# Positioning Errors in Coherence Scanning Interferometers: Determination of Measurement Uncertainties with Novel Calibration Artifacts

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## 1 Introduction

Coherence scanning interferometry (CSI) [1][2] is a non-contact versatile and fast technology for precision measurements of samples with lateral dimensions of a few micrometers up to a few centimeters. CSI can even measure on rough surfaces and have a large vertical measurement range which is only limited by the maximum displacement of the employed mechanical scanning stage. The resolution and accuracy in vertical direction can be in the nanometer range but are strongly dependent on the positioning noise and accuracy of the scanning stage.

Advances in high precision manufacturing technologies have lead to a demand for high accuracy, non-contact measurement technology which can be met by CSI. However, the CSI technique is accepted only slowly in the field of production metrology due to a lack of standardization and missing comparability to tactile techniques. So far, no standardized solution for the determination of the measurement uncertainty exists. In industrial quality inspection a well defined measurement uncertainty of the measuring instrument is one key requirement [3].

In this paper, we present the uncertainties for CSI originated by the vertical scanning stage. We show how these errors contribute to the uncertainty of step-height, parallelism, and flatness measurements. We have developed a simple description of the uncertainty contributions with parameters that can be determined in practice by calibration with appropriate calibration standards. We show how these components can be conservatively estimated by the user of the CSI. To allow the determination of these uncertainty components in practice, even by non-experts, we have developed a number of novel artifacts as candidates for calibration standards. A selection of these artifacts will be presented in this paper. Measurement examples on the novel artifacts are presented and how the results are used to estimate the measurement uncertainty. Finally an example is demonstrated for the estimation of the measurement uncertainty and the measurement gauge capability for CSI step-height measurements.

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## 2 Positioning Errors as a Relevant Uncertainty Contribution

Fig. 1 shows the positioning error of a lead screw driven linear stage measured with a displacement laser-interferometer.

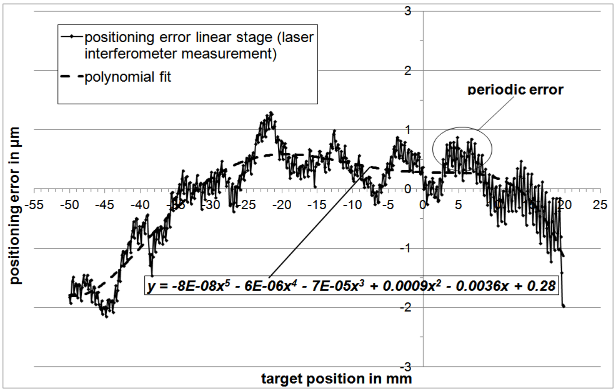


**Fig. 1** Positioning error of a linear stage measured with a displacement interferometer

This positioning error can be divided into a low frequency part and a high frequency part. The low frequency part which describes the non-linearity of the stage is mainly caused by linearity errors of the position feedback device or imperfections of the lead-screw and has a proper ansatz function in respect to Fig. 1

$$\Delta z_{lf} = \left(a \cdot z_{target}{}^{5} + \ldots + e \cdot z_{target} + f\right) - z_{target} \quad , \tag{1}$$

where $z_{target}$ is the target z-position and $a$, $b$, $c$, $d$, $e$, $f$ are unknown fitting coefficients of a polynomial. It should be mentioned that also high accuracy PZT driven stages can show relevant linearity errors. The high-frequency part of the positioning error (Fig. 1) is a periodic error and can be caused by a variation in the average lead-screw pitch, errors of the position feedback and the linear guides. It can be described by the equation

$$\Delta z_{hf} = A\left(z_{target}\right) \cdot \sin\left(\frac{2\pi}{S_{lead}} \cdot \left(z_{target} + \Delta z_{9}\right) + \varphi_{0}\right) - z_{target} \quad , \tag{2}$$

where $S_{lead}$ is the lead screw pitch, $\Delta z_0$ the position error of the stage referencing, $A$ the position dependent amplitude of the periodic error and $\varphi_0$ the initial phase of the periodic error. These errors are usually superimposed by an Abbe-error which results from imperfections of the linear guides in combination with the mechanical set-up of the CSI. Since CSI measurements are directly related to the positions of the scanning stage during camera-frame acquisition the errors described by Eqs. 1, 2, and the Abbe error are relevant contributions to the measurement uncertainty. Especially in macroscopic CSIs this influence is usually the dominant component.

It is impractical or even impossible to identify the coefficients in Eq. 1 to Eq.2 for evaluation of the uncertainty. Therefore, we propose a simplified approach which allows the user to determine the relevant parameters in practice by a calibration with appropriate calibration standards. As can be seen in Fig. 1 the linear stage exhibits a non-linearity which has a maximum deviation $\Delta z_{lin}$ from an ideal linear motion. In a worst case scenario $\Delta z_{lin}$ describes the maximum value for the low frequency part of the positioning error $\Delta z_{lf}$. As already demonstrated in [4] $\Delta z_{lin}$ can easily be determined by a measurement on an adapted coarse multi step-height standard. Thus, assuming an equal distribution for a positioning error between -$\Delta z_{lin}$ and +$\Delta z_{lin}$ the standard deviation for the uncertainty computation of the low-frequency error can be assumed to be $\Delta z_{lin} / \sqrt{3}$.

The uncertainty contribution described in Eq. 2 could be estimated by the maximum measured amplitude of the periodic error $A_{max}$, measured with an appropriate artifact. We assume an equal distribution of between 0 and the maximum amplitude $A_{max}$ for the high-frequency error. The uncertainty of a step-height measurement is influenced by two independent position measurement uncertainties $u_{pos}$ and results in the conservative, simplified estimation

$$U_{sh} = k\sqrt{2\left(\left[\frac{\Delta z_{lin}}{\sqrt{3}}\right]^2 + \left[\frac{A_{\max}}{\sqrt{3}}\right]^2 + u^2_{artifact}\right)} \quad , \qquad (3)$$

where $\Delta z_{lin}$ is the linearity (low frequency) error as derived from a calibration with a coarse artifact over the whole scanning range, $A_{max}$ the maximum amplitude of the high frequency (periodic) error as derived from a calibration with a finely spaced multi step-height artifact, $k$ the coverage factor, and $u_{artifact}$ the uncertainty of the used artifacts. The Abbe error can be ignored here as this error is already included in the measurement results for the calibration.

## 3 Novel Artifacts for Estimation of the Uncertainty by Calibration

A coarse multi step-height standard with 18 steps of 3.75 mm was previously presented [4], which is intended to calibrate the linearity error of a macroscopic CSI as requested by Eq. 3. For the calibration of the high frequency part of the measurement error we have developed some additional candidates for calibration artifacts as are shown in the following. The single piece step-height artifact in Fig. 2 is similar to the coarse standard in [4] and consists of 18 steps with height differences of 125 µm for an aliasing-free acquisition of the high frequency errors. The standard is adapted to the requirements of macroscopic devices. Due to the height range of only 2.25 mm a calibration with an overlap to the coarse standard is not feasible. The artifact in Fig. 3 consists of three interlocked step series in three orientations. Within each series the step height is 375 µm, the three rows interlacing by 125 µm. The artifact provides 35 symmetrical arranged pairs of areas over a height range of 4.375 mm. This enables areal as well as profile measurements adopting the rules of ISO 5436-1, allowing tactile comparison or a calibration measurement. With this artifact an overlap measurement with the coarse multi step-height standard [4] is possible. It was manufactured in PTB central workshop by a milling process with a special milling cutter.

**Fig. 2** Novel multi step-height artifact for the calibration of high frequency errors

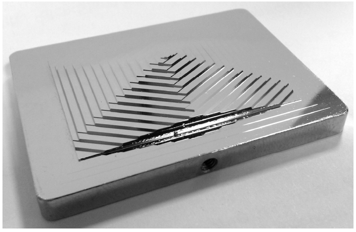

**Fig. 3** Trigonal multi step-height standard. The measurement field is about 40mm x 30mm

The multi step-height artifact shown in Fig. 4 is intended for the calibration of microscopic topography measuring systems over a height range of 240 µm. It is manufactured by a single micro-diamond turning process. To fulfil the manufacturing and tactile measurement conditions the profile is designed according Fig. 4b. The different sections of planes are arranged to have pairs of steps on the same height for levelling. The individual sections have been designed to fit into the usual field of view of a microscope with 10x magnification. The different step sections allow different evaluation strategies.

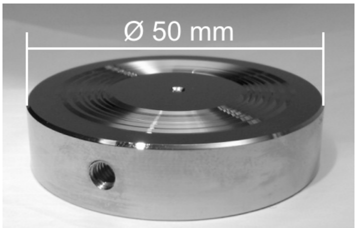


**Fig. 4a** Microscopic multi step-height artifact

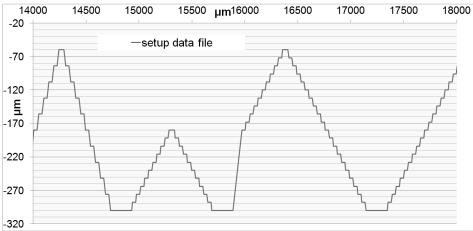


**Fig. 4b** Radial profile section of the microscopic multi step-height artifact

## 4 Estimation of the Uncertainty by Calibration

We have used the novel artifacts and Eq. 3 to analyze the uncertainty of a new CSI prototype with a sophisticated positioning stage and a novel synchronization procedure between stage position and camera frames. Fig. 5 shows the result of the calibration of this new CSI development using a coarse step-height standard.

The system shows a reproducible non-linearity $\Delta z_{lin}$ of 1.73 µm. After compensation we have measured an error $\Delta z_{lin}$ of 0.66 µm. The novel superfine multi step-height artifact from section 3 has been employed to analyze the high-frequency error. As the deviations for the measurements of the artifact in two different sections of the scanning range are nearly equal (see Fig. 5) it is eligible to assume that the deviation is caused due to the error of the artifact and that no significant high-frequency error is present or cannot be revealed with the artifact.

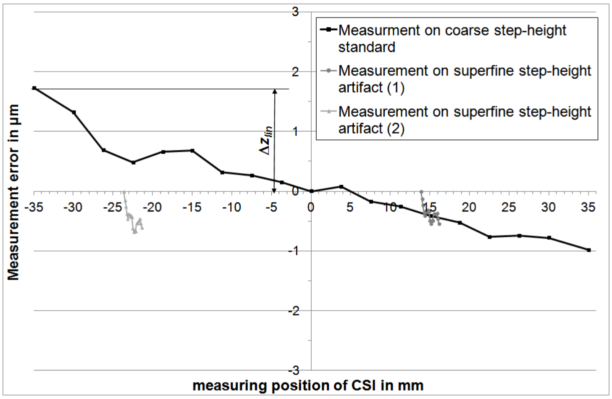


**Fig. 5** Calibration result for a macroscopic CSI using the coarse and the superfine multi step-height artifacts

The expanded uncertainty ($k$ = 2) for a step height measurement can be estimated with Eq. 3 for $\Delta z_{lin}$ = 0.66 µm, $A_{max}$ = 0 µm, and $u_{artifact}$= 0.215 µm to

$$U_{sh} = 2 \cdot \sqrt{2 \cdot \left( \left[ \frac{0.66\,\mu\text{m}}{\sqrt{3}} \right]^2 + 0.215\,\mu\text{m}^2 \right)} = 1.24\,\mu\text{m} \quad . \tag{4}$$

It is obvious that this maximum value for the uncertainty is dominated by the uncertainty of the standard and the deviation over the full range of the vertical stage. Therefore, we have employed a high precision depth-setting standard from the PTB [5] with different steps up to 5 mm to study the accuracy for measurements of smaller steps. These standards have a traceable uncertainty in the range of 100 nm. We have measured the steps in different sections of the 70 mm scanning range under reproducibility conditions. The result is shown in Table 1. It can be seen, that the measured deviations are well below the estimated uncertainty according to Eq. 4. The new CSI has been developed for applications in production testing to prove if a shape parameter of a manufactured sample is within the tolerances of the production capabilities. The QS9000 [3] describes the requirements for the measuring instrument to prove the production tolerances. The parameter which is the measurand for the measurement capability is the gauge capability index $C_{gk}$. Based on the statistics of the measurement series we calculated a $C_{gk}$ of 2.54 for a 5 mm step, a tolerance of 10 µm and coverage factor of 3 according to [3]. This indicates the capability of the measurement device for this step-height measurement. By evaluating the data we have calculated that our new CSI is capable ($C_{gk}$ = 1.33) to test steps with a tolerance of 5.5 µm.

**Table 1** Extract of the results of a measurement series (N = 26) on a PTB depth setting standard

| Nominal step-height [µm] | Calibrated step-height [µm] | Maximum measured deviation [µm] | Expanded measurement uncertainty (k = 2) [µm] |
|---|---|---|---|
| 5 | 4.986 | -0.04 | 0.06 |
| 450 | 450.002 | -0.08 | 0.09 |
| 5000 | 4999.320 | -0.24 | 0.33 |

## 5 Conclusions

We have demonstrated novel artifacts which are candidates for future calibration standards for CSI. The artifacts make it possible to measure the linear deviation as well as the non-lineatrity over the full scan range. The results can even be used to compensate the systematic errors. A combination of coarse and fine multistep artifacts allows determining the aliasing-free deviations at the desired positions. In addition, we have demonstrated the evaluation of the uncertainty with these new calibration artifacts and a very simple and practice-relevant equation. Finally we have used the new artifacts and our uncertainty estimation to calculate the uncertainty of a new CSI prototype. We have also demonstrated the evaluation of the measurement gauge capability with a step standard after the vertical axis has been compensated with the aid of our new artifacts. We have shown that the compensated CSI can prove step heights for a production tolerance of 5.5 µm aiming for a gauge capability index of $C_{gk}$ = 1.33 computed with a coverage factor of 3.

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