# ESAD – A Highly Accurate Deflectometric Flatness Standard

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We built a scanning facility for the highly accurate and traceable measurement of large near-flat and slightly curved optical surfaces based on ESAD (Extended Shear Angle Difference) shearing deflectometry. Sub-nm repeatability, reproducibility, and uncertainty of topography measurement have been achieved. ESAD utilizes the propagation of light as a natural straightness standard and traceable measurands to create a flatness standard with highest accuracy to replace the three-flat test or liquid mirrors as starting points of the traceability chain in flatness measurement.

## 1 ESAD Scanning Deflectometry

A method for the highly accurate measurement of the slope and topography of near-plane and slightly curved optical surfaces has been developed [1,2]. It is based on the measurement of differences of reflection angles at points on the surface of the specimen separated by large (mm to cm) lateral shears. It has been termed ESAD - *Extended Shear Angle Difference*. We built a scanning facility based on ESAD shearing deflectometry achieving sub-nm repeatability, reproducibility, and uncertainty of topography measurement [3,4].

In contrast to other deflectometry applications, ESAD combines deflectometric and shearing techniques in a unique way to optimize both error minimization and traceability. Mathematical algorithms allow the surface slope to be reconstructed from two sets of angle differences obtained with different shear values [5,6]. The reconstruction is (1) mathematically exact, (2) can be obtained over the whole surface area of the specimen (no margins missing), and (3) allows a high lateral resolution independent of the shear values applied. The topography is then derived from the slope by an accurate integration algorithm. The use of difference data to assess the surface slope (achieving the elimination of a host of error influences) distinguishes ESAD shearing deflectometry from other deflectometric systems, e.g., the LTP (*Long Trace Profiler*).

In contrast to conventional interferometry, ESAD scanning does not rely on calibrated reference surfaces of matched topography. Instead, it utilizes the propagation of light as a natural straightness standard. The measurands, from which the topography is derived by application of mathematical algorithms, can be directly traced back to the SI units of angle and length. ESAD is therefore capable of serving as a flatness standard with highest accuracy to provide the starting point of the traceability chain in flatness measurement.

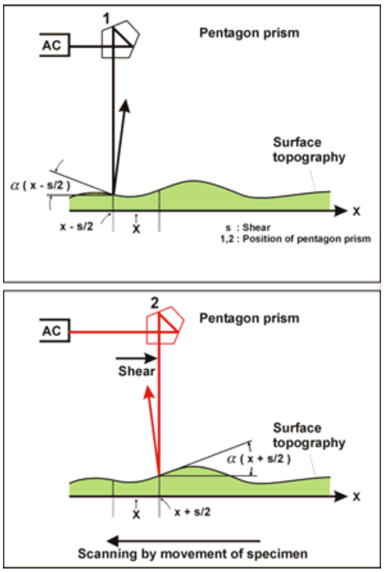

**Figure 1:** Sequential angle difference measurement using a pentagon prism as implemented in the ESAD device.

Figure 1 demonstrates the principle of ESAD scanning deflectometry. The local slope of the surface of the specimen is measured using a high-precision electronic autocollimator (AC). A pentagon prism deflects the beam of the autocollimator by 90°. The shearing measurements (to obtain slope differences between points on the surface separated by the two shear lengths) are performed sequentially by shifting the pentagon prism. In combination with the principle of difference measurement, influences of errors of the optical components (including the pentagon prism), angular errors of the scanning stages, long-time whole-body movements of the specimen, and slow deformations of the measurement device are reduced or eliminated. The scanning of the surface under test is performed by shifting the specimen mechanically using a precision 2D scanning stage; shearing (to obtain angle differences) and scanning of the surface under test are thus decoupled and performed sequentially.

The sequential implementation of the difference measurement using a pentagon prism has been chosen to (1) measure slope values under measurement conditions (optical paths, working distance of autocollimator) as identical as possible (2) using the same calibrated autocollimator. This aids in error minimization and traceability of the topography measurement.

## 2 Results

We built a scanning facility based on ESAD shearing deflectometry achieving sub-nm repeatability, reproducibility, and uncertainty of topography measurement, see [3,4] for details. A reproducibility of the reconstructed topography after tilt correction of approx. 0.1-0.2 nm is now routinely achieved with this device for optimum shear combinations and scan lengths of 100-200 mm.

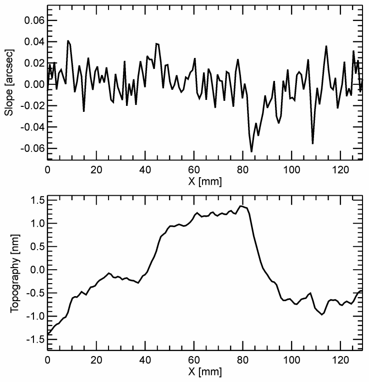

**Figure 2:** ESAD measurement of a near-plane substrate. Upper graph: slope (local surface inclination), lower graph: topography obtained by integration.

An example of a measurement with ESAD is shown in Figure 2. The upper graph shows the measured slope (local surface inclination) of the specimen, the lower graph the resulting topography obtained by integration. The deviation from flatness is approx. 3 nm over the scan length of 130 mm. The measurements were performed applying an optimized shear combination of 4 x 35 = 140 data points per scan (physical shears of 3.7 mm & 32.5 mm) and a spot size of 5 mm of the autocollimator. The repeatability of the topography measurements was 0.16 nm rms (root-mean-squares).

The measurement uncertainty with ESAD is a function of the position of a data point in the scan, as shown in Figure 3. It shows the standard measurement uncertainty of the slope (upper graph) and the topography (lower graph) for the measurements presented in Figure 2. The uncertainty is calculated in accordance with the *Guide to the Expression of Uncertainty in Measurement* GUM [7]. The minimum / median / maximum values for the standard uncertainty of the topography measurements of the scan are $u_{ESAD} = 0.15$ nm / 0.23 nm / 0.54 nm.

Figure 4 shows the components of the uncertainty budget of the ESAD topography measurements presented in Figure 2. The bars show the minimum, median, and maximum values for each component. The uncertainty components include random and systematic errors of the angle measurements and errors due to the limits of autocollimator calibration [4].

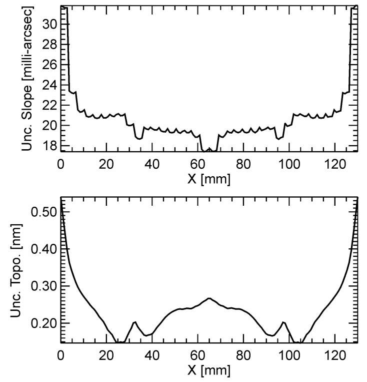

**Figure 3:** Standard uncertainty of ESAD measurements (upper graph: uncert. slope, lower graph: uncert. topography) for the data presented in Figure 2.

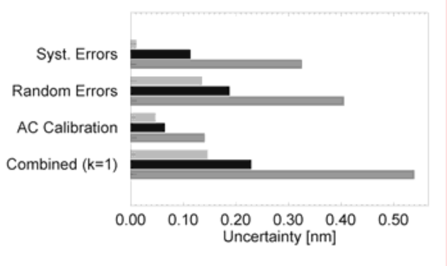

**Figure 4:** Components of the uncertainty budget of the ESAD topography measurements presented in Figure 2. The bars show the min., median, and max. values for the scan.

## 3 References

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