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The Meaning and Measure of Vertical Resolution in Optical Surface Topography Measurement

Peter J. de Groot

Zygo Corporation, Laurel Brook Road, Middlefield, CT 06455, USA; peterd@zygo.com

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Abstract: Vertical resolution is the most widely quoted and most frequently misunderstood performance specification for equipment that measures surface topography. Here I propose to use internationally standardized terms and definitions for measurement noise and surface topography repeatability as more meaningful quantifiers for measurement performance. A specific example is an interference microscope operating with a 100 Hz, 1 k × 1 k pixel camera, and a sinusoidal phase modulation to convert intensity data to a height map. The measurement noise is found experimentally to be 0.072 nm for a 1 s data acquisition using a surface topography repeatability test, which determines the random height-equivalent noise level for an individual pixel in the areal surface topography map. Under ideal conditions, the measured noise is equivalent to the instrument noise that may be published in a performance specification in place of the more common, but poorly defined, vertical resolution specification.

Keywords: topography; metrology; instruments; standards; interferometry; resolution

1. Introduction

Performance specifications are the starting point for selecting an instrument or technology for areal surface topography measurement. The precise measurement of surface texture requires sensitivity to small differences in surface height z as a function of position in the x-y plane, as illustrated in the topography map of Figure 1.

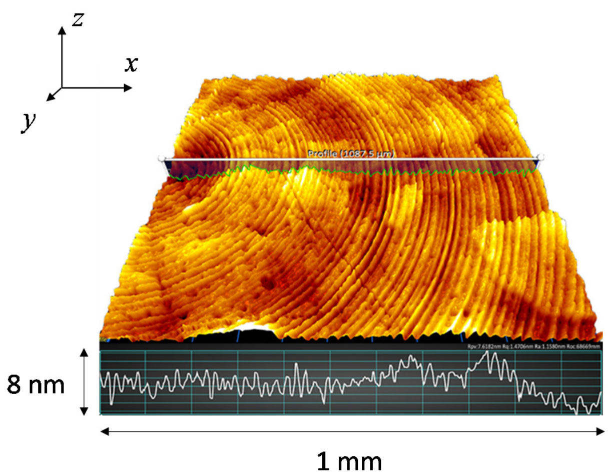

Figure 1. An example of optical surface topography measurement requiring nm-level sensitivity to surface heights.

The most frequently cited parameter related to surface height measurement sensitivity is the *vertical resolution*, qualitatively understood to mean the smallest surface height variation that we can detect. A review of instrument brochures, technical articles and international standards reveals a lack of consensus regarding how to determine the vertical resolution, with the result that, today, its numerical specification is of questionable value [1]. This is in contrast to the steady progress in understanding and quantifying sources of uncertainty in areal surface topography measurement [2–4]. Although there is no formal definition for vertical resolution, instrument makers, researchers and users are asked to specify its value quantitatively. This can lead to confusion and even commercial disputes. It is therefore important to re-evaluate the meaning of vertical resolution and perhaps identify a better way to characterize instrument performance.

2. What Is the Definition of Vertical Resolution?

Firstly, it is worthwhile questioning the use of the word *vertical*. While it is true that often the sample is horizontal and therefore surface heights are vertical, there is obviously no requirement to measure surface heights with respect to the distant horizon. The term appears informally in the context of stylus instruments in ISO 25178-601 [5]; however, a normative definition is absent from the areal texture standards. To correct for this, the most recent draft of ISO 25178-600 notes that the instrument *z*-axis that nominally corresponds to surface heights is sometimes referred to as the vertical axis, regardless of the orientation [6].

Next, in the international vocabulary of metrology (VIM) and in the guide to uncertainty in measurement (GUM), resolution refers to the smallest difference between displayed indications that can be meaningfully distinguished (VIM 4.15 [7]; GUM F.2.2.1 [8]). A traditional interpretation of this guidance in computer-based metrology is that the resolution corresponds to the least significant bit (LSB) of the height-sensor digitization. As an example, a sensor may have an analog-to-digital (A/D) converter that reads 0 or 1 nm for the LSB. If used for profiling surface heights, this sensor would have a vertical resolution of 1 nm—you cannot measure a smaller height difference than this in a single measurement with this particular A/D converter.

The definition of resolution is not as clear with full-field instruments that derive surface height data from a sequence of tens or even hundreds of digitized camera frames, as is the case with confocal and coherence scanning interference microscopes. A decade or two ago, when heights were computed as 16-bit integers, the tradeoff between height range and resolution often led to a minimum measureable height that corresponded to the data storage format. Today, however, computer storage and display capabilities have advanced to the point where these factors are no longer a limit in distinguishing surface heights. As an example, ZYGO Mx™ software uses 64-bit, double-precision internal representation, with an LSB of one-billionth of a nanometer (10^{-9} nm). It is unlikely that such a value would be understood and accepted as useful information on a specification sheet. The conclusion is that currently there is no standardized definition of vertical resolution in optical surface topography measurement.

3. Possible Interpretations

Given the ambiguity in its meaning, it is not surprising that there is a diversity of interpretations of vertical resolution. This leads to a wide discrepancy in the quoted values for related specifications, by as much as three orders of magnitude, for instruments that in many cases have similar abilities to detect small variations in surface texture. Table 1 is a sampling of typical published specifications [4]. The range in quantitative values is more a reflection of the divergence in understanding of what is meant by vertical resolution than actual differences in performance. In some cases, the specification corresponds to the computer data representation, as described in the previous paragraph. In other cases, the specification is the standard deviation of the topography RMS (root mean square) or S_q parameter, which, in the limit of a perfectly featureless object surface, is simply the repeatability of the measurement noise level.

Table 1. Published specifications related to the concept of vertical resolution for a selection of commercially manufactured 3D interference microscopes.

Instrument	Specification	Value (nm)
A	Height resolution	0.001
B	Repeatability of surface RMS (Z)	0.003
C	RMS repeatability (RMSσ)	<0.01
D	Vertical resolution	0.01
E	RMS repeatability of surface accuracy	0.01
F	RMS repeatability	<0.02
G	Noise floor	0.05
H	Vertical resolution	<0.1
I	Vertical resolution	0.1
J	RMS repeatability	0.3
K	Vertical resolution	1

There is a temptation to interpret vertical resolution as the z-axis equivalent of *lateral* resolution, which ISO documents define as the smallest distance between two surface features in the x-y plane for which the features are clearly distinguishable [6,9]. For optical instruments, an influence factor for lateral resolution is the diffraction limit, while for stylus tools it is the radius of the stylus tip. Can we apply this concept to surface heights in the z direction?

The analogy between lateral and *axial* resolution has meaning for optical coherence tomography (OCT), where the axial resolution quantifies the ability to separate scattering centers along a common line of sight (that is, within a single axial scan, equivalent to a single pixel). In OCT, this is a fundamental performance parameter that does not improve with averaging, related to spectral bandwidth and focus depth [10]. In contrast to the nanometer values listed in Table 1, axial resolution of less than a micron is considered to be exceptionally good [11]. The comparable specification for surface structures is the minimum transparent film thickness for which there are clearly separable confocal or interferometric height signals [12,13].

Vertical resolution usually refers to the ability to measure the difference height of widely separated surface features in the x-y plane of an opaque object. In this case, the analogy between lateral and vertical no longer applies. The smallest detectable difference in z for widely separated points on the two plateaus of a step height specimen is not limited by any fundamental principle other than random noise. Indeed, it can easily reach the picometer range, with sufficient optical power, lateral smoothing and measurement time.

4. Instrument Noise

From the observations above, it would appear prudent to avoid quoting the vertical resolution of instrument, except as a qualitative idea. This leaves us without a performance parameter related to the minimum detectable height difference. A reasonable alternative is to explicitly quantify the measurement noise—an idea supported by established norms (VIM 4.14 [7]). For the purpose of specifying instrument performance, ISO 25178 documents recognize instrument noise as the internal noise added to the output signal by the metrology system when it is placed in an ideal environment with minimal disturbances [6,9].

A basic test for noise in areal surface topography maps consists of repeated measurements on a polished, flat part. The surface topography repeatability (STR) tells us how close we can expect the indicated height value for a specific sample point (or camera pixel) to repeat if we measure it over and over again without changing the conditions of measurement [9]. The value is a standard deviation or noise-equivalent S_q, and is readily computed from statistics over a full image of surface points.

A simple STR test is to measure a smooth, flat part twice, subtract the difference of the two resulting topography maps, and calculate the standard deviation S_q of this difference map [6,9,14]. The STR, denoted here as N_M, is

$$N_M = S_q/\sqrt{2} \tag{1}$$

Several methods use multiple measurements to provide a robust estimate of STR [9,15,16].

Common practice in areal measurement specifications for decades has been to quote a vertical resolution or its equivalent without any indication of how long it would take to achieve it. This is contrary to good engineering practice in specifying sensor noise [17,18]. Excluding the measurement time in a specification can lead to expectations that do not correspond to realistic instrument use. Conversely, once we have a noise level expressed with respect to a time bandwidth, we can often adjust the data acquisition time or number of averages to reach a desired measurement precision. To illustrate the importance of including data acquisition time in an STR evaluation, Figure 2 shows the use of time averaging with sinusoidal phase shifting interferometry [19]. A 100 Hz, 1024 × 1024 pixel camera allows for five averages per second, resulting in a measurement noise level of 0.072 nm/$\sqrt{\text{Hz}}$. Another approach to reducing noise is to more densely sample the signal, which can trade a longer acquisition time for lower noise levels without averaging individual measurements [20].

For instruments that scan over an adjustable range of surface heights, the data acquisition rate is not easily expressed as a time bandwidth in Hz. For these systems, a meaningful expression of STR would be a dimensional value together with a height-scanning rate and the corresponding camera format, as in STR = 0.1 nm at 10 μm/s for 1 k × 1 k pixels.

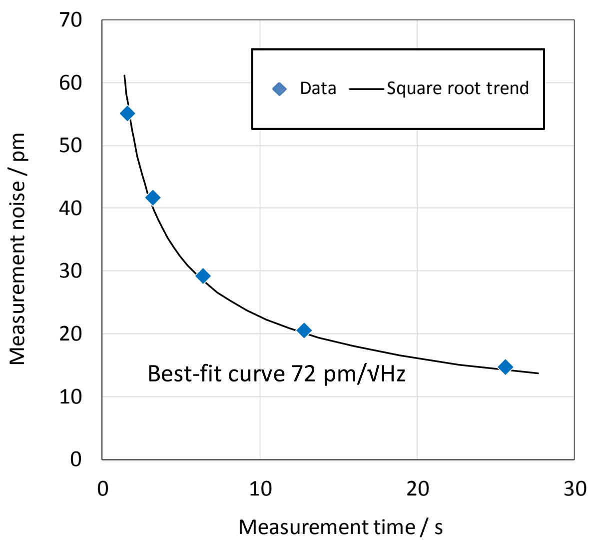

Figure 2. Experimental demonstration of the reduction of measurement noise as a function of data acquisition time for the ZYGO Nexview™ 3D interference microscope.

Another important factor in evaluating the STR as a measure of performance relates to spatial filtering. The application of a denoising or high spatial frequency S filter can improve the STR at the expense of reduced lateral sampling. In some cases, pixel averaging is part of the normal or default operation of the instrument, while in other cases, it may be mandated by a surface texture analysis procedure. In all cases, it is important to document or record the spatial filtering so that its effects are understood.

5. A Useful Specification

Based on the previous paragraphs, one way to address the ambiguity in the meaning and measure of vertical resolution would be to redefine it in terms of the ISO 25178 definition of instrument noise, perhaps with a scaling factor [21,22]. This is a good solution, but there are obstacles to its general acceptance. There are already many different interpretations of vertical resolution, such as the digital data representation, that are not directly tied to random instrument noise. The task would be to convince instrument makers to accept the new definition, even when it results in a commercial disadvantage with respect to quoted specifications from competitors who use a more generous interpretation of the same term. This reality could place early adopters in a disadvantageous position for years until the new definition is fully standardized by the ISO and accepted by the user community.

Some specification sheets have begun using the STR directly, thereby simultaneously providing a quantitative performance value while defining a test procedure to validate it [4,23]. If performed under ideal conditions, this STR specification corresponds directly to the ISO-defined instrument noise, which is another term that can be used in a specification sheet without ambiguity. Both STR and instrument noise appear in published ISO standards as well as in additional draft standards, so this solution can be implemented immediately [6,24].

6. Conclusions

The thesis of this paper is that we should avoid using the term *vertical resolution* as a performance specification for areal surface topography instruments, unless it is clearly announced on the specification sheet that it is synonymous with or scaled to an ISO-defined term such as instrument noise or STR. An alternative is to use instrument noise or STR directly, to avoid confusion. In all cases, any quantitative performance statement related to noise in the surface height measurement should be accompanied by the data acquisition rate or bandwidth, the number of independent 3D image points, and any implicit filtering or post-processing that alters the effective lateral sampling.

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Conflicts of Interest: The authors declare no conflict of interest.

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