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Peter de Groot, Jack DiSciacca, "Surface-height measurement noise in interference microscopy," Proc. SPIE 10749, Interferometry XIX, 107490Q (18 August 2018); doi: 10.1117/12.2323900

Event: SPIE Optical Engineering + Applications, 2018, San Diego, California, United States

Invited Paper

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ABSTRACT

The pursuit of low noise in interference microscopy for 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. Noise is a random error source that may be quantified using a repeatability test. Here we propose a *noise density* normalized to the square root of the number of data points per unit time, to evaluate performance independent of measurement speed and areal filtering. Consistent with standardized vocabulary, we also distinguish between measurement noise, which is specific to a part and environmental conditions, and instrument noise, which is an apparatus specification corresponding to measurement noise under the best possible conditions. 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-second data acquisition of 1 million surface topography image points, after application of a 3×3-pixel median filter. The results follow the expected inverse square root dependence on the data acquisition time.

Keywords: Interferometry, surface topography, measurement noise, standards, vertical resolution.

1. INTRODUCTION

A common performance specification in areal surface topography measurement is the quantity of random noise added to the measured height values. This specification may be referred to as height sensitivity, precision, or vertical resolution. The noise level is relevant to many demanding metrology tasks, including measurements of super-polished surfaces, as illustrated by Figure 1. However, the importance of measurement noise is not limited to exceptionally smooth surface textures. Noise plays a role in measurements of waviness of optical components [1, 2], stitching multiple fields using surface microstructure [3], and complex or weakly-reflecting surface structures that require a high signal to noise ratio in order to obtain useful results [4, 5]. Measurement noise is a fundamental metrological characteristic of areal surface topography metrology equipment, and is an essential component of instrument calibration and specification [6, 7].

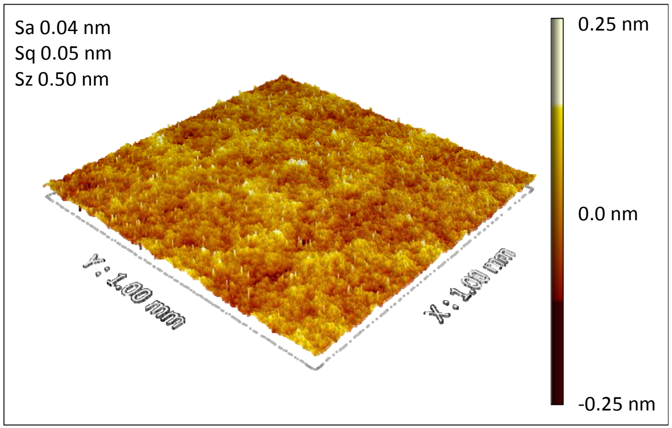

Figure 1: Measurement of a super-polished optical surface using a low-noise interference microscope. The measured RMS surface roughness Sq over a 1×1 mm field of view is 0.05 nm.

Interferometry XIX, edited by Katherine Creath, Jan Burke, Michael B. North Morris, Angela D. Davies,
Proc. of SPIE Vol. 10749, 107490Q · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2323900

Here we review the definition of measurement noise in surface topography using concepts and mathematical properties that are closely associated with distance and position measuring sensors [8-10]. An appropriate expression for surface topography measurement noise is a standard deviation for the estimation of any individual surface height value. We further define a measurement noise density normalized to the square root of the data rate, to facilitate a sensible comparison of instruments. In addition to definitions for measurement noise and measurement noise density, we provide methods for its evaluation, drawn from current best practice. As an example and experimental demonstration of the ideas presented here, we report on recent results of noise measurements on a commercial optical microscope operating in phase shifting mode.

2. DEFINITION OF MEASUREMENT NOISE

Noise is distinguished from other error sources by its random quality, as opposed to systematic effects, distortions, and thermal drift [11]. The final output of a measurement is an array of surface heights, with a random 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 [12].

A random process can be averaged over time t, resulting in improved noise N_M at the cost of reduced measurement speed [8, 9]. In areal topography measurement, an equally important consideration is the number T 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.

To aid in estimating noise values for specific data rates, 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 [13]. Here we propose a definition of the noise density η_M for surface topography measurements such that

$$N_M = \eta_M \sqrt{T / t} \ , \tag{1}$$

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 T 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 η_M.

The inclusion of the data rate in the noise density specification η_M addresses common strategies for reducing noise when setting up an application for the instrument. These strategies include acquiring data more slowly and oversampling [4], averaging repeated measurements over time [14], or applying low-pass topography filters that average across neighboring data points [15]. This is important not only for comparing between instruments and measurement techniques, but also for providing ways in which a particular measurement task can be optimized by trading noise levels for measurement throughput or the total number of independent data points.

In some cases, the time t required for data acquisition is a function of the total surface-height measurement range, while the noise level N_M remains constant. This is the case for focus variation [16], confocal [17] and coherence scanning interferometry [18]. 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 that a user can readily calculate the noise density η_M for a given scan length [19]. The components of such a specification would be the noise N_M, the number of data points T 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 3D image. These systems include chromatic confocal and point autofocus sensors [20, 21]. In this case, the measurement noise can be expressed as the single-point noise level combined with a statement of the data rate, so that it is possible to calculate the time to acquire T data points and hence the measurement noise density η_M consistent with Eq.(1).

In all of these cases, the time to post-process 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 other peripheral device that manages 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 [22]; it is possible to define instrument noise as the value for the measurement noise under the most ideal conditions, for example, in a metrology lab [12, 23]. 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 [24-26].

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 pseudo-random systematic errors that manifest themselves as variations in results from measurement to measurement. Figure 2 summarizes this distinction.

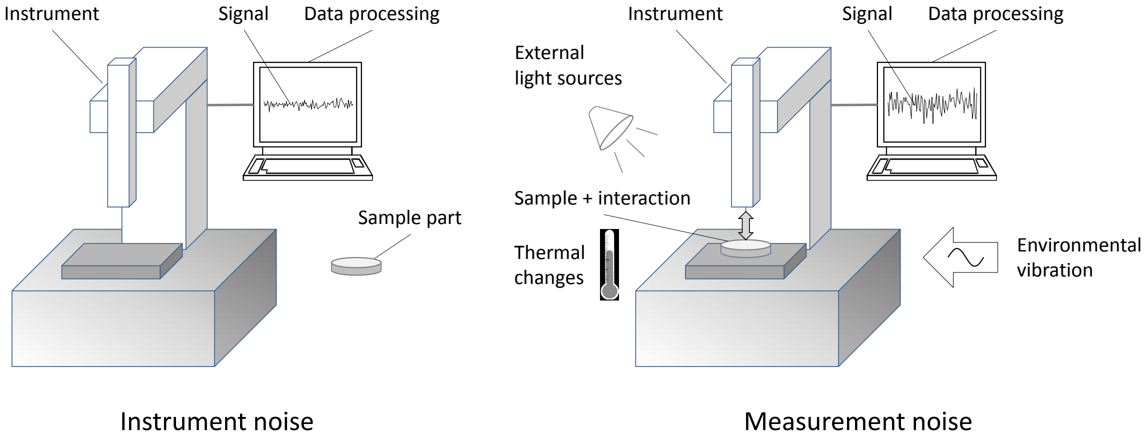

Figure 2: Illustration of the distinction between instrument noise (left) and measurement noise (right). Most specifications refer to instrument noise, which is an idealization of the measurement assuming no external disturbances [23].

4. ESTIMATING MEASUREMENT NOISE

Measurement noise may depend on a number of 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 n of successive measurements of the topography map $h_i(x,y)$ so as to approximate a noise-free areal image of the surface topography [11, 14]:

$$\overline{h}(x,y) = \frac{1}{n}\sum_{i=0}^{n-1} h_i(x,y). \tag{2}$$

Subtracting this averaged map $\bar{h}(x,y)$ from any single measurement shows how the single measurement deviates from an approximately noise-free topography:

$$\delta h_i = h_i(x,y) - \bar{h}(x,y). \tag{3}$$

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

$$N_M = \sqrt{\frac{1}{n-1}\sum_{i=0}^{n-1} S_i^2} \tag{4}$$

where

$$S_i = \sqrt{\frac{1}{XY}\sum_{x=0}^{X-1}\sum_{y=0}^{Y-1} \delta h_i(x,y)^2} . \tag{5}$$

An evaluation of the repeatability under idealized conditions, with a sample considered to be compatible with 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 S and the calculation reduces to

$$N_M = \frac{1}{\sqrt{2}}\sqrt{\frac{1}{XY}\sum_{x=0}^{X-1}\sum_{y=0}^{Y-1}\left[h_1(x,y) - h_0(x,y)\right]^2} . \tag{6}$$

This is equivalent to the ISO surface RMS parameter Sq of the difference map between two successive measurements of surface topography, divided by the square root of 2. In the ISO standards, Eq.(6) is the working definition of the *surface topography repeatability* or STR, with the calculation for larger numbers of measurements as an option for improving the stability of the outcome [11, 14, 27, 28].

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 [29]. Averaging or filtering of neighboring image pixels or measurement points is common, and may be part of the normal use of the instrument [15, 30]. A caution is that effect of small-scale filters is to reduce the number of independent data points, which, depending on the sampling density or magnification, could adversely affect 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. The most 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 study.

5. EXPERIMENTAL RESULTS

Figure 3: Interference microscope for areal surface topography measurement.

The candidate instrument for measurement noise evaluation is a ZYGO Nexview™ NX2, a visible-wavelength interference microscope [31]. The system shown in Figure 3 has multiple measurement modes, including phase shifting interferometry (PSI). The PSI measurement employs high-speed, continuous sinusoidal phase shift [25, 32], which makes it ideal for illustrating the tradeoff between data acquisition time and measurement noise. Data reduction relies on a 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. A single data acquisition is therefore the result of a user-selectable number of internal PSI averages prior to reporting a final result for each measurement.

Consistent with the normal configuration of the instrument, a 3×3 median noise filter is applied as part of post processing. This improves the noise level while also introducing a neighboring-pixel correlation that effectively reduces the number of independent data points T by a factor of 9, to approximately 110,000. 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 [33]. 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 26s acquisition time, equivalent to 256 continuous averages of the 20-camera frame sinusoidal PSI analysis. The precision and low noise level of this measurement may be appreciated by noting that the height scale is ±1 nm. Figure 5 shows the difference of two successive individual measurements similar to that of Figure 4. The `Sq` of the difference map is 0.010 nm, corresponding to a noise level of $N_M = 0.007\ \mathrm{nm}$, following Eq.(6).

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 an STR of $0.03\ \mathrm{nm}\big/\sqrt{t\cdot \mathrm{Hz}}$. The corresponding instrument noise density after normalizing to $\sqrt{T}$ is $\eta_M = 9\times 10^{-5}\ \mathrm{nm}\big/\sqrt{\mathrm{Hz}}$.

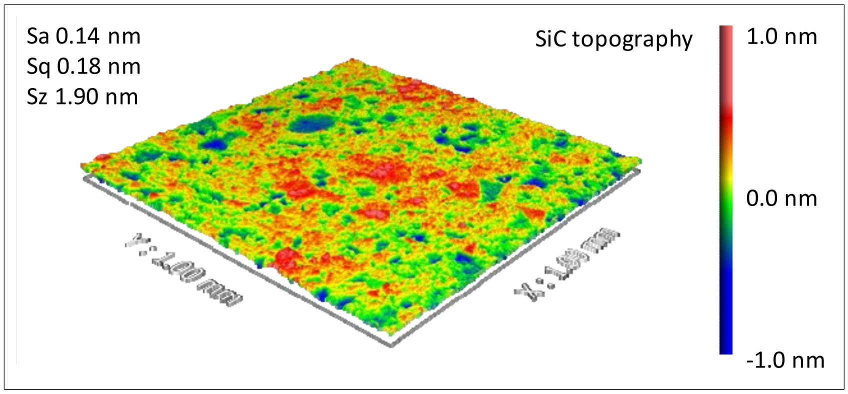

Figure 4: Measured surface topography map for a SiC flat for a 26s data acquisition.

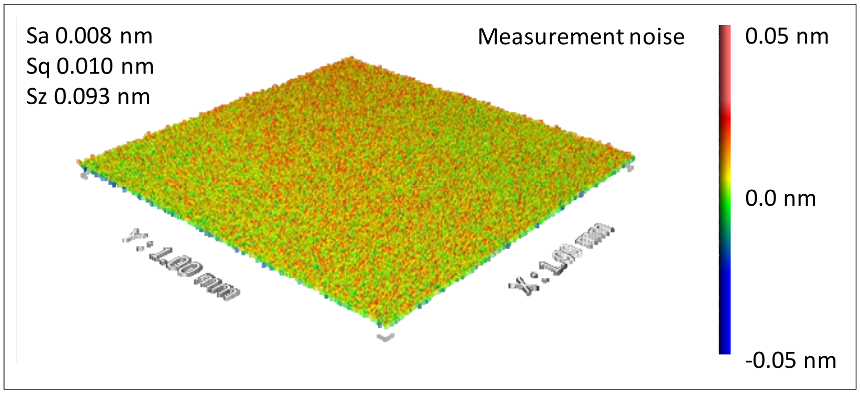

Figure 5: Difference between two successive individual measurements of a SiC flat with a 26s data acquisition. The noise is essentially random on the spatial scale of individual pixels.

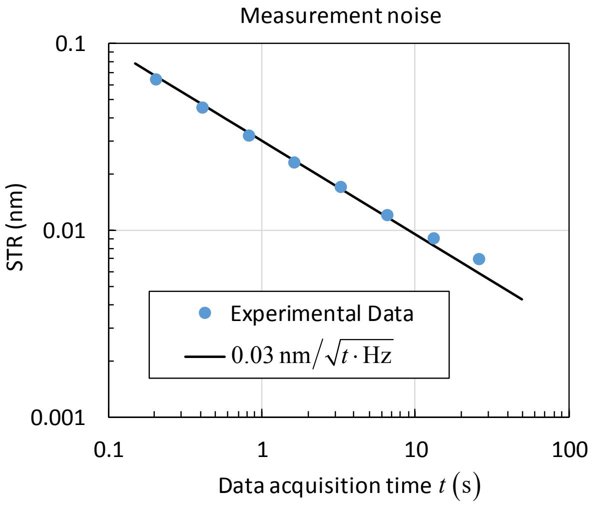

Figure 6: Improvement in noise level with increased data acquisition time in a quiet environment. The STR is the experimentally-determined measurement noise. The object surface is a polished SiC object aligned to minimize tip and tilt.

6. MEASUREMENTS OF ROUGH PARTS

The benefits of low noise extend to surfaces that are far from smooth, particularly if the ability to capture data become limited by signal to noise. Improvements in signal-to-noise using oversampling methods, low-noise cameras and stable platforms have extended the range of application to applications where the surface structure was previously considered beyond the reach of interference microscopy [34]. Figure 7 illustrates the results of a measurement using coherence scanning interferometry (CSI) on an additive manufacturing part having steep slopes and highly variable optical signal strength [5, 35]. Low instrument noise allows for detection and evaluation of weak interference signals that would otherwise be lost or indiscernible because of random instrument noise.

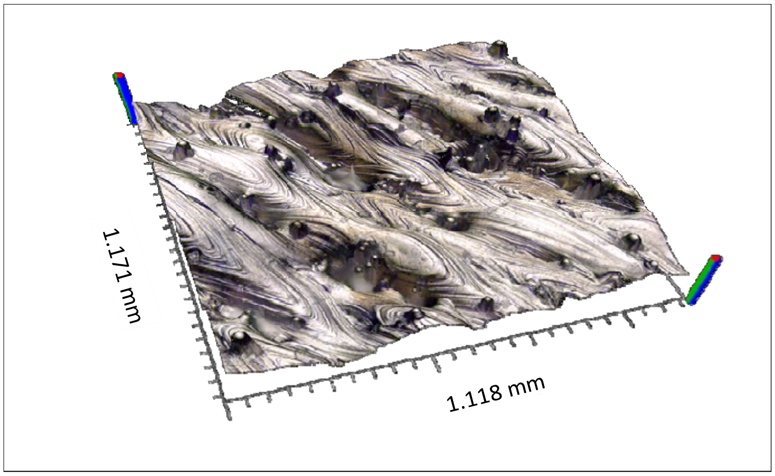

Figure 7: True color surface topography measurement for a Ti-6Al-4V laser powder bed fusion sample measured with a CSI microscope [35]. The measurement represents a 4×4 laterally-stitched 3D image for a 50× objective lens (NA=0.55). The height range is 150 µm.

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 [36, 37]. This consideration reveals a residual ambiguity in the definition of noise: We consider instrument noise to be random from pixel to pixel, whereas the difference between successive measurements on complex surface structures very often has a large correlation length across the field of view, resulting from slope errors or vibrations that vary from one acquisition to the next. Consequently, meaningful statements of noise are closely tied to the specifics of the measurement task [22]. 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 (GR&R) performed on the part of interest close to the actual conditions of measurement [38].

7. SUMMARY AND ACKNOWLEDGEMENTS

Here we have proposed a definition of measurement noise in areal surface topography measurement that builds upon established usage in other fields of dimensional sensing. A key conclusion is that a 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.

The Authors gratefully acknowledge Prof. Richard Leach (University of Nottingham) and Prof. Han Haitjema (KU Leuven) for productive discussions and contributions to this work.

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