Definition and evaluation of topography measurement noise in optical instruments

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Abstract. The pursuit of low noise in optical instruments for areal surface topography measurement is relevant to many surface types, ranging from super-polished optical surfaces to weakly reflecting or scattering textures that require enhanced signal sensitivity. We clarify the definition and experimental methods for quantifying random noise in areal surface topography measurements. We also propose a parameter, the topographical noise density, that concisely summarizes the effects of measurement bandwidth. To illustrate these ideas, we present results from a commercial phase-shifting interference microscope showing an RMS measurement noise of 0.03 nm for a 1-s data acquisition of 1 million surface topography image points, after application of a $3 \times 3$-pixel convolution filter. The results follow the expected inverse square root dependence on the data acquisition time for fast averaging of topography maps, resulting in a measurement noise of $<0.01$ nm for a 10-s data acquisition. © 2020 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.59.6.064110]

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1 Introduction

An important performance specification in areal surface topography measurement is the quantity of random noise added to the measured height values. The noise level is relevant to many demanding metrology tasks, including measurements of super-polished surfaces. In the image provided in Fig. 1, for example, the measured ISO surface RMS parameter $S_q$ is 0.05 nm. It is reasonable to wonder whether such a small number properly represents the surface texture or is simply the random noise in the measured topography. Noise is also an important consideration in measurements of waviness of optical components, stitching multiple fields using surface microstructure, and capturing data from complex or weakly reflecting surface structures that require a high signal-to-noise ratio to obtain useful results. Confidence in the results requires a meaningful determination of the additive noise and how it can be reduced using data averaging or surface smoothing at the expense of reduced data rates.

Although specification of measurement noise is well established in metrology sensor engineering, there is a wide range of inconsistent specifications related to noise in optical instruments that measure surface form and texture. It is common in commercial and academic literature to see terms such as vertical resolution, RMS repeatability, accuracy, precision, and height sensitivity, even though these terms have no standardized quantitative meaning. As a consequence, published specifications can vary by as much as three orders of magnitude for instruments that in reality have similar abilities in detecting small variations in surface texture. Added to the confusion are ambiguity regarding the data acquisition time required to meet a given performance specification and the role of filtering or smoothing to improve the noise level at the expense of lateral resolution.

A straightforward approach to resolving these issues is to define measurement noise in a manner consistent with established practice in sensor engineering—as a standard deviation of individual surface height values for repeated measurements. The specified value should

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include a statement of the data rate, in terms of data points per unit time.\textsuperscript{11} This definition of measurement noise has been adopted in the ISO 25178-600:2019 standard for surface topography measurement.\textsuperscript{12}

In support of this approach, we propose here the use of a “noise density” for areal surface topography measurements that is normalized to the square root of the data rate. The noise density builds on the ISO definition of the measurement noise as a metrological characteristic that is independent of the specific instrument design or enabling technologies.\textsuperscript{12} By expressing the measurement noise as a function of data rate, a user may develop applications that identify the best compromise between the surface measurement points, noise level, and available time to measure. Although such a characterization is limited to white Gaussian noise with a uniform spectrum, there are many important influence quantities in surface metrology that can be at least approximated in this way and are relevant to such comparisons.

2 Definition of Measurement Noise

Noise is often distinguished from other error sources by its random quality, as opposed to systematic effects and thermal drift.\textsuperscript{13} The final output of a topography measurement is an array of surface heights, with a noise-equivalent height added to the results for each image point in the final reported surface topography. It is this randomization of the height value that we would like to parameterize as the measurement noise $N_M$ for a specific measurement task.\textsuperscript{12}

A random process can be averaged over time $t$, resulting in improved noise $N_M$ at the cost of reduced measurement speed.\textsuperscript{7,8} In areal topography measurement, an equally important consideration is the number $P$ of independent, uncorrelated image points in the field of view. Just as we can average over time to reduce noise, field-averaging or smoothing filters reduce random noise at the expense of lateral resolution. These two parameters, data acquisition time and lateral resolution, are equally as important for practical surface measurement applications as the measurement noise level.

To aid in estimating noise values for specific data rates, a good practice in dimensional sensor specification is to express random noise as a spectral density. Stated most generally, the measurement noise is the product of the noise density and the square root of the measurement bandwidth.\textsuperscript{14} Here we propose a definition of the noise density $\eta_M$ for surface topography measurements such that

$$N_M = \eta_M \sqrt{P/t},$$

where $N_M$ is the standard deviation of the measurement noise. In practice, a measurement noise value can be expressed by the value of $N_M$ together with the corresponding array size $P$ and data acquisition time $t$, or any other combination that is consistent with the definition in Eq. (1). The key idea is to have all of the necessary information to be able to determine the measurement noise density $\eta_M$.

The inclusion of the data rate in the noise density specification $\eta_M$ addresses common strategies for reducing noise when setting up an application for the instrument. These strategies

Fig. 1 Measurement of a super-polished optical surface using a low-noise interference microscope. The measured RMS surface texture $S_q$ over a $1 \times 1$ mm field of view is 0.05 nm.
include acquiring data more slowly and oversampling, averaging repeated measurements over time, or applying low-pass topography filters that average across neighboring data points. This is important not only for comparing between instruments and measurement techniques, but also for providing ways in which a measurement task can be optimized by trading noise levels for measurement throughput or the total number of independent data points.

If the number of data points $P$ is a fixed value and the more important consideration is noise reduction through data averaging, it is useful to define an alternative noise density as

$$\beta_M = \eta_M \sqrt{P},$$

such that

$$N_M = \beta_M / \sqrt{t}.$$  

The units for $\beta_M$ are distance over the square root of the data frequency, for example, nm/√Hz. This is a familiar specification for single-point sensors. For areal surface topography, this is the noise level for a single-independent image point, with the implicit assumption that the noise is the same over the full field of view.

In some cases, the time $t$ required for data acquisition is a function of the total surface-height measurement range, whereas the noise level $N_M$ remains constant. This is the case for focus variation, confocal, and coherence scanning interferometry (CSI). These instruments operate by scanning through a range of possible surface height values. In such cases, it can be convenient to consider the ratio of measurement range to the full-scale range, so a user can readily calculate the noise density $\eta_M$ for a given scan length. The components of such a specification would be the noise $N_M$, the number of data points $P$ and the data acquisition rate expressed as the measurement range for a given time $t$.

Another class of areal topography measuring instruments relies on single-point sensing and lateral scanning to construct a profile or array of height values. These systems include chromatic confocal and point autofocus sensors. In this case, the measurement noise can be expressed as the single-point noise level combined with a statement of the data rate, so it is possible to calculate the time to acquire $P$ data points and hence the measurement noise density $\eta_M$.

In all of these cases, the times to postprocess and display a result are excluded, even though this part of the measurement arguably has a direct impact on overall measurement throughput experienced by the user. The time $t$ relates exclusively to the data acquisition time as this is most relevant to the fundamental limitations of the instrument, as opposed to the speed of the computer, the display graphics card, or peripheral devices that manage the results of a measurement.

### 3 Instrument Noise

Closely associated with measurement noise is the concept of “instrument noise.” Although strictly speaking measurement uncertainty applies only to a measurement not to an instrument, it is possible to define instrument noise as the value for the measurement noise with an ideal part and under the most ideal conditions, for example, in a metrology lab. The instrument noise quantifies the minimum achievable value for the measurement noise and is a frequently cited instrument specification. For many optical instruments such as interference microscopes, the majority of instrument noise arises from the digital electronic camera, which has random noise contributions from pixel to pixel determined in part by the well depth.

The measurement noise in practice is expected to be greater than the quoted instrument noise, given contributions from environmental disturbances, effects specific to the optical or topographical features of an object, and pseudorandom systematic errors that manifest themselves as variations in results from measurement to measurement. Figure 2 summarizes this distinction.
4 Estimating Measurement Noise Experimentally

Measurement noise may depend on several factors, and it is both useful and practical to quantify the noise empirically under conditions relevant to the intended measurement task. To perform such a measurement, we need to isolate the noise contribution from the measured surface topography. One strategy is to first calculate an average topography map from a large number \( M \) of successive measurements of the topography map \( h_m(x, y) \) to approximate a noise-free areal image of the surface topography:\(^{13,15}\)

\[
\bar{h}(x, y) = \frac{1}{M} \sum_{m=1}^{M} h_m(x, y),
\]

(4)

where \( x, y \) are coordinates within the plane of dimensions \( X, Y \) that defines the measurement area and the height \( h \) is orthogonal to this plane. Subtracting this averaged map \( \bar{h}(x, y) \) from any single measurement shows how the single measurement deviates from an approximately noise-free topography:

\[
\delta h_m(x, y) = h_m(x, y) - \bar{h}(x, y).
\]

(5)

The same measurements that contribute to the averaged map \( \bar{h}(x, y) \) can be repurposed for estimating the measurement noise \( N_M \) from the RMS deviations \( \sigma_m \) for the difference maps \( \delta h_m(x, y) \):

\[
N_M = \sqrt{\frac{1}{M-1} \sum_{m=1}^{M} \sigma_m^2},
\]

(6)

where

\[
\sigma_m = \sqrt{\frac{1}{P_x P_y} \sum_{i=1}^{P_x} \sum_{j=1}^{P_y} \delta h_m(x_i, y_j)^2},
\]

(7)

and the indices \( i, j \) are for a rectangular grid of size \( P_x, P_y \), respectively. An evaluation of the repeatability under idealized conditions, with a sample considered to be ideally suited to the measurement principle, provides a measure of the intrinsic instrument noise that is often quoted as a basic specification for commercial instruments.
Another frequently encountered limit case is when there are just two surface topography maps, in which case there is only one value \( \sigma_1 \) and the calculation summarizes to

\[
N_M = \frac{1}{\sqrt{2}} \sqrt{\frac{1}{P_x P_y} \sum_{i=1}^{P_x} \sum_{j=1}^{P_y} [h_2(x_i, y_j) - h_1(x_i, y_j)]^2}.
\]  

(8)

This is equivalent to the \( Sq \) of the difference map between two successive measurements of surface topography, divided by the square root of 2:

\[
N_M = \frac{Sq(\text{difference})}{\sqrt{2}}.
\]  

(9)

Equation (9) is the ISO standardized definition of the surface topography repeatability (STR), with the calculation for larger numbers of measurements as an option for improving the stability of the outcome.13,15,28,29

The current draft ISO standard 25178-700 states that, in addition to the time required to acquire the signal data for each individual measurement in a measurement noise evaluation, it is required to report any filtering that alters the noise value at the expense of lateral sampling density.30 Averaging or filtering of neighboring image pixels or measurement points is common, and may be part of the normal use of the instrument.16,31 A caution that we have already noted is that effect of small-scale filters to reduce the number of independent data points, which, depending on the sampling density or magnification, could compromise lateral resolution. Occasionally, a noise evaluation may also include removal of spherical or other large-scale form errors for the purpose of isolating random pixel-level noise from other effects, such as vibrations and air turbulence. A common default is to remove tip and tilt as irrelevant to the repeatability test, but more comprehensive form removal is an option as long as it is properly announced with the results of the STR study.

5 Example: Phase-Shifting Interferometry

A calibration of the measurement noise \( N_M \) using the STR and the noise density \( \eta_M \) does not require detailed knowledge of how an instrument works. However, it is useful to consider a specific example measurement technique to illustrating the effects of data acquisition bandwidth.

The example chosen for this study is a sinusoidal phase-shifting interference microscope,26 shown schematically in Fig. 3.26 The camera views interference patterns superimposed on the image of the part, with an intensity at each image point given by the interference intensity equation:

![Interference microscope](image-url)
where \( \phi_j \) is a phase shift imparted by a controlled mechanical motion of the interference objective, \( V \) is the interference fringe contrast, \( q \) is a scaling factor related to how the intensity is expressed numerically, and \( \epsilon \) is additive random noise on the same scale. Here we will define the phase shift as a sinusoidal variation:

\[
\phi_j = u \cos(\alpha_j),
\]

with camera frame captures at positions:

\[
\alpha_j = j\Delta \alpha + \Delta \alpha/2,
\]

where \( j = 0, 1, \ldots, W - 1 \) for a total of \( W \) data samples over one sinusoidal phase shift cycle and \( u \) is the amplitude phase shift. An example algorithm with four camera frames designed for \( \Delta \alpha = \pi/2 \) and phase-shift amplitude \( u = 2.45 \) is given by

\[
\tan(\theta) = \frac{1.4176(-I_0 + I_2)}{(-I_0 + I_1 - I_2 + I_3)}.
\]

The measured surface height is then

\[
h = \theta \lambda_{eq}/4\pi,
\]

where \( \lambda_{eq} \) is the equivalent wavelength of the system, including the light source emission spectrum, camera spectral sensitivity, and geometrical effects of the Köhler illumination.\(^{26}\)

Table 2 in Appendix A provides a list of example algorithms for 4 to 20 camera frames, optimized for differing error compensation requirements, including resistance to environmental vibration and camera nonlinearity. Determining the characteristics of these algorithms follows from a Fourier analysis of the algorithm coefficients, resulting in frequency-dependent filter functions.\(^{32-33}\) Of special interest for this paper is the response of these algorithms to intensity noise, which is dominated by the photon statistics for the digital electronic camera. All of these algorithms have intensity noise sensitivity that is strongly dependent on noise frequency. However, if we assume that the camera noise is random with a uniform distribution of frequencies, then this sensitivity may be expressed as a standard deviation of the resulting phase value for repeated single measurements.\(^{36}\) The result is written simply as

\[
N_M = cS,
\]

where \( S \) is the signal-to-noise ratio for the interference intensity, defined here as the standard deviation of the random intensity noise \( \epsilon \) divided by the amplitude \( qV \) of the interfer-ence signal defined in Eq. (10), and \( c \) is a sensitivity coefficient calculated from a filter-function analysis of the algorithm characteristics \( \lambda_{eq}.\)\(^{37}\)

Table 1 provides the random noise sensitivities, for example, sinusoidal phase-shifting algorithms provided in Appendix A for an equivalent wavelength \( \lambda_{eq} = 570 \) nm. As a specific example, a typical signal to noise for an electronic camera with 8-bit digitization is \( S = 1\% \). For a phase-shifting interferometry with 20 camera frames of data, the expected noise contribution attributable to the camera is 0.18 nm, consistent with the reputation of this technique for sub-nm measurements.

<table>
<thead>
<tr>
<th>( W )</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c ) (nm)</td>
<td>41</td>
<td>29</td>
<td>27</td>
<td>23</td>
<td>21</td>
</tr>
</tbody>
</table>
Importantly, although these algorithms are very different in their response to a range of measurement error sources, the coefficient c for random intensity noise trends downward at a rate approximately equal to \( \sqrt{W} \). This behavior has already been noted by Brophy in 1990 for interferometry with linear phase shifts.\(^{27}\) The improvement with the number of samples comes at the cost of an increasing number of data samples for lower noise and a correspondingly longer data acquisition time.

To further reduce noise, a clear strategy is to continue to increase the number of camera frames available for data analysis. One option is to create additional PSI data reduction algorithms with increased sampling of the interference signal. An alternative is to average a sequence of completed measurements of phase—often referred to as phase averaging. Benefits of phase averaging include a greater tolerance of low-frequency vibrations and overall drift in the object position. Phase averaging also has the advantage of flexibility, in that a user can select any degree of noise reduction desired by simply selecting the number of phase averages, or equivalently, by selecting a total data acquisition time consistent with throughput requirements. Consequently, instrument designers and users alike seek a balance between oversampling and phase averaging to achieve the best performance with the greatest flexibility. The underlying concept is that we expect the noise level to decrease when increasing the overall number of camera frames involved in the calculation.

6 Experiment

A candidate instrument for measurement noise evaluation is a Zygo Nexview\textsuperscript{TM} NX2 interference microscope.\(^{38}\) This system has multiple measurement modes, including continuous sinusoidal phase-shifting interferometry, which makes it ideal for illustrating the trade-off between data acquisition time and measurement noise. Data reduction relies on the 20-camera frame data reduction algorithm for surface heights, averaged continuously at the rate of approximately 10 complete surface topography results per second, with a data array of 1,000,000 pixels.\(^{37}\) For a 200-Hz camera, this is 10 phase averages per second. A single data acquisition is the result of a user-selectable number of internal PSI averages prior to reporting a result for each measurement.

Consistent with the normal configuration of the instrument, a 3 × 3 pixel Gaussian convolution filter is applied as part of postprocessing. This improves the random noise level by approximately a factor of 2 while also introducing a neighboring-pixel correlation that reduces the number of independent data points \( P \) by approximately a factor of 4 to 250,000. At most magnifications above 10× with a 1× tube lens, there is no significant loss of lateral resolution because the camera sampling is intentionally superior to the optical resolution.\(^{39}\) For the noise measurements presented here, there is no large-scale form removal beyond subtraction of tip and tilt variations between data acquisitions.

A silicon carbide (SiC) reference flat serves as an object surface for the topography repeatability test. The polished SiC surface is both sufficiently smooth to be considered an ideal sample while exhibiting crystalline surface structure on the nanometer scale that is of interest for illustrating the benefits of low noise. Figure 4 shows the height map for a 26-s acquisition time, equivalent to 256 continuous averages of the 20-camera frame sinusoidal

![MeasurementErrorImage](image_url)

**Fig. 4** Measured surface topography map for a SiC flat for a 26-s data acquisition.
PSI analysis. The precision and low-noise level of this measurement may be appreciated by
noting that the height scale is $10^{-6}$ m.

Figure 5 shows the difference of two successive individual measurements. The $S_q$ of the difference map is 0.010 nm, corresponding to a noise level of $N_M = 0.007$ nm.

The observed noise level for this instrument has the expected dependence of measured noise on the data acquisition time. Figure 6 shows the expected straight-line trend with a slope of $-0.5$ on the log–log scale, corresponding to a noise density as defined by Eq. (3) of $\beta_M = 0.03$ nm/$\sqrt{\text{Hz}}$. The corresponding instrument noise density after normalizing to $\sqrt{P}$ is $\eta_M = 6 \times 10^{-5}$ nm/$\sqrt{\text{Hz}}$.

To determine if this measured noise level is consistent with expectations, we compare it with the results of Sec. 5 for a 20-frame sinusoidal phase-shifting algorithm and the example of a typical 1% SNR based on camera noise alone. For a single measurement without averaging or lateral filtering, the measurement noise is $N_M = 0.18$ nm. A $3 \times 3$ Gaussian convolution filter reduces this by a factor of 2 to $N_M = 0.09$ nm. At 10 averages per second, the expected noise density is $\beta_M = 0.028$ nm/$\sqrt{\text{Hz}}$, essentially equal to the result in Fig. 6. We conclude that the observed measurement noise under idealized conditions is dominated by random noise from the electronic camera, consistent with the concept of instrument noise as defined in Sec. 3.

7 Measurements of Rough Parts

The benefits of low-noise extend to surfaces that are far from smooth, particularly if the ability to capture data becomes limited by signal to noise. Improvements in signal-to-noise by sampling the interference signal more densely prior to processing—sometimes known as oversampling—have extended the range of application to applications in which the surface structure was...
previously considered beyond the reach of interference microscopy. Figure 7 illustrates the results of a measurement using CSI and oversampling on an additive manufacturing part having steep slopes and highly variable optical signal strength. Low instrument noise allows for detection and evaluation of weak interference signals that would otherwise be lost or indiscernible because of random instrument noise.

Of course, it is one thing to be able to acquire data and quite another to determine the contributors to measurement repeatability values that may exceed the specified instrument noise value by more than an order of magnitude, depending on the surface type and environmental conditions. A recent study of noise reduction methods for interference microscopy showed that, with a tilted flat part in the presence of modest environmental vibration, averaging topography maps provides the expected square root of time reduction, whereas oversampling increases the number of measured points but does not improve the final measurement noise value. These observations reveal a residual ambiguity in the definition of noise: The measurement noise is usually modeled as entirely random, whereas the difference between successive data samples on complex surface structures may have correlated errors over the field of view and over time. The noise may have a value that depends on local surface structure and error contributions that vary over the field of view. Consequently, meaningful statements of noise are closely tied to the specifics of the measurement task. Quality control experts have understood this for some time, which is the reason for empirical evaluations such as the classic test for gage repeatability and reproducibility performed on the part of interest close to the actual conditions of measurement.

8 Summary

We have proposed a definition of measurement noise in areal surface topography measurement that builds upon established usage in other fields of dimensional sensing and has clearly defined meanings in the international standards. It is also clear that the experimental determination of the ISO defined STR is the calibration method most closely associated with the measurement noise. An additional key conclusion is that any statement regarding measurement noise, assuming that it is a random source of uncertainty, should always be accompanied by a data acquisition time, the number of independent data points, and a statement of filtering or other relevant processing steps. Defining noise in this way makes it easier to compare instruments and to track advances in the enabling technologies for interference microscopy and other techniques for surface topography metrology.

9 Appendix A: Algorithms for Sinusoidal Phase-Shifting Interferometry

Table 2 summarizes the sinusoidal phase shifting algorithms for which the intensity noise sensitivity is given in Table 1.
Table 2 Phase estimations algorithms of the same form as Eq. (13)

<table>
<thead>
<tr>
<th>W</th>
<th>$\Delta \alpha$</th>
<th>$u$</th>
<th>$\tan(\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$\pi/2$</td>
<td>2.450</td>
<td>$1.4176(-l_0 + l_5)$ $(l_0 - l_4 + l_3 - l_2) + (l_2 - l_3 + l_4 - l_5)$</td>
</tr>
<tr>
<td>8</td>
<td>$\pi/4$</td>
<td>2.930</td>
<td>$1.6647(-l_1 + l_2 + l_6 - l_8)$ $(l_0 - l_3 - l_4 - l_7) + (l_1 + l_2 + l_6 + l_8)$</td>
</tr>
<tr>
<td>12</td>
<td>$\pi/8$</td>
<td>3.384</td>
<td>[1.24605($l_0 - l_5 - l_6 + l_{11}$) + $l_1 + l_4 + l_7 - l_{10}$] $+2.57462(-l_2 + l_3 + l_4 - l_9)$ $+2.70558(-l_0 + l_5 + l_6 + l_{11})$ $+2.64592(-l_1 - l_4 - l_7 - l_{10})$ $+2.37526(2l_2 + l_3 + l_6 + l_8)$</td>
</tr>
<tr>
<td>16</td>
<td>$\pi/16$</td>
<td>5.410</td>
<td>[0.05613($l_0 - l_7 + l_8 - l_{15}$) + $l_1 + l_6 + l_9 + l_{13}$] $+0.18507(-l_5 + l_3 + l_1 + l_{12})$ $+0.22875(2l_0 + l_5 + l_6 + l_{13})$ $+0.10162(-l_1 + l_3 + l_8 + l_{10})$ $+0.21027(-l_6 + l_7 + l_5 - l_{13})$ $+0.15590(l_1 + l_3 + l_4 + l_{16})$</td>
</tr>
<tr>
<td>20</td>
<td>$\pi/20$</td>
<td>4.180</td>
<td>[0.07014($l_0 - l_9 - l_{10} - l_{19}$) + $l_1 + l_8 + l_{11} + l_{18}$] $+0.02966(-l_5 + l_3 + l_{10} - l_{18})$ $+0.01048(-l_4 - l_7 + l_{12} + l_{17})$ $+0.13572(-l_3 + l_5 + l_{10} - l_{16})$ $+0.14926(-l_4 + l_5 + l_{13} - l_{18})$ $+0.10611(l_0 + l_5 + l_{10} + l_{15})$ $+0.14129(-l_1 - l_8 - l_{11} - l_{18})$ $+0.01346(-l_2 - l_7 - l_{12} - l_{17})$ $+0.08222(-l_3 - l_6 - l_{13} - l_{16})$ $+0.17686(l_4 + l_5 + l_{14} + l_{15})$</td>
</tr>
</tbody>
</table>

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References


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