## **Optics Letters**

## Noise analysis for through-focus scanning optical microscopy

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A systematic noise-analysis study for optimizing data collection and data processing parameters for through-focus scanning optical microscopy (TSOM) is presented. TSOM is a three-dimensional shape metrology method that can achieve sub-nanometer measurement sensitivity by analyzing sets of images acquired through focus using a conventional optical microscope. We show that the best balance between signal-to-noise performance and acquisition time can be achieved by judicious spatial averaging. Correct background-signal subtraction of the imaging system inhomogeneities is also critical, as well as careful alignment of the constituent images in the case of differential TSOM analysis. © 2016 Optical Society of America

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As the use of three-dimensional (3D) components in nanotechnology increases, high throughput, and economical 3D shape analysis and process monitoring of nanoscale objects, are increasingly desirable [1–5] and, at the same time, increasingly challenging [5,6]. It would be further beneficial if this could be done using a widely available, low-cost tool, such as a conventional optical microscope. We and other researchers have shown that this can be achieved using through-focus scanning optical microscopy (TSOM) [6–16]. Furthermore, the same approach can be extended to larger microscale targets making TSOM a valuable 3D metrology method for targets ranging from the nanoscale to the microscale.

Application of TSOM has been demonstrated for several metrology challenges. For this reason TSOM is being increasingly recognized as a viable nanometrology method, as evidenced by being listed in several technology roadmaps and guides [17–19], patent applications [20,21], and science news reports [22,23].

Given the increasing attention, it is important that we systematically address how to optimize the data collection and analysis conditions. Here we present common parameters that affect the noise, and study how these parameters can be practically optimized for reduction of the noise. The parameters under consideration are commonly known, but they are here applied uniquely to TSOM.

A typical TSOM image is a cross section constructed from the four-dimensional (4D) optical data [11] acquired using a conventional optical microscope, as a target is scanned along the focus direction [11,14]. A multimedia figure depicting the method for constructing a TSOM image is presented in [14]. In the TSOM image, the X (horizontal), Y (vertical), and color scale axes represent the spatial position across the target, the focus position, and the optical intensity, respectively. A differential TSOM image (DTI) is produced by subtracting two TSOM images (usually obtained from two similar targets). Thus, the produced DTIs highlight the dimensional differences down to a sub-nanometer scale [6,11]. In addition, the DTI patterns are distinct for different types of parameter changes, but qualitatively similar for different magnitude changes in the same parameter [10,11].

Optical content of a DTI provides valuable information about the 3D shape of the targets being compared. Optical content includes both the pattern created by variations in the optical signal strength and the magnitude of the optical signal itself. One of the ways to quantify the optical signal strength is by using an optical intensity range (OIR) [6], defined as the absolute difference between the maximum and the minimum optical signal strength in a given TSOM image (or DTI) multiplied by 100. If the OIR of a given dimensional difference (between any two targets) is safely above the noise level, then that dimensional difference can be detected with no ambiguity. However, as the magnitude of the dimensional difference decreases, there comes a point where the OIR of the signal generated due to the dimensional difference is similar to or less than that of the OIR of the microscope system noise. Under these circumstances, this dimensional difference cannot be detected with confidence as the signal from the noise dominates the signal from the dimensional difference. This necessitates optimal reduction and determination of the base level of the optical system noise. We perform this exercise in this Letter.

The following method was chosen to quantify the total noise. Generate a DTI using two independently acquired and constructed TSOM images from the same target under the same experimental conditions. If done correctly, this process will subtract the signal from the target and optical signal due the presence of optical and illumination aberrations. The resultant DTI is a representation of the total system noise. It is observed that this noise is usually random in nature. The following parameters (that affect the noise) have been studied here: background signal, smoothing filter span, width of the window of analysis (explained below), camera pixels, focus step height, number of interpolation points, and optical image signal strength.

An isolated Si line (nominally 31 nm linewidth and 70 nm height) on a Si substrate was used as the target. The fabrication of the target is similar to that reported earlier [6,11]. The TSOM data were acquired using a bright-field optical microscope (Zeiss Axio Imager.Z1) in the reflection mode [focus reproducibility =  $\pm 10$  nm, objective magnification =  $50 \times$ , collection numerical aperture (NA) = 0.55, illumination NA = 0.157, illumination wavelength = 520 nm (narrow bandpass filtered LED light source, unpolarized, total focus range of about 25 µm)]. Each analysis requires three throughfocus data sets under the same experimental conditions: two datasets (essentially repeats) from the selected isolated line and one data set from a smooth, clean Si surface. The third dataset (from the smooth Si surface) is required to remove the background signal from the two target datasets. TSOM analysis was done using software developed at NIST. The software performs the following steps to the data. It normalizes each through-focus image with its own mean intensity, as given in [8]; subtracts the through-focus background noise optical image from the target optical image at each focus-height step; selects the through-focus optical images (from the backgroundsubtracted target image) bound by a box [as shown in Fig. 1(a)]; extracts an intensity profile by averaging along the box width "W" [Fig. 1(a)] at each focus height; and constructs TSOM images by stacking the intensity profiles at their respective focus positions, interpolates, and smoothens. The normalization process (first step) eliminates the effect of overall image intensity variations, if present. The two processed TSOM images obtained in this way are then cross-correlated in both horizontal and vertical directions to achieve the best aligned position. They are then subtracted to obtain DTIs.

We have arrived at the following optimized conditions (or processes) for our current experimental setup based on the noise analysis and practical limitations: background signal must be subtracted, box width for analysis  $W = 1 \mu m$ , camera pixels =  $694 \times 520$  (65 nm/pixel), focus step height = 300 nm, interpolated pixel size = 20 nm/pixel, smoothing filter span = 400 nm, and mean optical image signal strength = 100 A.U. (Arbitrary Unit). Of course, some variation in the optimized parameter values is likely, depending on the specific experimental setup, measurement needs, and personal judgment. In the following paragraphs, we study the individual effect of each parameter on the noise by keeping the other parameters fixed. The OIR values provided are averages from five independent measurements. Mean OIR Standard deviations of all the TSOM images and all the DTIs calculated for this Letter are about 1.4% and 9%, respectively.

Background signal removal has a profound effect on the TSOM image noise. In Figs. 1(a) and 1(b), we show optical images at approximately the best focus position for the target and for the smooth Si surface (which serves as the background signal image), respectively. No dramatic change can be observed in the background image subtracted target image [Fig. 1(c)], except for a change in the optical intensity scale. However, a dramatic change can be observed in the TSOM image after performing this operation. Raw TSOM images of the target



**Fig. 1.** Raw optical images of (a) the target; (b) a smooth Si surface, which serves as the background signal; and (c) the background signal-subtracted target. The box shows the area selected for analysis. Raw TSOM images of (d) the target, (e) the background signal, and (f) the background signal-subtracted target. (g) Processed TSOM image. (h) Intensity profiles at the dotted lines shown in (g). (i) Optical and TSOM image planes showing their relative orientations.

[Fig. 1(d)] and the background signal [Fig. 1(e)] show background signal (or microscope noise) as streaks running from top to bottom. These streaks are completely removed in the background signal subtracted raw TSOM image [Fig. 1(f)]. The subsequent image processing steps performed on the raw TSOM image remove pixilation [Fig. 1(g)]. However, they also result in a loss in OIR (i.e., optical signal strength, which is essentially the absolute range of the color scale bar on the right side of the image) from 21.5 to 12.3. However, this process is necessary for a meaningful analysis. Any method that satisfactorily removes pixilation can be adopted. Variations in the optical intensity profiles at the different focus positions [Fig. 1(h)] and relative orientations of the optical image plane with respect to the TSOM image plane [Fig. 1(i)] are provided for better visualization of the TSOM images.

Smoothing the intensity profiles is a critical step for reducing noise. Even though there are several possible smoothing methods, to demonstrate the process, we here apply the moving average method independently both in the horizontal and the vertical directions. The span of the moving average is the variable that needs to be optimized. The span determines the number of points (or pixels) over which the averaging is performed. Initial smoothing was performed at half the nominal span length, first in the horizontal direction, followed by in the vertical direction. In the second step, the same process was repeated at the full span length, completing the smoothing process. Smoothing significantly affects the OIR and also the noise. The TSOM image that is not smoothed shows a high OIR but, at the same time, has excess pixel noise [Fig. 1(f)], which interferes with repeatable analysis. A small span length of 0.1 µm still results in a pixelated TSOM image [Fig. 2(a)], even though the OIR decreases significantly from 21.5 to 14.5. The DTI showing noise has a large OIR of 2.0 [Fig. 2(a')]. A fourfold increase in the span length from 0.1  $\mu$ m to 0.4  $\mu$ m reduces the OIR of the TSOM image by a small amount [from 14.5 to 12.3, Fig. 2(b)], but it significantly reduces the noise OIR from 2.0 to 0.7 [Fig. 2(b')]. A further increase in the span length to 1.0 µm significantly distorts the TSOM image [Fig. 2(c)] and, hence, is over smoothed for most purposes, even though the noise OIR has a further reduced value of 0.26 [Fig. 2(c')]. A summary of these results is plotted in Fig. 2(d). The goal here is to maximize the TSOM image signal strength (i.e., the OIR of the TSOM image) and minimize the noise (i.e., the OIR of the noise DTI), while at the same time minimizing distortion in the TSOM image. We aim to get a noise OIR of less than 1. In this Letter, a span length of 0.4 µm satisfies these conditions and, hence, it was selected as the optimized span length.

It is important to note that in the DTIs [Figs. 2(a')-2(c')] no residual optical signal from the line can be detected. They appear to be dominated by purely noise, indicating that the other parameters selected and cross-correlation performed to obtain the DTIs are well chosen.

We turn now to the effect of box width "W" [as shown in Fig. 1(a)], which is related to the number of profiles that are averaged to get a mean intensity profile. In Fig. 3(a), we plot the effect of box width on the noise OIR. As expected, smaller widths result in higher noise. The plot shows that widths in the range of 0.5–2  $\mu$ m provide a noise OIR of less than 1. From this range we chose 1  $\mu$ m, but it could also be 0.5  $\mu$ m.

The digital monochrome camera used has a native pixel count of  $1040 \times 1388$  (1.44 MP). Under the magnifications used, this results in a scale of 32 nm/pixel in the digital image. Different pixel counts (pixel scale) can be achieved by pixel



**Fig. 2.** (a)–(c) TSOM images and (a')–(c') the DTIs showing noise for spans of 0.1, 0.4, and 1.0  $\mu$ m, respectively. (d) Summary plot showing the effect of moving average span on OIRs of the TSOM images and the noise DTIs as a function of the smoothing filter span. The red double arrow indicates the span selected.



**Fig. 3.** Effect of (a) the box width "W" [Fig. 1(a)] and (b) the camera pixels on the noise OIR. The inset in (b) shows the same data as a function of the pixel scale. The red arrows indicate the selected optimized values.

binning which has two opposing effects. Binning increases signal-to-noise ratio of cameras, but it also reduces image resolution (reduces pixel count). For image analysis, the former is beneficial, but the latter is detrimental. In this Letter, we varied the illumination source intensity to maintain the image signal strength at the same level for the different pixel binning levels selected. In this way, we could study only the effect of pixel count on the noise. Different pixel counts of  $208 \times 276$ (0.057 MP, 161 nm/pixel), 346 × 462 (0.16 MP, 95 nm/ pixel), and 520 × 694 (0.36 MP, 65 nm/pixel) were achieved by pixel binning. A large pixel count of 2080 × 2776 (5.7 MP, 16 nm/pixel) was also obtained by using the CCD sensor's piezo-scanning feature of the camera. The OIR of the noise plotted as a function of the pixel count shows a continuous decrease in the noise OIR with increased pixel count [Fig. 3(b)]. The same data plotted as a function of the pixel scale [inset of Fig. 3(b)] shows a nearly linear decreasing trend in the noise OIR with the decreasing pixel scale. This clearly demonstrates the benefit of using high pixel count in reducing the noise. Based on the less-than-1 noise OIR criteria, we chose the  $520 \times$ 694 pixel count which produces a noise OIR of 0.7. However, if the noise needs to be reduced further, a higher pixel count could be selected (for example, 2080 × 2776 pixels). However, in this case, it would require 16 times more disk storage space compared to  $520 \times 694$  pixel count and has a disadvantage of slower processing of the data. Practical feasibility also needs to be considered in selecting the optimum pixel count.

Interpolation can be used as a means of artificially increasing the pixel count. In the above pixel count study, an interpolated pixel scale (using spline method) of approximately 20 nm/pixel was maintained irrespective of the image pixel count (except for the  $2080 \times 2776$  pixel count, where it was 16 nm/pixel). Here we present the effect of varying interpolated pixel scales for the  $520 \times 694$  pixel count (65 nm/pixel). A plot of the noise OIR as a function of the interpolated pixel scale also shows a decreasing trend in the noise with decreasing interpolated pixel size [Fig. 4(a)]. From this, we chose a 20 nm pixel size [shown by an arrow in Fig. 4(a)]. This results in a smooth TSOM image and a noise OIR much less than 1 [Figs. 2(b) and 2(b')]. Technically, we could choose a 32 nm/pixel scale also, as it results in a noise OIR less than 1. However, a larger interpolated pixel size has an undesirable effect of residual intensity (color pattern) in the DTIs. For example, at 65 nm/pixel scale (no interpolation), a residual color pattern in the DTI can be clearly seen, as highlighted by a circle in Fig. 4(b). This is due to imperfect alignment for cross-correlation that is limited by the



**Fig. 4.** (a) Effect of the interpolated pixel scale on the noise OIR. (b) A DTI showing the residual optical content (highlighted by a circle) due to imperfect cross-correlation as a result of a large scale of 65 nm/pixel.

large pixel size. Any pixel size (either original or interpolated) that produces a residual color pattern should be avoided as much as possible. The interpolation primarily has the benefit of decreasing noise while using images of larger pixel sizes (smaller stored image sizes). However, the reduction in noise is not as good as acquiring images directly at a smaller pixel scale. For example, images acquired directly at 16 nm/pixel scale show a noise OIR of 0.21 [from Fig. 3(b)] while, at the similar interpolated pixel scale, the noise OIR has a value of about 0.65 [from Fig. 4(a)], which is nearly three times the former. At the same time, the interpolation has the benefit of reducing the noise OIR from 1.03 to 0.55 (Fig. 4).

Optical image signal strength also has a strong influence on the noise level. Under a given set of experimental conditions, a combination of illumination source intensity and the camera exposure time determines the image signal strength. Here we varied the camera exposure time to obtain the different image signal strengths. Mean image signal strength was calculated from the set of through-focus images obtained using a smooth Si background surface. The data presented here were collected at a higher source intensity, compared to the other data presented earlier. As shown in Fig. 5(a), noise OIR decreases with increased image signal strength. This suggests that higher image signal strengths are desirable to reduce the noise level.

Similar to pixel scale [Fig. 3(b)], focus-step size shows increased noise with increased step size, as shown in Fig. 5(b). However, unlike pixel scale, the noise tapers out above 1000 nm step size under the current experimental conditions. (These data were collected at a mean Si background image irradiance of 90 A.U.) As far as noise is concerned, any step size



**Fig. 5.** Effect of (a) the image signal strength and (b) the focus-step size on the noise OIR. The inset in (a) shows the same data as a function of the camera exposure time.

results in below 1 noise OIR. However, DTIs appear distorted for larger step sizes and, hence, we chose a step size of 300 nm.

In summary, we have presented the steps we typically use to process through-focus optical data for the TSOM method of analysis. We have studied the effect of several parameters on the noise signal strength (OIR). The parameters can be adjusted to suit individual needs. We usually strive to achieve a noise OIR of less than 1. It is wise to perform the noise test often to monitor the continued integrity of the measurement and analysis process.

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