The meaning and measure of vertical resolution in surface metrology

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Abstract:

"Vertical resolution" is the most widely quoted and most frequently misunderstood performance specification for surface topography metrology equipment. Commercial pressures compel manufacturers to provide an attractive numerical value for this parameter, even though the term does not have a standardized meaning. A proposed solution is to use internationally-recognized definitions for "instrument noise," "precision" or "surface topography repeatability," and to provide detailed conditions of measurement to facilitate direct verification of the specification.

Keywords: *topography, metrology, instruments, standards, interferometry*

1. Introduction

Performance specifications are the starting point for selecting an instrument or technology for areal surface topography measurement. Perhaps the most frequently cited parameter is the "vertical resolution," qualitatively understood to mean the smallest surface height variation that we can detect, for example, in the topography map shown in Fig. 1. However, a review of instrument brochures, technical articles and international standards does not reveal a consensus regarding the meaning of vertical resolution, with the result that today, its numerical specification is of questionable value [1]. This reality notwithstanding, instrument makers, researchers and users are asked to specify the vertical resolution quantitatively. This can lead to confusion, disappointment, and commercial disputes. It is therefore important to re-evaluate the use of the term "vertical resolution," and identify a better way to characterize instrument performance.

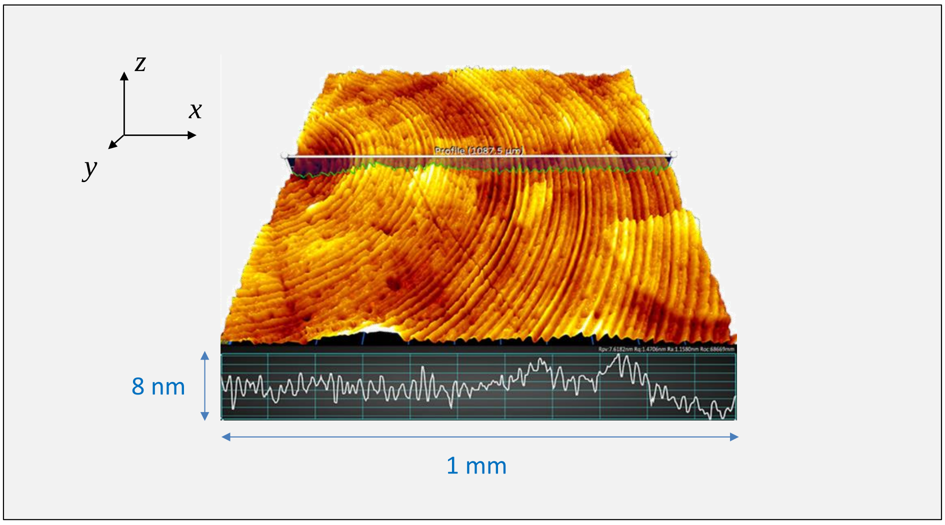

Fig. 1. The precise measurement of surface texture requires that we be able to detect small differences in surface height z as a function of position in the x-y plane. This is the qualitative definition for the "vertical resolution" frequently appearing on instrument specification sheets.

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 no formal requirement to measure surface heights with respect to the distant horizon. The ISO 25178 standards do not define “vertical” as the direction of surface heights—rather, this is the *z* axis direction, where the *x*-*y* plane contains the coordinates of surface points, as in Fig. 1. The precise measurement of surface texture requires that we be able to detect small differences in surface height *z* as a function of position in the *x*-*y* plane. This is the qualitative definition for the “vertical resolution” frequently appearing on instrument specification sheets.

Next, in standardized metrology vocabulary, “resolution” refers to the smallest difference between displayed indications that can be meaningfully distinguished (VIM 4.15 [2]; GUM F.2.2.1 [3]). One interpretation therefore is that the *z*-axis resolution refers to the number of digits displayed on screen or in a data file, rather than a fundamental limitation of the sensing technology. In many instruments, the only difference between low and high resolution is the digital storage allocation, for example 8 bits or 16 bits. In surface texture measurement, modern storage and display of topography is at a digital resolution that can be orders of magnitude below the noise level of the instrument.

3. Possible interpretations

Because there is no internationally-accepted definition of “vertical resolution” for surface topography measurements, it is not surprising that there is a diversity of interpretations of the term. This leads to a wide discrepancy in the quoted value for vertical resolution, by as much as two orders of magnitude, for instruments that in reality have comparable abilities to evaluate small variations in surface texture. Table 1 is a sampling of typical published values related to vertical resolution [4]. The range in quantitative values reflects the divergence in the understanding of what is meant by vertical resolution, rather than actual differences in instrument performance. For some manufacturers, the resolution is indeed limited by the internal data storage format, as described in the previous paragraph. For others, it is the repeatability of a derived surface parameter such as *Sq*. Some authors use the terms “resolution” and “accuracy” interchangeably, often defending a numerical result by a repeatability test on a step-height feature with an unspecified measurement time.

Table 1. Published specifications related to the concept of vertical resolution for a selection of commercially manufactured 3D interference microscopes. Table reproduced from Ref. [4].

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

Searching through the ISO specification standards, we find that the definition for *lateral* resolution is the smallest distance between two surface features in the *x*-*y* plane for which the features are clearly distinguishable [5, 6]. For optical instruments, an influence factor is the diffraction limit, while for stylus tools it is the width of the stylus tip. Can we perhaps borrow this idea, and apply it to surface heights in the *z* direction?

The analogy between lateral and *z*-axis resolution has meaning for optical coherence tomography (OCT), where the 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, related to spectral bandwidth and focus depth, that does not improve with averaging [7]. In the context of surface structures, the comparable specification would be the minimum transparent film thickness for which there are separable confocal or interferometric height signals [8].

Unfortunately, if we are considering widely-separated surface features in the *x*-*y* plane, the analogy between "lateral" and "vertical resolution" 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 the term "vertical resolution" entirely, except as a qualitative concept. This leaves us without a performance parameter related to the minimum detectable height difference. A reasonable alternative is to quantify the measurement noise with a specified time and spatial bandwidth—an idea supported by established norms (VIM 4.14 [2]). 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 [5, 6]. A basic test for instrument noise consists of repeated measurements of surface topography measurement on a polished, flat part [9, 10]. The "surface topography repeatability" 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. The value is a root-mean-square (RMS) or standard deviation, and is readily computed from statistics over a full image of surface points.

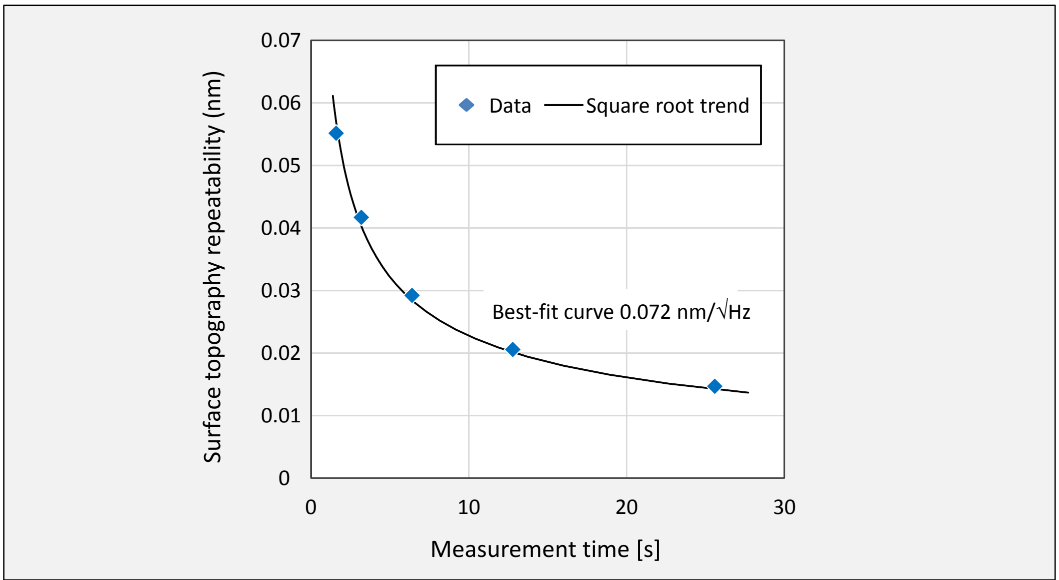

Fig. 2. Experimental demonstration of the reduction of measurement noise as a function of data acquisition time for the ZYGO Nexview™ 3D interference microscope. Figure reproduced from Ref. [11].

Given that repeatability relates to a *random* noise, it can be reduced by taking data over a longer period of time. Fig. 2 illustrates the use of time averaging with a sinusoidal phase shifting interferometry algorithm [11]. A 100 Hz, 1024 × 1024 pixel camera allows for 5 averages per second, resulting in a measurement noise level of 0.072 nm/√Hz. Common practice in areal measurement specifications for decades has been to quote a specification for minimum detectable height differences without an indication of how long it would take to achieve it. This can lead to expectations that may not correspond to the realistic use of the instrument in practical applications. 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.

A similar argument relates to spatial filtering. The requirement is that the specification sheet announce any intrinsic or optional averaging across image points to achieve the quoted specification. 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. But there is always some compromise to the effective lateral sampling, which must be clear from the specification.

5. A useful specification

Some specification sheets have begun to use the measured surface topography repeatability directly as a specification, thereby simultaneously providing a quantitative performance value while defining the test employed to demonstrate it. The specification includes footnotes to describe the measurement conditions [12, 13].

Another approach is to bend to tradition and quote a "vertical resolution," but define it as the DIN or ISO definition of instrument noise, perhaps with a scaling factor, as proposed for the *Faires Datenblatt* [14]. This is a reasonable approach, as long as the specification includes the measurement bandwidth and filtering, together with a clear explanation of how the resolution relates to noise.

My own personal view is that we should avoid using the term "vertical resolution" entirely, as it has a confusing history. Even if some of us were to agree that it should be linked to instrument noise, there is already widespread use of "vertical resolution" based on other interpretations, often leading to impressively small numbers driven by commercial and academic competition. Better is to use "surface topography repeatability" or "instrument noise" directly. If we *must* have a synonymous term, I would propose for discussion the introduction of "measurement precision," since this is a positive-sounding term and is defensible based on established metrology vocabulary (VIM 2.15 [2]).

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