{\Delta y'}{2(n-1)f'}[\cdot 206265 \text{ arcsec}] = \frac{\sigma}{2(n-1)}.$$

Where:
$\alpha$ : deviation of parallelism of the specimen
$n$ : refractive index of the specimen
$\sigma$ : angle to autocollimator axis
$\Delta y'$ : distances in the autocollimation image plane
$f'$ : focal length of the autocollimator
$\Delta\theta_y$ : angular reading of autocollimators with angular graduation
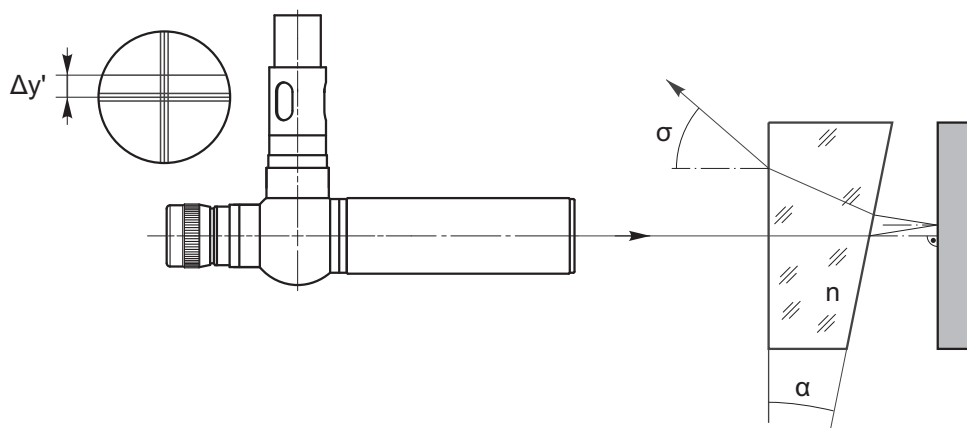
## 2.5   Testing of Transparent Wedges — Simultaneous Determination of Wedge Angle and Refractive Index

For the simultaneous measurement of wedge angle and refractive index of the substrate the evaluation by double cross (2.3) and against reference mirror (2.4) have to be carried out both as described.

The wedge angle and the refractive index can be calculated from the angular readings of the autocollimator according to the following equations:

$$\alpha = \Delta\theta_{y2} - \Delta\theta_{y1}$$
$$n = \frac{\Delta\theta_{y2}}{\Delta\theta_{y2} - \Delta\theta_{y1}} = \frac{\Delta\theta_{y2}}{\alpha}$$

Where:
  $\alpha$      :   deviation of parallelism of the specimen
  $n$      :   refractive index of the specimen
  $\Delta\theta_{y1}$:   angular reading of autocollimators for measurement against reference mirror (2.4)
  $\Delta\theta_{y2}$:   angular reading of autocollimators for measurement by double cross (2.3)

## 2.6 Testing of Transparent Wedges — Evaluation by Angular Deviation

**Set-up**

- Telescope with double-micrometer, eyepiece reticle S127 (double crossline)

or

- Telescope with eyepiece reticle S304 (reticle with millimeter graduation) or S401...431 (reticle with angle graduation, values have to be multiplied by two).

and

- Collimator with reticle S115 (Single crossline).

**Measurement**

a) Adjust the telescope to the collimator in such a way, that the image of the collimator reticle (single cross) is in the centre of the telescope reticle.

b) Insert the specimen and adjust the angle to the optical axis of the telescope so, that it is smaller than approx. 5°. Rotate the specimen so that the angular deviation of the other reticle image is zero in $x'$-direction.

After reading the $\Delta y'$ respective $\Delta\theta_y$, the angular deviation $\alpha$ can be calculated by (for $\alpha < 5°$):

$$\alpha = \frac{\Delta\theta_y}{n-1} = \frac{\sigma}{n-1}$$

or

$$\alpha = \frac{\Delta y'}{(n-1)f'}[\cdot 206265 \text{ arcsec}] = \frac{\sigma}{n-1}.$$

Where:
$\alpha$ : Deviation of parallelism of the specimen
$n$ : refractive index of the specimen
$\sigma$ : angle to collimator axis
$\Delta y'$ : distances in the telescope image plane
$f'$ : focal length of the telescope
$\Delta\theta_y$ : angular reading of telescopes with angular graduation
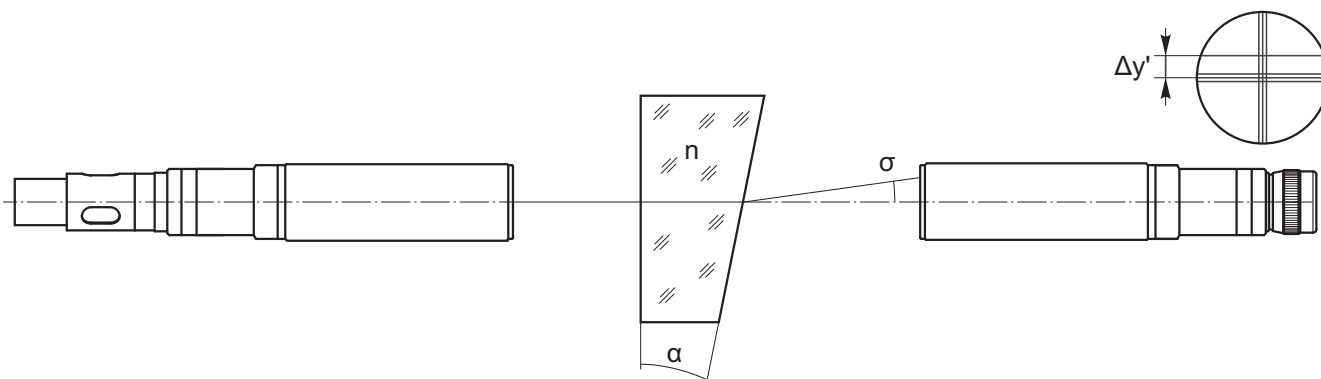
## 2.7 Testing of the 90° angle of a 90°-Glass Prism in double pass

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator)

or

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401…S431 (reticle with graduation)

and

- Vertical stand (e.g. MELOS-measuring stand).

With ELCOMAT direct the measurement is more precise and the measurement time is reduced.

**Measurement**

Obstruct one half of the hypotenuse surface. Adjust the autocollimator to the base of the 90°-prism as shown in the sketch below. The autocollimation image from the base surface should be located in the centre of the measuring range. If the 90°-angle deviates from squareness ($\Delta\alpha$), a second autocollimation image appears, which is produced by the internal reflection. The horizontal displacement $\Delta x'$ respectively $\Delta\theta_x$ is connected with the deviation $\Delta\alpha$ of the 90° angle of the prism. The error can be calculated according to (for $\Delta\alpha < 5°$):

$$\Delta\alpha = \frac{\Delta\sigma_x}{4n} = \frac{\Delta x'}{4nf'}[\cdot 206265 \text{ arcsec}] \qquad \text{or} \qquad \Delta\alpha = \frac{\Delta\theta_x}{2n}$$

Where:

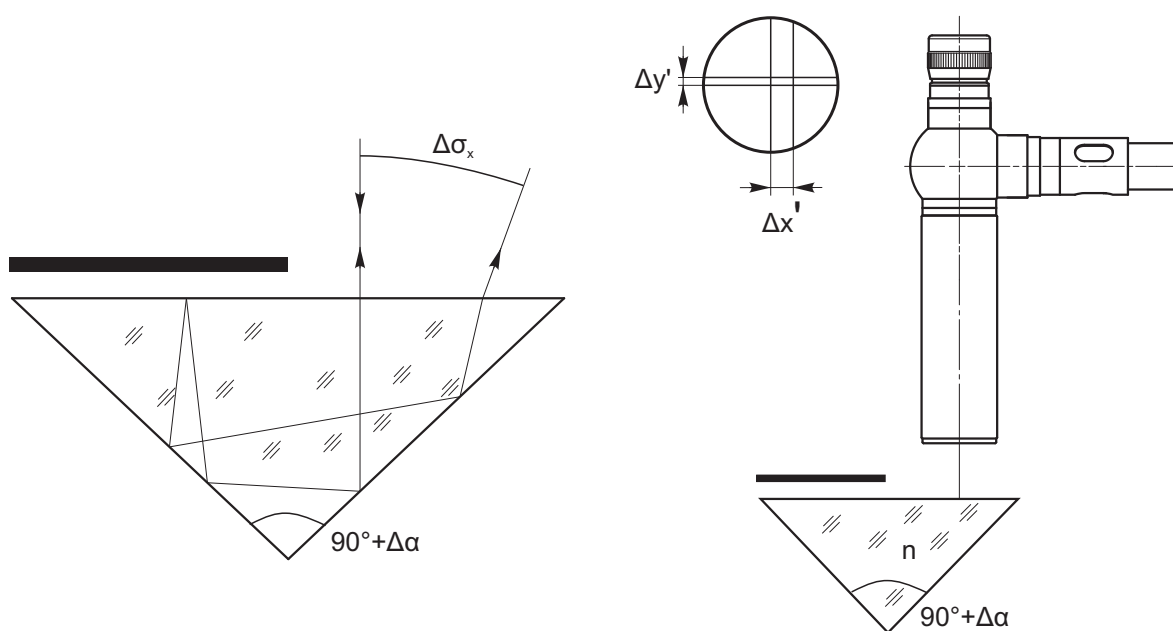| | | |
|---|---|---|
| $\Delta\alpha$ | : | deviation of 90°-angle |
| $\Delta\sigma_x$ | : | $x$-angle difference |
| $\Delta\theta_x, \Delta\theta_y$ | : | difference of angular readings of autocollimators with angular graduation |
| $\Delta x', \Delta y'$ | : | distances in the autocollimation image plane |
| $n$ | : | refractive index of the specimen |
| $f'$ | : | focal length of the autocollimator |

## 2.8 Testing 45° Angles of 90°-Glass Prism

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator)

or

- Autocollimator with double micrometer, collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (single crossline) and eyepiece reticle S411…S431(angle graduation)

and

- vertical stand (for example MELOS-Measuring stand).

With ELCOMAT direct the measurement is more precise and the measurement time is reduced.

**Measurement**

Adjust the autocollimator to one of the short faces. Two autocollimation images appear observed, which coincide only, when the 45°-angle is exact. If this is not the case, the autocollimation images are separated by a distance $\Delta x'$. This distance can be measured e.g. with a double micrometer or read from a reticle with graduation. On condition, that the 90° angle is known the error of the 45° angle can be determined by (for $\Delta\alpha, \Delta\beta < 5°$):

$$\Delta\beta = \frac{\Delta x'}{4nf'}[\cdot 206265\,\text{arcsec}] - \frac{\Delta\alpha}{2} \qquad \text{or} \qquad \Delta\beta = \frac{\Delta\theta_x}{2n} - \frac{\Delta\alpha}{2}$$
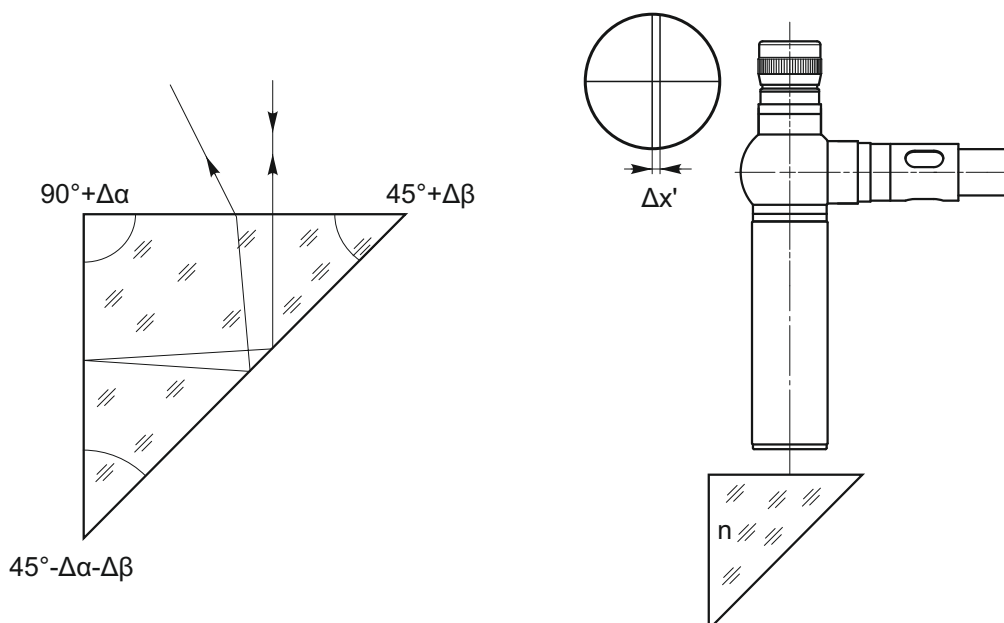
Where:
$\Delta\alpha$ : error of the 90°-angle
$\Delta\beta$ : error of the 45°-angle
$\Delta\theta_x$: angular reading of autocollimators with angular graduation
$\Delta x'$ : distance in the autocollimation image plane
$n$ : refractive index of the specimen
$f'$ : focal length of the autocollimator

## 2.9    Testing of the 90° angle of a 90°-Glass Prism in single pass

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator)

or

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S 115 (crossline) and eyepiece reticle S304 or S401…S431 (reticle with graduation)

and

- Vertical stand (e.g. MELOS-measuring stand).

With the ELCOMAT direct the measurement is more precise and the measurement time is reduced.

**Measurement**

Adjust the autocollimator to the hypotenuse surface of the 90°-prism. Three reticle images appear in the eyepiece. Two bright ones from the internal reflection inside the prism and one dim image from the hypotenuse surface. When rotating the prism around the roof edge, the first two images remain in place.

If the 90°-angle deviates from from squareness ($\Delta\alpha$), the images from ther internal reflection are separated by a distance $\Delta x'$ respectively $\Delta\theta_x$. When additionally the images are separated in height, the prism has also a pyramid error ($\Delta\beta$). These error can be calculated according to (for $\Delta\alpha, \Delta\beta < 5°$):

$$\Delta\alpha = \left|\frac{\Delta\sigma_x}{4n}\right| = \left|\frac{\Delta x'}{4nf'}\right| [\cdot 206265 \text{ arcsec}] \qquad \text{or} \qquad \Delta\alpha = \left|\frac{\Delta\theta_x}{2n}\right|$$

$$\Delta\beta = \left|\frac{\Delta\sigma_y}{4n}\right| = \left|\frac{\Delta y'}{4f'}\right| [\cdot 206265 \text{ arcsec}] \qquad \text{or} \qquad \Delta\beta = \left|\frac{\Delta\theta_y}{2n}\right|$$

Where:
- $\Delta\alpha$ : deviation of 90°-angle
- $\Delta\beta$ : pyramidal error of the prism
- $\Delta\sigma_x$ : x-angle difference
- $\Delta\theta_x, \Delta\theta_y$: difference of angular readings of autocollimators with angular graduation
- $\Delta x', \Delta y'$ : distances in the autocollimation image plane
- $n$ : refractive index of the specimen
- $f'$ : focal length of the autocollimator

In contrast to method described under 2.7 this method does not allow the determination of the sign of the error $\Delta\alpha$. Therefore this method cannot be used to measure the error of the 45°-angle according to 2.8.
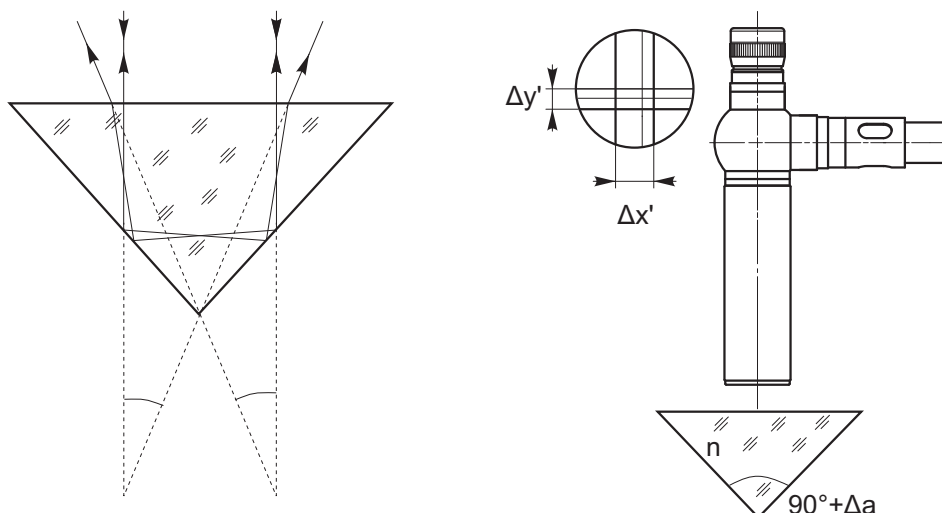
## 2.10   Relative Measurement of Angular Error of Prisms

**Set-up**

- Two ELCOMAT direct (PC-based electronic autocollimators)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline),
- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline),

and

- Reference prism (master prism),
- Swiveling holder,
- Adjustable holder for second autocollimator,
- Tiltable supporting table.

With ELCOMAT direct the measurement is more precise and the measurement time is reduced.

**Measurement**

The reference prism is positioned on the tiltable supporting table. Both autocollimators are adjusted to respective surfaces of the prism. The fine adjustment of the prism to the first autocollimator is done with the adjustment screws of the supporting table. The fine adjustment of second autocollimator is made with the adjustment screws of the adjustable holder.

Now the reference prism is replaced with the test prism. The prism is adjusted to the first autocollimator with the supporting table. Additionally the prism has to be adjusted such, that the x-deviation is zero in the the second autocollimator, as well. At the second autocollimator the distance of the reticle image in $y$- direction is measured. The angular error can be calculated according to (for $\Delta\beta < 5°$):

$$\Delta\beta = \frac{\Delta y'}{2f'}[\cdot 206265 \text{ arcsec}] \qquad \text{or} \qquad \Delta\beta = \Delta\theta_y$$

Where:
$\Delta\beta$ :   deviation of the prism angle
$\Delta\theta_y$:   angular reading of autocollimators with angular graduation
$\Delta y'$ :   $y$-distance in the autocollimation image plane
$f'$   :   focal length of the autocollimator
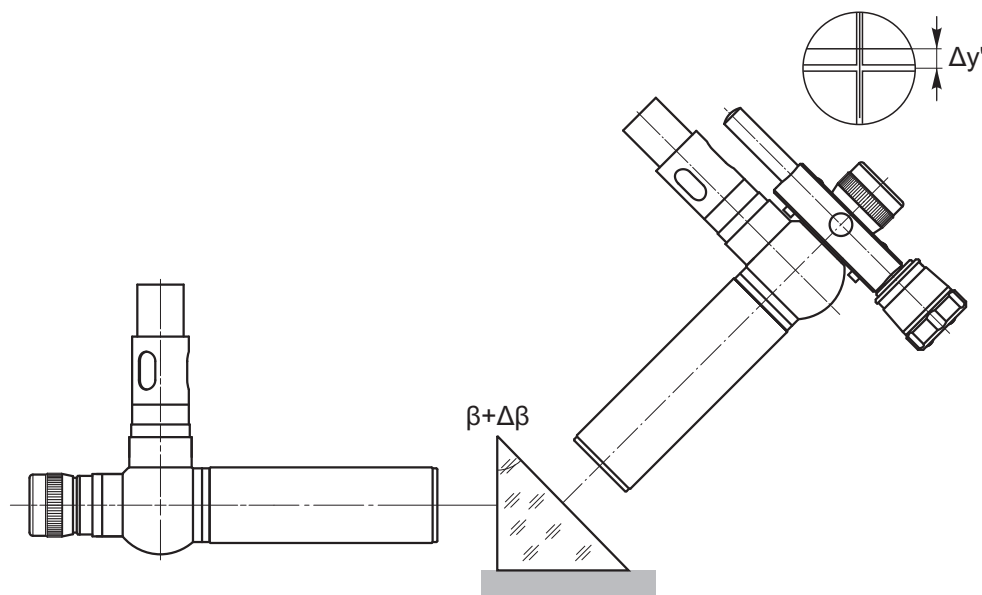
## 2.11    Testing of Camera Objectives

**Set-up**

- Autocollimator with tube extension and collimator reticle S201, S202 (Siemens Star ), S211 or S212 (resolution test) and eyepiece reticle S111
- plane mirror
- adjustable holder

**Testing of the flange distance**

Place a mirror or a film exactly in the image plane of the objective. If the autocollimation image appear sharply in the eyepiece, the position of the object is correct.

**Testing of the distance setting**

The autocollimator with tube extension is set to the distance to be tested (virtual setting). Place a mirror or a film exactly in the image plane of the objective. Set the objective by distance ring to the selected distance. If the distance setting is correct, the autocollimation picture is shown sharp.
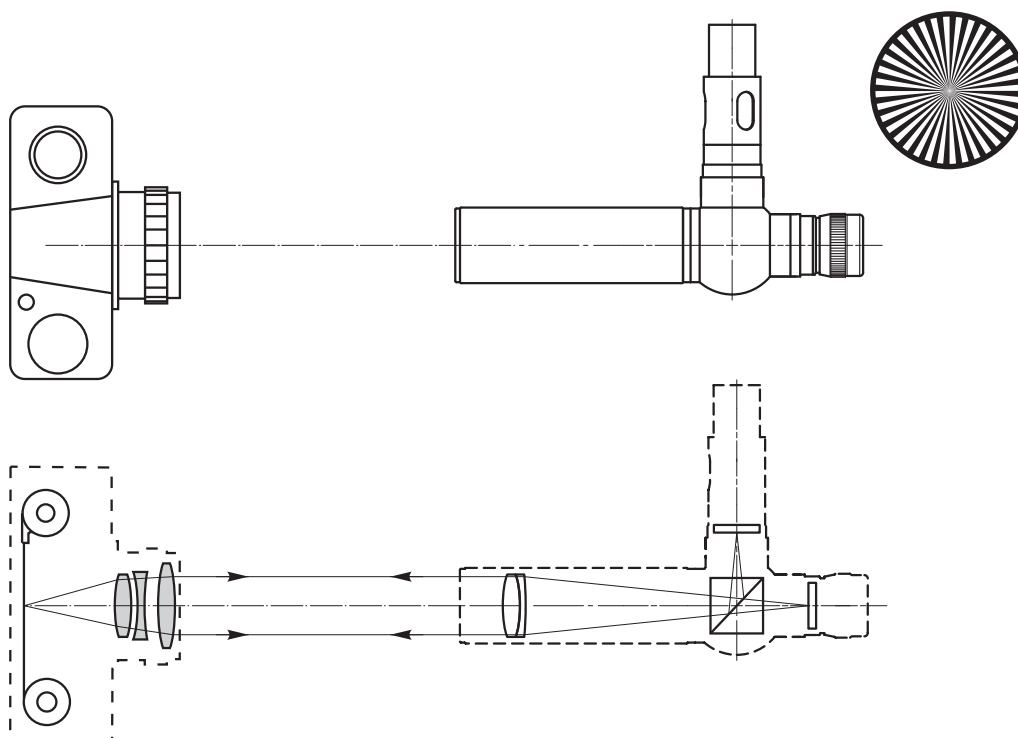
## 2.12   Radius Measurement of Concave Spherical Surfaces

**Set-up**

- Autocollimator with collimator reticle S201 or S202 (Siemens star)
- Attachment achromat (Available lenses: f = 50 / D11 to f = 600 / D28 depending on the radius to be measured.)
- Measuring slide with length measuring system or MELOS stand

or

- MELOS (complete instrument)

**Measurement**

With this method the concave radius of curvature of the front surface of optical components like. e.g. mirrors or lenses can be measured. The attachment achromat converts the parallel beam to divergent or convergent beam (finite setting). If the autocollimator is focused to the vertex of the surface an autocollimation image occurs (a). The second autocollimation image occurs when the focal point of the attachment achromat coincidences with the center of curvature of the surface (b). The translation range to move the autocollimator from one picture to the next corresponds to the radius.

The measurement is done as follows:

a) Move the autocollimator along the translation slide until a sharp image occurs (Siemens star sharp).  Index the position.

b) Move the autocollimator to the next position until the image is sharp.  Index the second position.  The difference of both index positions is the radius:

$$R = \Delta L$$

Where:
$R$  :   Radius of the surface
$\Delta L$:   Distance between the autocollimation images

When measuring transparent lenses additionally autocollimation images form the lower surfaces occur. That has to be taken in mind when selecting the corresponding pictures for radius measurement.



a)                                                  b)
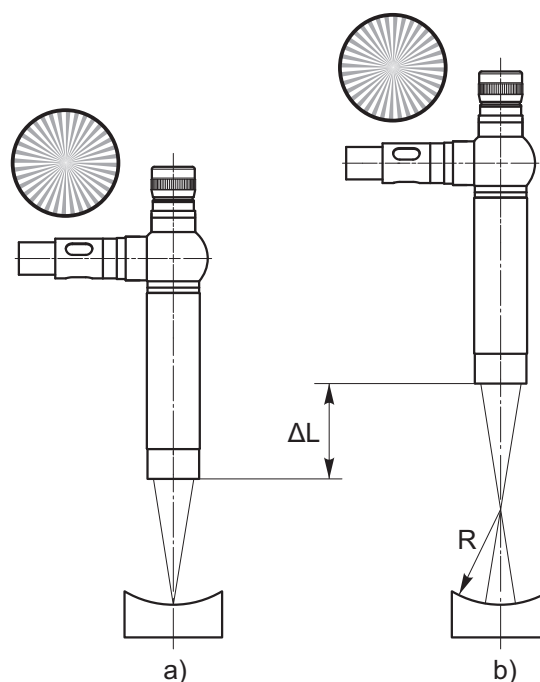
## 2.13    Radius Measurement of Convex Spherical Surfaces

### Set-up

- Autocollimator with collimator reticle S201 or S202 (Siemens star)
- Attachment achromat (Available lenses: f = 50 / D11 to f = 600 / D28 depending on the radius to be measured.)
  Important: The back focal length of the attachment achromat must be larger than the radius of the surface.
- Measuring slide with length measuring system or MELOS stand

or

- MELOS (complete instrument)

### Measurement

With this method the convex radius of curvature of the front surface of optical components like. e.g. mirrors or lenses can be measured. The attachment achromat converts the parallel beam to divergent or convergent beam (finite setting). If the autocollimator is focused to the vertex of the surface an autocollimation image occurs. The second autocollimation image occurs when the focal point of the attachment achromat coincidences with the centre of curvature of the surface. The translation distance to move the autocollimator from one image to the other corresponds to the radius. When measuring transparent lenses additionally images from the back surface can occur. That has to be kept in mind when selecting the corresponding images for radius measurement.

The measurement is done as follows:

a) Move the autocollimator along the translation slide until a sharp image occurs (Siemens star sharp). Index the position.

b) Move the autocollimator to the next position until the image is sharp. Index the second position. The difference of both index positions is the radius:
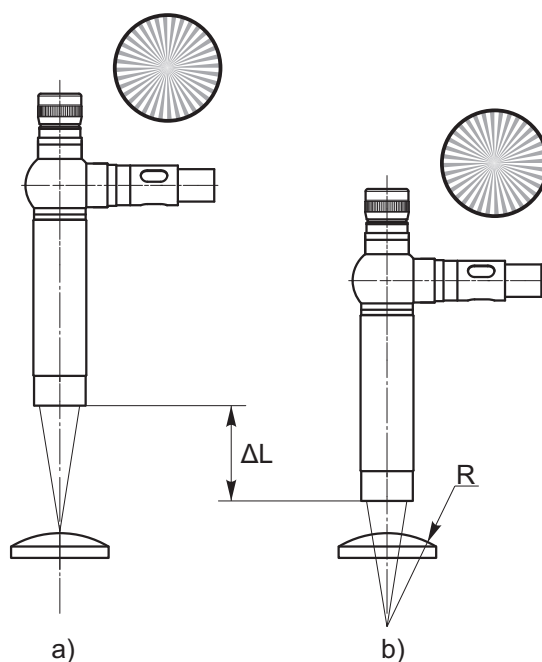
$$R = \Delta L$$

Where:
 $R$  :   Radius of the surface
 $\Delta L$:   Distance between the autocollimation images

When measuring transparent lenses additionally autocollimation images form the lower surfaces occur. That has to be taken in mind when selecting the corresponding pictures for radius measurement.



a)                               b)

## 2.14 Measurement of Focal Length of Lenses and Optical Systems

### Set-up

- Collimator with special reticle with distance marks and Siemens star for focal length measurement
- Telescope; eyepiece reticle S127 (double crossline)
- Attachment achromat (Available lenses: f = 50 / D11 to f = 600 / D28 depending on the lens to be measured.)
- Stand for axial translation of the telescope
- Transversal translation stage with measurement system
- Chuck for holding of the lens

or

- MELOS (complete instrument)

### Measurement

The specimen is inserted in the exiting beam of the collimator. The specimen produces an image of the reticle in its rear focal plane, which is usually locate behind the last lens surface. The size $\Delta y'$ of the reticle image is determined by measuring the transversal shift of the telescope with attachment achromat between two marks of the reticle.

The image size $\Delta y'$ is only depending on the known distance of the marks $\Delta y$, the known focal length of the collimator $f'_{Co}$ and the focal length of the specimen $f'_T$:

$$f'_T = \frac{\Delta y'}{\Delta y} f'_{Co}$$

Where:
$f'_T$ : Focal length of the specimen
$f'_{Co}$ : Focal length of the collimator
$\Delta y'$: Distance of the marks in the reticle image
$\Delta y$ : Distance of the marks on the reticle

For the measurement of negative lenses the same principle is used. In this case the the rear focus is located in front of the last surface. Therefore the working distance of the attachment achromat must be longer than the negative back focal length of the specimen.
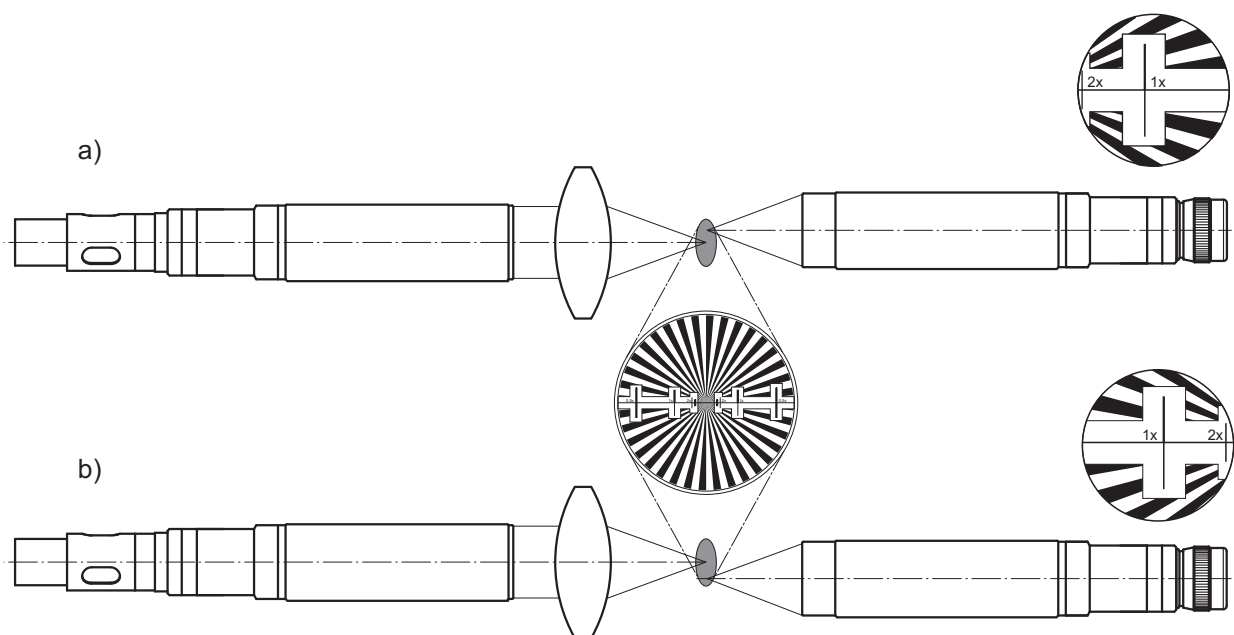
## 2.15   **Measurement of the Back Focal of Lenses and Optical Systems**

- Collimator with reticle S201 or S202 (Siemens star)
- Telescope; eyepiece reticle S127 (double crossline)
- Attachment achromat (Available lenses: f = 50 / D11 to f = 600 / D28 depending on the lens to be measured.)
- Stand with measurement system for axial translation of the telescope
- Chuck for holding of the lens

or

- MELOS (complete instrument)


**Measurement**

For the measurement of the back focal length the distance between the rear focus and the surface is measured.

The specimen is inserted in the exiting beam of the collimator. The specimen produces an image of the reticle in its rear focal plane, which is usually located behind the last lens surface. The measurement is done in two steps:

a) First the telescope with attachment achromat is shifted such that the image of the collimator reticle appears in the eyepiece.

b) In the second step, the telescope is shifted such that the surface of the specimen is sharp in the eyepiece.
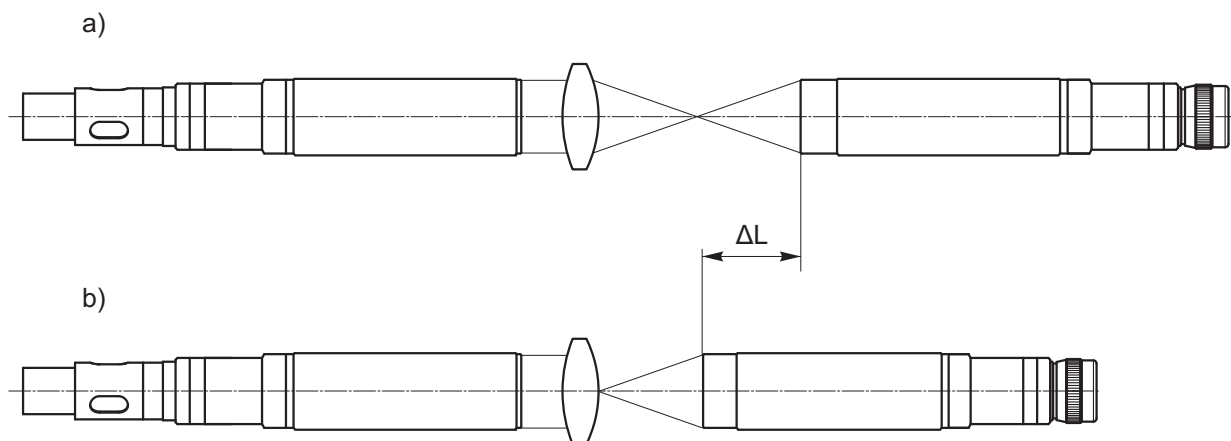
The distance between the two positions is the back focal length $s'$ to be measured:

$$s' = \Delta L$$

Where:
$s'$ :   Back focal length of the lens
$\Delta L$:   Distance between the autocollimation images

a)



b)

## 2.16  Measurement of the Centration Error of Spherical Surfaces

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator)

or

- Autocollimator with double micrometer, collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

and

- Attachment achromat (Available lenses: f = 50 / D11 to f = 600 / D50 depending on the radius to be measured. For convex surfaces please make sure, that the back focal length of the lens is longer than the radius of the surface.)
- Precise rotation stage with small axial run-out and chuck for mounting the lens

With ELCOMAT direct the measurement is more precise and the measurement time is reduced.

**Measurement**

The distance between the center of curvature of the spherical surface and axis of rotation (reference axis) is measured (fig. a). In case of the first lens surface, the autocollimator with attachment achromat is shifted in vertical direction, as described in the sections 2.13 and 2.12 on radius measurement, until the focus of the attachment achromat and the center of curvature of the surface coincide.

When the lens is rotated and the center of curvature is not lying on the axis of rotation, the movement of the autocollimation image forms a circle. The diameter of the circle is a measure for the centration error and is determined with the double micrometer. The centration error is given by:

$$a = \Delta y' \frac{f'_{Va}}{4 f'_{Ak}}$$

respectively:

$$\sigma = \frac{a}{R}[\cdot 3438.8\,\text{arcmin}] = \frac{\Delta y'}{R}\frac{f'_{Aa}}{4 f'_{Ac}}[\cdot 3438.8\,\text{arcmin}]$$



Where:
- $a$ : Distance of the center of curvature to the axis of rotation (centration error)
- $\sigma$ : Angle between the axis of rotation and the surface normal at the intersection point
- $\Delta y'$: Diameter of the circle of movement in the autocollimator image plane
- $f'_{Aa}$ : Focal length of the attachment achromat
- $f'_{Ac}$ : Focal length of the autocollimator
- $R$ : Radius of curvature of the surface (or its image)
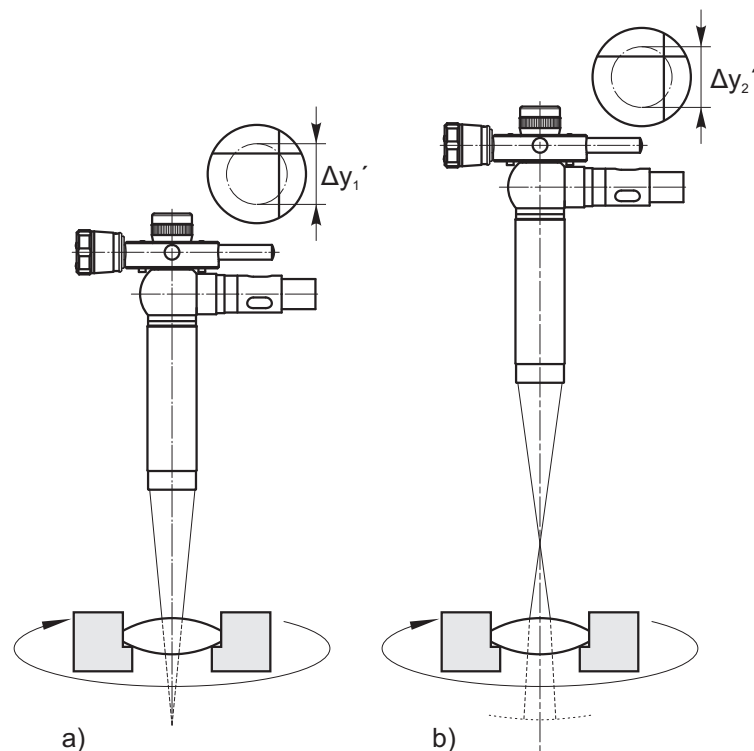
The centration measurement can also be carried out on rear lens surfaces (fig. b). In this case the autocollimator is adjusted to the image of the rear surface, that is produced by the front surface. Before doing this the centration error of the front surface has to be brought to zero. Otherwise it will spoil the measurement result for the rear surface. Additionally the magnification of the image formation by the front surface has to be taken into account when calculating the centration error.

## 2.17 Measurement of Centration Error of Lenses in Transmission using Collimator and Telescope

**Set-up**

- Collimator with reticle S115 (single crossline)
- Telescope with double micrometer with eyepiece reticle S127 (double crossline)
- Attachment achromat (Available lenses: f = 50 / D11 to f = 600 / D50 depending on the lens to be measured.)
- Precise rotation stage with small axial run-out and chuck for mounting the lens

**Messung**

The distance between the focus of the lens and axis of rotation (reference axis) is measured. The specimen is inserted in the exiting beam of the collimator. The specimen produces an image of the reticle in its rear focal plane, which is usually located behind the last lens surface. The telescope wih attachment achromat is shifted in vertical direction until the focus of the attachment achromat and the image of the collimator reticle are located in the same plane and the reticle can be observed in the telescope eyepiece.

When the lens is rotated and the image in the focal plane of the specimen is not lying on the axis of rotation, the movement of the telescope image forms a circle. The diameter of the circle is a measure of the centration error and is determined with the double micrometer. The centration error with respect to the axis of rotation is given by:

$$a = \Delta y' \frac{f'_{Aa}}{2 f'_{Ac}}$$

Where:
- $a$ : Distance of the center of curvature to the axis of rotation (centration error)
- $\Delta y'$ : Diameter of the circle of movement in the telescope image plane
- $f'_{Aa}$ : Focal length of the attachment achromat
- $f'_{Ac}$ : Focal length of the telescope
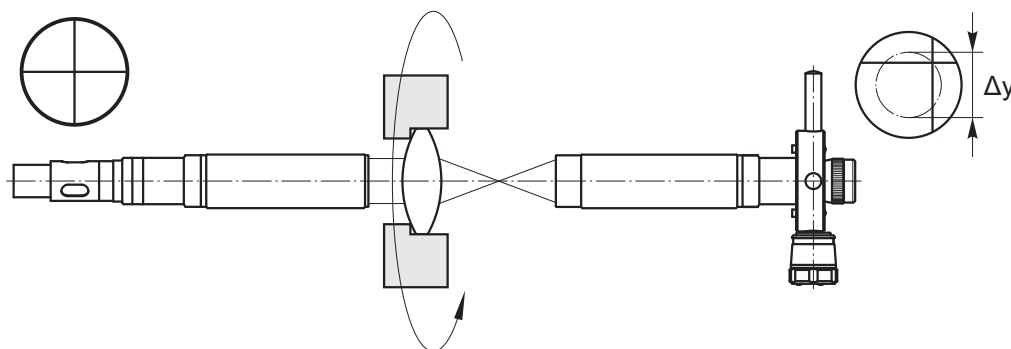
## 2.18   Measurement of Centration Error of Lenses in Transmission using Autocollimator and Mirror

**Set-up**

- ELCOMAT direct (PC-based electronic autocollimator)

or

- Autocollimator with double micrometer, collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

and

- Attachment achromat (Available lenses: f = 50 / D11 to f = 600 / D50 depending on the radius to be measured. For convex surfaces please make sure, that the back focal length of the lens is longer than the radius of the surface.)
- Precise rotation stage with small axial run-out and chuck for mounting the lens
- Plane mirror

With ELCOMAT direct the measurement is more precise and the measurement time is reduced.

**Measurement**

The distance between the focus of the lens and the axis of rotation (reference axis) is measured. The autocollimator with attachment achromat is shifted in vertical direction until the focus of the attachment achromat lies in the focal plane of the specimen. In this case the specimen collimates the exiting beam. After reflection at the mirror the lens produces again an image in its focal plane. This image can be observed in the autocollimator.

When the lens is rotated and the image in the focal plane of the specimen is not lying on the axis of rotation, the movement of the autocollimator image forms a circle. The diameter of the circle is a measure of the centration error and is determined with the double micrometer. The centration error with respect to the axis of rotation is given by:

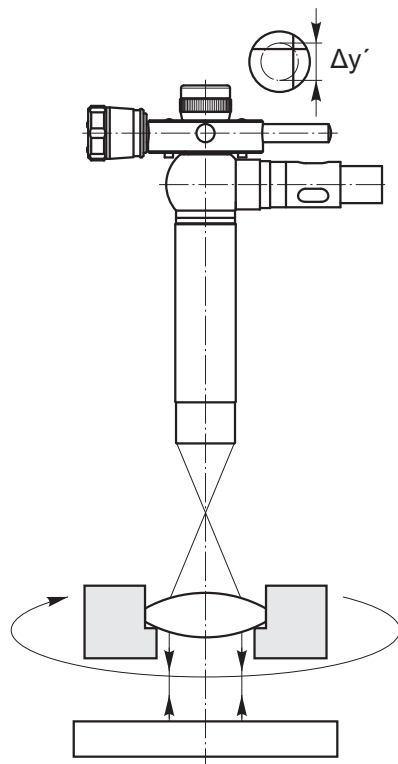$$a = \Delta y' \frac{f'_{Aa}}{4 f'_{Ac}}$$

Where:
- $a$   :   Distance of the center of curvature to the axis of rotation (centration error)
- $\Delta y'$:   Diameter of the circle of movement in the auto-collimator image plane
- $f'_{Aa}$ :   Focal length of the attachment achromat
- $f'_{Ac}$ :   Focal length of the autocollimator

## 2.19   Flatness Testing of Rough Surfaces using Collimator and Telescope

**Set-up**

- Collimator with collimator reticle S201 or S202 (Siemens star)
- Telescope with tube extension and eyepiece reticle S115 (single crossline)

**Measurement**

By using the tube extension the distance between the objective and the reticle increases or decreases. In this case the telescope is set to a virtual or real object. The telescope head can be displaced by measurable values in both directions from zero position.

a) If the Siemens star is sharp in the zero position of tube extension the surface is flat.

b) If the Siemens star is sharp only after displacement, $\Delta L$, of the telescope head, the surface is spherical. The radius of curvature is determined from the equation:

$$R = \frac{2 \cdot f'^2 \cdot a}{\Delta L \cdot b}$$

Where:
$R$ :   Radius of the surface
$\Delta L$:   Distance to the zero setting
$f'$ :   Focal length of the telescope
$a$ :   Length of the illuminated area of the surface
$b$ :   Width of the illuminated area of the surface (corresponds to the diameter of the collimator objective)

c) If the Siemens star has a different sharpness within the single test-directions the surface is irregularly curved. The different directions are to be adjusted sharply one after the other.
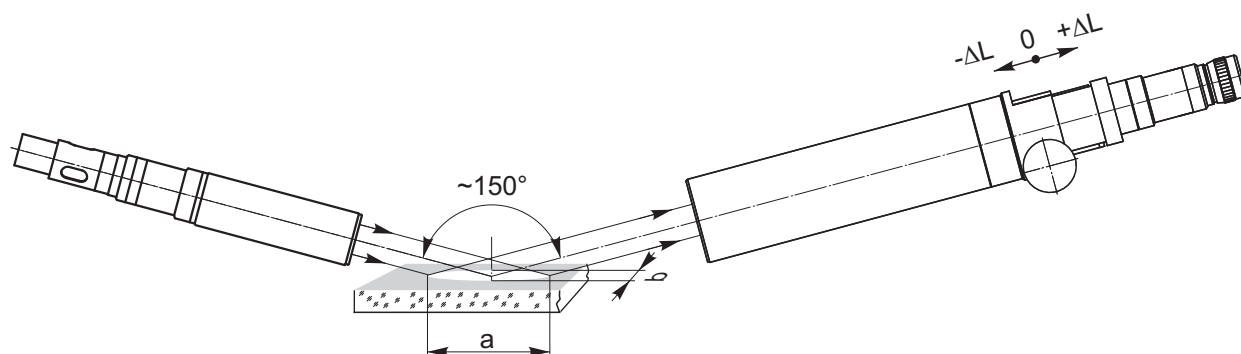
## 2.20   Flatness Testing of Reflecting Surfaces using an Autocollimator

**Set-up**

- Autocollimator with tube extension, collimator reticle S201 or S202 (Siemens star) and eyepiece reticle S115 (single crossline)

**Measurement**

By using the tube extension the distance between the objective and the reticles increases or decreases. In this case the autocollimator is set to a virtual or real object. The autocollimation head can be displaced by measurable values in both directions from the zero position.

a) If the Siemens star is sharp in the zero position of tube extension the surface is flat.

b) If the Siemens star is sharp only after displacement $\Delta L$ of the autocollimation head, the surface is spherical. The deviation from flatness (radius) is determined from the equation:

$$R = \frac{f'^2}{\Delta L}$$

Where:
- $R$ : Radius of the surface
- $\Delta L$ : Distance with respect to zero setting
- $f'$ : Focal length of the autocollimator

c) If the Siemens star has a different sharpness within the single test-directions the surface is irregularly curved. The different directions are to be adjusted sharply one after the other.
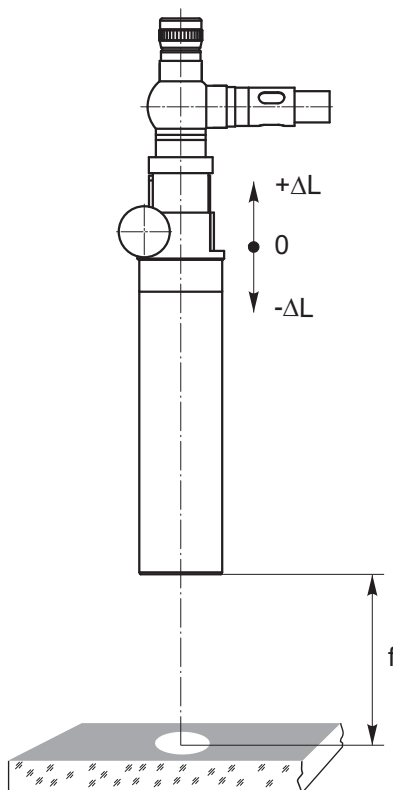
## 2.21   Testing of Opaque Wedges and Double-Sided Mirrors

**Set-up**

- two ELCOMAT direct (PC-based electronic autocollimators)

or

- Autocollimator with double micrometer, collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)
- Autocollimator with collimator reticle S115 and eyepiece reticle S127

and

- Plane parallel plate or reference wedge
- Tiltable table

With ELCOMAT direct the measurement is more precise and the measurement time is reduced.


**Measurement**

Both surfaces of the specimen should be flat and polished. Adjust both autocollimators with the help of the plane parallel plate or reference wedge. Insert the specimen and tilt it in such a way, that the single crossline is centered in the double crossline of the first autocollimator. Rotate the specimen around the optical axis, until x-axis reading in the second autocollimator is zero. Read out the displacement of the autocollimation image of the second autocollimator by means of the double micrometer or the graduated reticle. The angle error can be determined from the graduated scale or the micrometer displacement according to this formula:

$$\alpha = \Delta\theta_y = \frac{\Delta y'}{2f'}[\cdot 206265 \text{ arcsec}]$$

Where:
- $\alpha$    :  Wedge angle of the specimen
- $\Delta y'$ :  distance in the autocollimation image plane
- $f'$    :  focal length of the autocollimator
- $\Delta\theta_y$:  angular reading of autocollimators with angular graduation
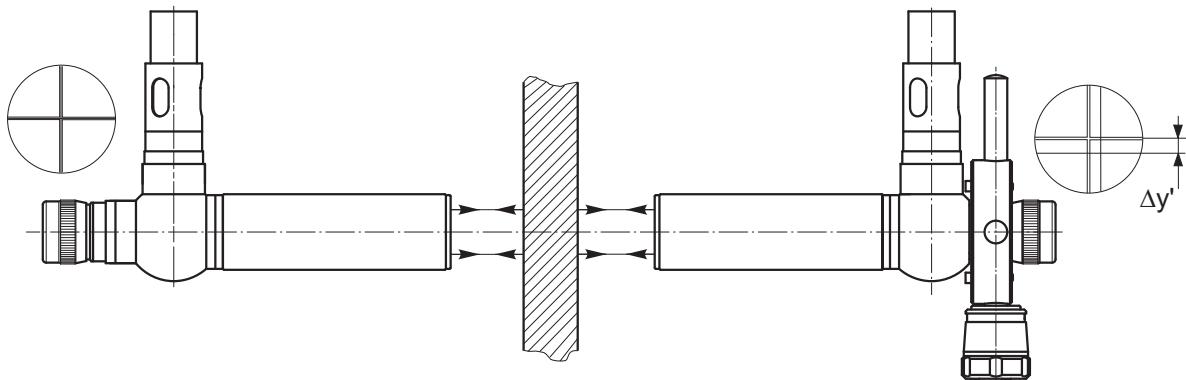
# 3   Applications in Mechanical Engineering

## 3.1   Measurement of Parallelism of Two Surfaces

**Set-up:**

or

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S401 (reticle with mm-graduation)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S411…S431 (reticle with arcmin-graduation)

and

- ELCOMAT (electronic autocollimator)

- Vertical stand
- Plane parallel mirror

**Measurement**

a) Put the mirror on one of the planes. Adjust the autocollimator in such a way, that the autocollimation image is in zero-position.

b) Put the mirror on the second plane and adjust the latter to the autocollimator. For determination of deviation from parallelism do not adjust the latter but readout $\Delta x'$ and $\Delta y'$.

The angular deviation from parallelism can be calculated from:

$$\Delta\alpha = \frac{\Delta x'}{2f'}[\cdot 206265\,\text{arcsec}] \qquad \text{or} \qquad \Delta\alpha = \Delta\theta_x$$

$$\Delta\beta = \frac{\Delta y'}{2f'}[\cdot 206265\,\text{arcsec}] \qquad \text{or} \qquad \Delta\beta = \Delta\theta_y$$

Where:

| | | |
|---|---|---|
| $\Delta\alpha$ | : | Angular deviation in $x$-direction |
| $\Delta\beta$ | : | Angular deviation in $y$-direction |
| $\Delta\theta_x, \Delta\theta_y$ | : | angular reading of autocollimators with angular graduation or with ELCOMATs |
| $\Delta x', \Delta y'$ | : | Displacements of the autocollimation image in the image plane |
| $f'$ | : | focal length of the autocollimator |



a)                                                    b)
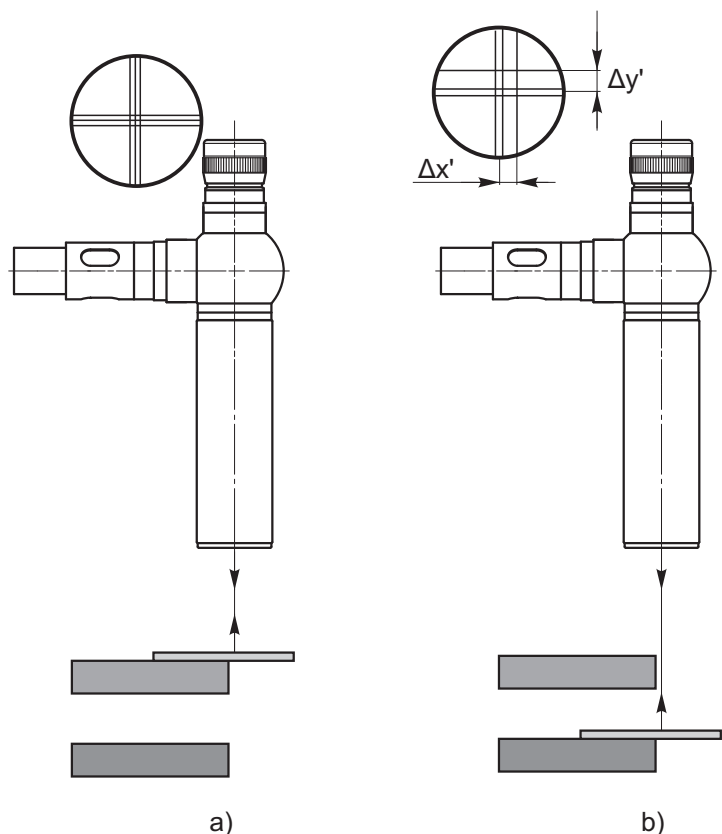
## 3.2   Measurement of Perpendicularity of Two Surfaces

**Set-up:**

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S401 (reticle with mm-graduation)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S411...S431 (reticle with line- and grad graduation)

or

- ELCOMAT (electronic autocollimator)

and

- 90°-prism
- Pentagon prism
- Adjustable holder

**Measurement**

a) Set the 90°-prism on one of the surfaces to be tested. Adjust the autocollimation telescope by means of the prism to a plane.

b) After alignment of the autocollimator, set the prism to the second surface to be tested. Use a pentagon prism to deflect the light bundle exactly by 90°. Read out $\Delta y'$ or $\Delta \theta_y$ to determine the deviation from the 90°-angle:

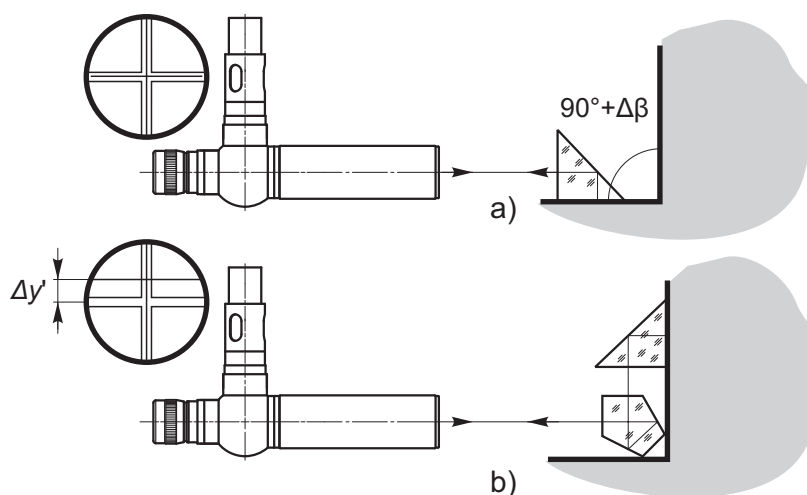$$\Delta\beta = \frac{\Delta y'}{2f'}[\cdot 206265 \text{ arcsec}] = \Delta\theta_y$$

Where:
 $\Delta\beta$ :   Deviation from 90°-angle
 $\Delta\theta_y$:   Angular reading of autocollimators with angular graduation or with ELCOMATs
 $\Delta y'$ :   Displacements of the autocollimation image in the image plane
 $f'$   :   focal length of the autocollimator

## 3.3   Parallel Setting of Rolls

**Set-up:**

- Autocollimator with collimator reticle S115 (single crossline) and eyepiece reticle S127 (double crossline)

or

- ELCOMAT (electronic autocollimator)

and

- V-Prism with flat mirror and cross-level

**Measurement**

a) Adjust the prism with the reflecting mirror at the first roll to the cross-level; put the longitudinal-level by means of a corresponding set-screw at the zero position. Adjust autocollimator to the mirror so that the reflected crossline reticle image is in the centre of the double crossline reticle.

b) Put the mirror on the second roll and adjust it to the cross-level. Align the rolls so that the longitudinal level is at zero and that the reflected reticle is centered in x-direction again in the eyepiece reticle. Now both rolls are parallel.

In the same way with unchanged position of the autocollimator additional rolls can be adjusted, too.



a)



b)
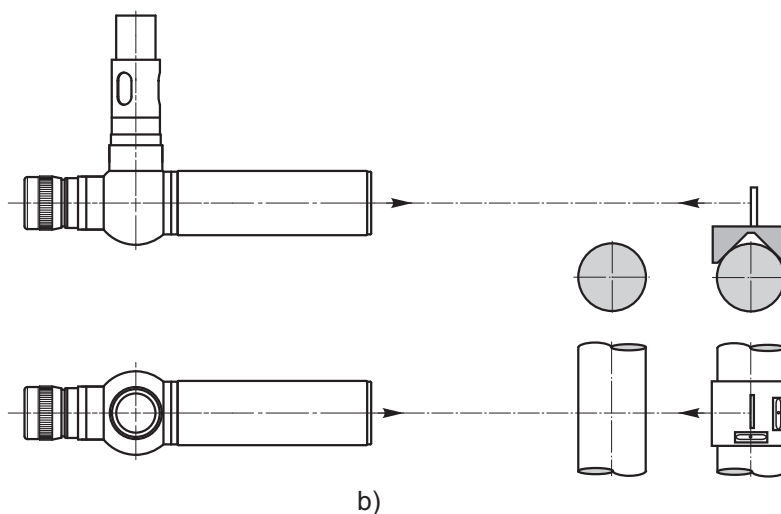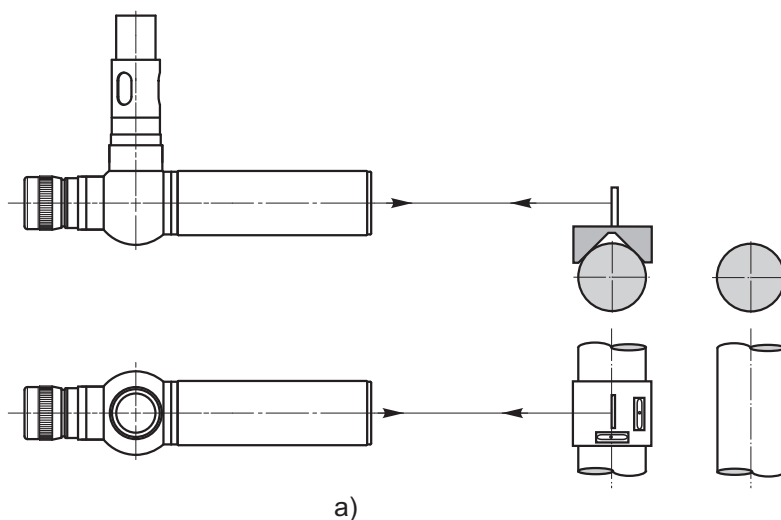
## 3.4    Pitch and Yaw Measurement of Slides

**Set-up:**

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S401 (reticle with mm-graduation)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S411…S431 (reticle with arcmin-graduation)

or

- ELCOMAT (electronic autocollimator)

and

- Base mirror
- Tripod
- Adjustable holder

**Measurement**

A plane mirror (base mirror or mirror with magnetic clamp) is fixed to the table. The autocollimator is aligned to the mirror. The table is moved in steps or continuously. If there is a pitch or yaw error the autocollimation image moves. The extrema of the image movement are recorded and the angular error $\Delta\beta$ is determines by:

$$\Delta\beta = \frac{y'_{max} - y'_{min}}{2f'}[\cdot 206265\,\text{arcsec}] \quad \text{or} \quad \Delta\beta = \Theta_{max} - \Theta_{min}$$

Where:
$\Delta\beta$ : Angular tilting of the slide
$y'_{min}, \Theta_{min}$ : Minimum displacement/angle value
$y'_{max}, \Theta_{max}$ : Maximum displacement/angle value
$f'$ : Focal length of the autocollimator

With ELCOMAT 3000 or ELCOMAT vario the measurement is more precise and the measurement time decreases rapidly.
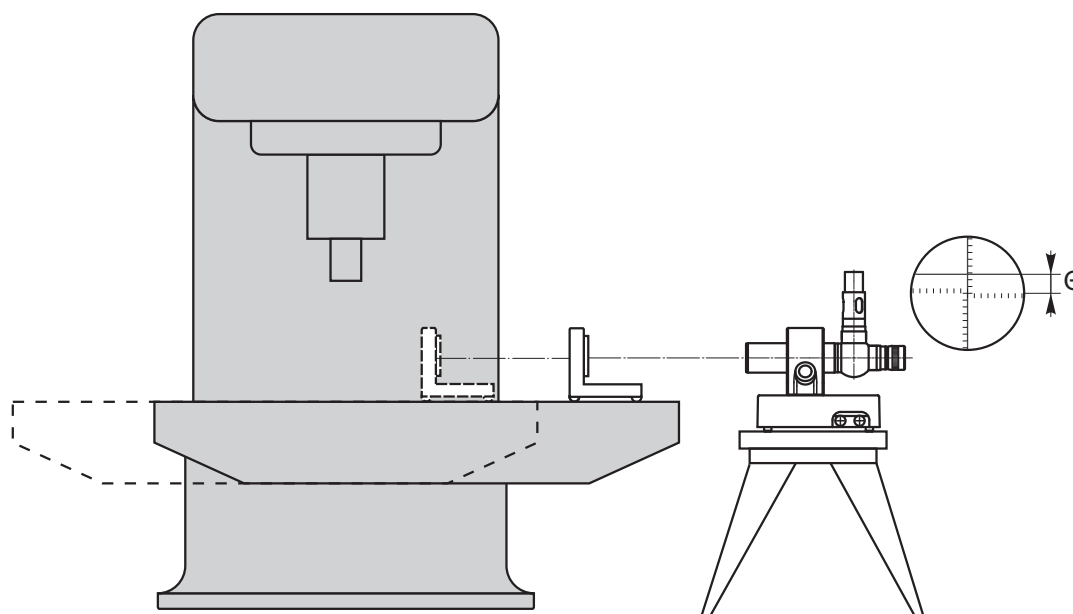
## 3.5   Measurement of Roll-Angle

### Set-up

- Autocollimator with double-micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)
- Transparent wedge, the wedge angle should be chosen such that the autocollimation images of the front and rear surface are both visible, but separated as far as possible

### Measurement

The wedge is adjusted to the autocollimator such that the images of the front and rear surface are lying symmetrically with respect to the center of the measuring range. The double-micrometer is used to measure the $x$- and $y$-coordinates of the autocollimation images ($(x_{f1}, y_{f1})$ and $(x_{r1}, y_{r1})$ in fig. a).

When the wedge rotates around the autocollimator axis (roll) both autocollimation images move on a circle around their common center. In order to determine the roll-angle value the $x$- and $y$-coordinates of the autocollimation images ($(x_{f2}, y_{f2})$ and $(x_{r2}, y_{r2})$ in fig. b) are measured again.

The value $\Delta\theta_z$ can be calculated from:

$$\Delta\theta_z = \arctan\left(\frac{x_{f2} - x_{r2}}{y_{f2} - y_{r2}}\right) - \arctan\left(\frac{x_{f1} - x_{r1}}{y_{f1} - y_{r1}}\right).$$
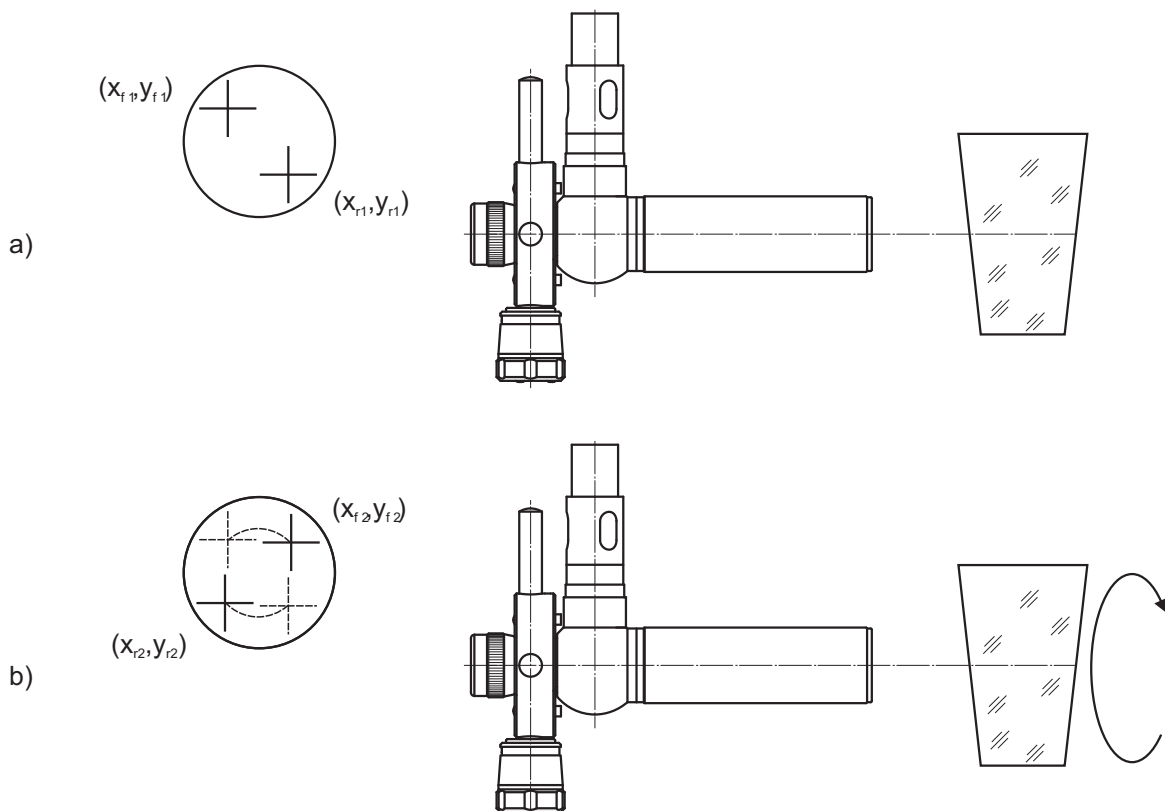
Where:

$\Delta\theta_z$ :   Roll angle

$x_{f1}, y_{f1}$:   $x$- and $y$-coordinates of the front surface before roll movement

$x_{r1}, y_{r1}$:   $x$- and $y$-coordinates of the rear surface before roll movement

$x_{f2}, y_{f2}$:   $x$- and $y$-coordinates of the front surface after roll movement

$x_{r2}, y_{r2}$:   $x$- and $y$-coordinates of the rear surface after roll movement

## 3.6    Straightness Measurement

**Set-up:**

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- ELCOMAT (electronic autocollimator)

and

- Base mirror
- Straight edge
- Tripod
- Adjustable holder

**Measurement**

Set mirror on slide. Adjust autocollimator to the mirror. Move the slide and observe the autocollimation image. Each tilting of the mirror in the guiding direction effects a y-displacement of the autocollimation image from the zero-position. A tilting vertical to the guide can be tested by a rectangular prism instead of a mirror. Move the mirror by the base length of the mirror (100 mm or 50 mm) and read out each difference $\Delta\theta_y$ or $\Delta y'$ to the previously recorded value. The local slope $m$ of the slide is determined by:

$$m = \frac{\Delta y'}{2f'} \quad \text{or} \quad m = \tan \Delta\theta_y \approx \Delta\theta_y$$

Where:
$\Delta\beta$ :    local slope of the slide over the base length of the mirror
$\Delta\theta_y$:    angular reading of autocollimators with angular graduation
$\Delta y'$ :    distance in the autocollimation image plane
$f'$  :    focal length of the autocollimator
The height difference from the mirror position to the previous position is:

$$\Delta h = m \cdot b$$

Where:
$\Delta h$:    Height difference between the supporting points of the base mirror
$b$  :    Base length (distance between the supporting points) of the base mirror

The height profile $h(l)$ can be calculated by accumulation of the height deviation in each measurement position. With the ELCOMAT 3000 or ELCOMAT vario the measurement can be carried out with higher accuracy and in shorter time compared to visual autocollimators
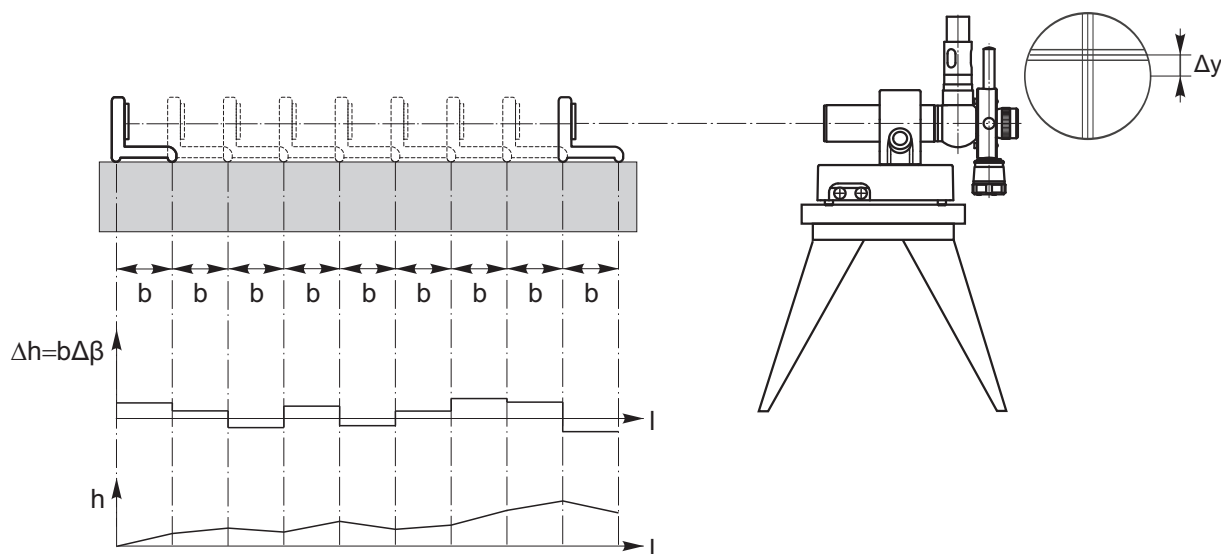
## 3.7   Flatness Measurement

**Set-up:**

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- ELCOMAT (electronic autocollimator)

and

- Base mirror
- Straight edge
- Tripod
- Adjustable holder

**Measurement**

For the measurement of planarity of surfaces several straightness measurements (s. p. 30) are carried out. The straightness measurements form a geometrical pattern, e.g. the so-called "Union Jack" pattern (fig. a). The autocollimator is put at one end of the line of measurement and adjusted such, that the light beam from the autocollimator is propagating in the direction of measurement. A straightness measurement is carried out using the base mirror. A ruler can be used as a guide way for the base mirror. This procedure is repeated for the other lines of measurement.

The height profiles of the lines are combined to a two dimensional pattern, here the "Union Jack", by linking at the intersection points (fig. b). This evaluation is most easily carried out on a computer, for which a special evaluation software is available.

With the use of the ELCOMAT3000 or ELCOMAT vario the accuracy can be increased with an even shorter measurement time. In this case the time-consuming manual data input is reduced.
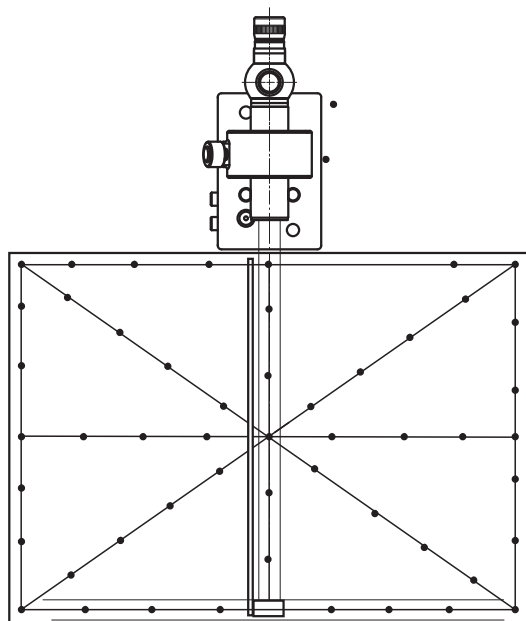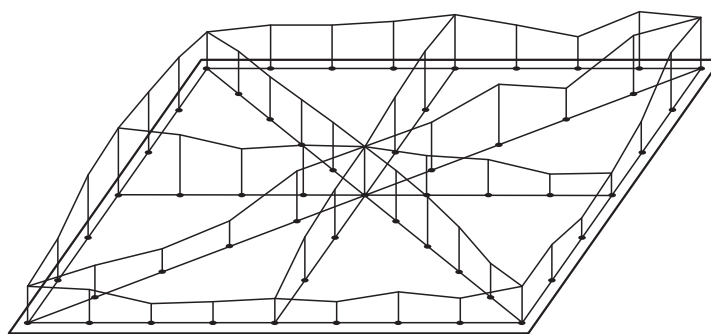


a)                                                          b)

## 3.8 Squareness Measurement between a Vertical Spindle and a Machine Bed

**Set-up:**

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S401 (reticle with mm-graduation)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S411...S431 (reticle with arcmin-graduation)

or

- ELCOMAT (electronic autocollimator)

and

- Two plane parallel mirrors
- Pentagon prism with wedge
- Adjustable holder
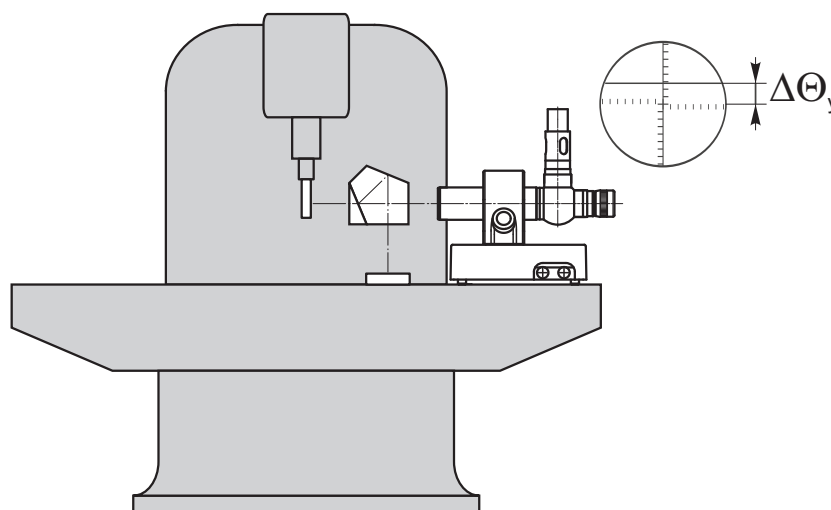
**Measurement**

The measurement is done in two steps:

a) The Autocollimator is adjusted in straight view through the pentaprism to the plane parallel mirror at the spindle. Then the mirror is turned by 180° around the spindle axis. The vertical deviation of the reticle image is read out and divided by two. The mirror is realigned by this value. After a second rotation by 180° the vertical deviation should remain constant.

b) A second plane parallel mirror is put on the machine bed. By the pentagon prism the light bundle is deflected onto the second mirror, so that a second autocollimation image appears.

The deviation $\Delta\beta$ from squareness can be calculated directly from the vertical distance of the autocollimation images according to:

$$\Delta\beta = \frac{\Delta y'}{2f'}[\cdot 206265 \, \text{arcsec}] \quad \text{or} \quad \Delta\beta = \Delta\theta_y$$

Where:
- $\Delta\beta$ : Deviation from 90°-angle
- $\Delta\theta_y$: Angular reading of autocollimators with angular graduation or with ELCOMATs
- $\Delta y'$ : Displacements of the autocollimation image in the image plane
- $f'$ : focal length of the autocollimator

## 3.9   Parallelism Measurement of Cylindrical Bore Holes

**Set-up:**

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S401 (reticle with mm-graduation)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S411...S431 (reticle with arcmin-graduation)

or

- ELCOMAT (electronic autocollimator)

and

- 45° bending mirror
- Flat mirror
- Adjustable holder

**Measurement**

The flat mirror is fixed to the head side of a bolt. The bolt is placed in the first hole and the autocollimator is adjusted until the image is reflected in the middle of the measuring range. If test holes in parallel above each other a 45° bending mirror is used to deflect the light bundle by 90°. Read out the position of the micrometer drums or the eyepiece reticle with mm graduation. Then the bolt is placed into the next hole. Again the values must be registered, and this must be done for each hole. Read the valued $\Delta y'$ or $\Delta\theta_y$ and calculate the angle $\Delta\beta$ between axes of bore holes according to:

$$\Delta\beta = \frac{\Delta y'}{2f'}[\cdot 206265 \, \text{arcsec}] \quad \text{or} \quad \Delta\beta = \Delta\theta_y$$
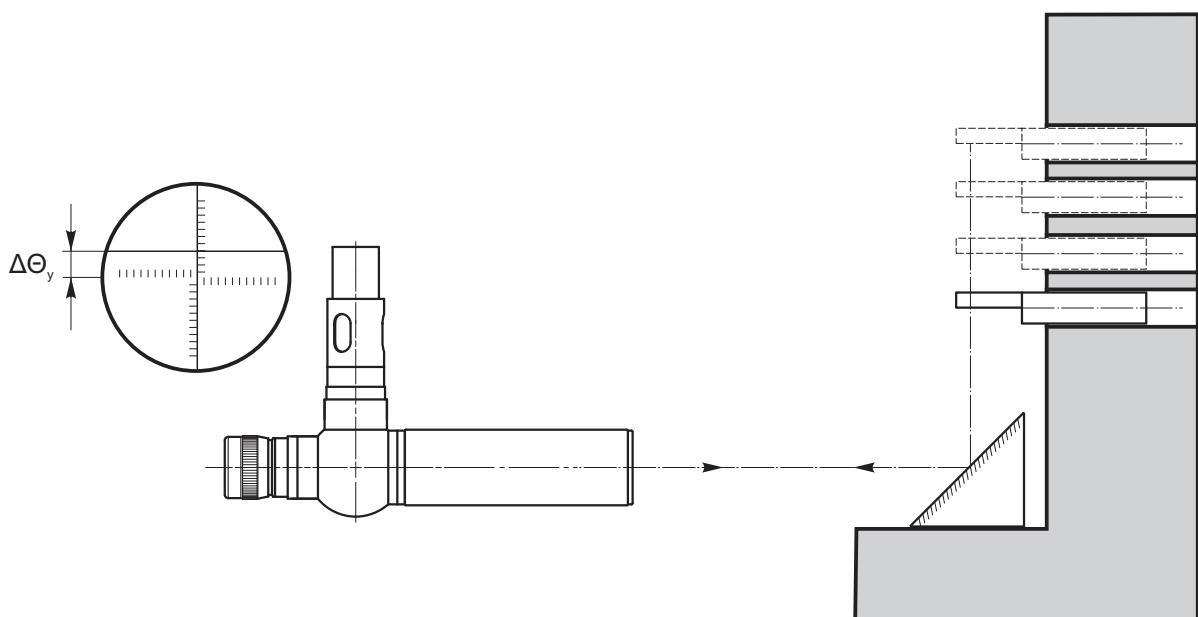
Where:
  $\Delta\beta$ :   Angular displacement between two drillings
  $\Delta\theta_y$:   Angular reading of autocollimators with angular graduation or with ELCOMATs
  $\Delta y'$ :   Displacements of the autocollimationimage in the image plane
  $f'$   :   focal length of the autocollimator
With ELCOMAT 3000 or ELCOMAT vario the measurement is more precise and the measurement time is reduced.

## 3.10   Testing of Accuracy of Rotary Tables and Index Tables

**Set-up:**

- Autocollimator with double micrometer, collimator reticle S115 (crossline) and eyepiece reticle S127 (double crossline)

or

- Autocollimator with collimator reticle S115 (crossline) and eyepiece reticle S411...S431 (reticle with arcmin-graduation)

or

- ELCOMAT (electronic autocollimator)

and

- Polygon mirror
- Adjustable holder

**Measurement**

Adjust the reading of the rotary table position indicator or of the index table in such a manner, that a whole number is displayed. Place a polygon on the table and adjust the autocollimator to one of the surfaces in such a manner that the image of the projected reticle is in the centre of the eyepiece reticle. There are two measuring methods:

1) Rotate the table with polygon by angle 360°/n (n - number of polygon sides). Measure the distance $\Delta x'$ relative to the zero position with the aid of the double micrometer. The error $\Delta\varphi$ is determined according to:

$$\Delta\varphi = \pm\frac{\Delta x'}{2f'}[\cdot 206265\,\text{arcsec}] \quad \text{or} \quad \Delta\varphi = \pm\Delta\theta_x$$

The sign has to be determined by comparing the direction of rotation of the rotary table and the autocollimator. In case the direction is the same a negative sign has to be used, in the other case a positive sign.

2) Rotate the table with polygon until the autocollimation image of the next polygon surface is in the centre of the eyepiece reticle. Read out the angle position of the table $\varphi$. The error is determined according to:

$$\Delta\varphi = \frac{360°}{n} - \varphi$$

Where:
- $\Delta\varphi$ :   error of the table in measured angular range
- $n$ :   number of polygon sides
- $\Delta\theta_x$:   Horizontal displacement of the reticle for autocollimators with angular graduation or with ELCOMATs
- $\Delta x'$ :   horizontal displacement for autocollimators with mm-reading
- $f'$ :   Focal length of the autocollimator
- $\varphi$ :   Angle position of the table

With ELCOMAT 3000 or ELCOMAT vario the measurement is more precise and the measurement time is reduced.

Notes

Notes