Qualification of a Coherence Scanning Interferometer for Calibration of Step Height Standards

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Learning Objectives:

By the end of the presentation, the audience will learn some of the characteristics of surfaces, and some details of the ASME and ISO standards related to surfaces. The audience will learn the principles of stylus-based and scanning interferometric measurements of surfaces. The audience will learn the traceability path for surface texture measurements using interferometry. The audience will see the motivation for calibrating step height standards using coherence scanning interferometry, and some of the strengths and weaknesses of this measurement method.

Abstract

Measurement of surface topography has traditionally been performed using stylus-based instruments. The standards used in calibrating surface roughness are typically step height standards, used to calibrate the vertical scale of a surface topography instrument, and an engineered surface, such as a sinusoid or triangular profile, to verify the instrument and the mathematical algorithms used to calculate surface characteristics parameters. Documentary standards used in describing surface topography include ASME B46.1:2009, ISO 4287:1997; ISO 13565-1:1996; and ISO 25178 (2011). This paper presents the qualification and use of a white light interferometer based instrument, specifically a coherence scanning interferometer, for calibration of standards used in surface texture and roughness. An analysis of measurement uncertainty in the calibration of step height standards is detailed. Calibration of standard reference materials such as sinusoid profiles or triangular profiles are also discussed.

Introduction

Surface topography is an important characteristic of mechanical products. The surface of a part influences the performance of the part: For example, bearing races require a smooth surface, as a rough surface would cause wear, or would contain asperities that would serve as crack initiators that would reduce fatigue life. The surface finish of a part is an indicator of the machining process: Tool wear can lead to rougher surfaces in machining, and these characteristics can be used to monitor the performance of the manufacturing process[1].[1]

[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the authors,

Surface finish (i.e. surface texture) is called out as a geometric specification, both in the US (ASME/ANSI standards[2],[3]) and internationally (ISO TC 213, "Dimensional and geometrical product specifications and verification"). The description of surface texture is detailed in ASME B46.1:2009[4], or similarly in ISO 4287[5] and ISO 25178[6][2]. A list of standards is provided in Table 1.

Table 1. List of published standards (not including standards "in development"). This is not a comprehensive list, but includes most documentary standards relating to surface metrology as of April 2012.

Standard number	Short title (GPS→Geometrical Product Specifications)
ASME Y14.36M:1996	Surface texture symbols
ASME Y14.5:2009	Dimensioning and Tolerancing
ASME B46.1:2009	Surface Texture (Surface Roughness, Waviness, and Lay)
ISO 1302:2002	GPS-Surface texture-Indication of texture in product documentation
ISO 4287:1997	GPS-Surface texture-Profile method-terms, definitions…
ISO 4288:1996	GPS-Surface texture-Profile method-Rules and procedures
ISO 5436-1:2000	GPS-Surface texture-Profile method-measurement stds
ISO 5436-2:2000	GPS-Surface texture-Profile method-software
ISO 8785:1998	GPS-Surface imperfections-terms, definitions …
ISO 12085:1996	GPS-Surface texture-Profile method-Motif parameters
ISO 12179:2000	GPS-Surface texture-Profile method-Calibration of stylus instruments
ISO 13565-1:1996	GPS-Surface texture-Profile method-stratified functional-filtering
ISO 13565-2:1996	GPS-Surface texture-Profile method-stratified functional-height ratio
ISO 13565-3:1996	GPS-Surface texture-Profile method-stratified functional-material prob
ISO 16610-1:2006	GPS-Filtration-overview
ISO 16610-20:2006	GPS-Filtration-linear filters-basic concepts
ISO 16610-21:2011	GPS-Filtration-linear filters-Gaussian filters
ISO 16610-22:2006	GPS-Filtration-linear filters-Spline filters
ISO 16610-28:2010	GPS-Filtration-linear filters-end effects
ISO 16610-30:2009	GPS-Filtration-Robust profile-basic concepts
ISO 16610-31:2010	GPS-Filtration-Robust profile-Gaussian regression
ISO 16610-32:2009	GPS-Filtration-Robust profile-Spline
ISO 16610-40:2006	GPS-Filtration-Morphological-basic concepts
ISO 16610-41:2006	GPS-Filtration-Morphological-Disk and horizontal line segment filters
ISO 16610-49:2006	GPS-Filtration-Morphological-Scale space techniques
ISO 25178-2:2012	GPS-Surface texture-Areal-Terms, definitions
ISO 25178-6:2010	GPS-Surface texture-Areal-Classification of methods
ISO 25178-601:2010	GPS-Surface texture-Areal-characterisitics of stylus instruments
ISO 25178-602:2010	GPS-Surface texture-Areal-characteristics of confocal chromatic probe
ISO 25178-701:2010	GPS-Surface texture-Areal-Calibration and standards for stylus instr.

Sandia National Laboratories, or NCSL International, nor does it imply that the materials or equipment identified are the only or best available for the purpose.

[2] The ISO 25178 family of standards include a number of published standards, such as ISO 25178-6:2010; ISO 25178-601:2010; etc., and a number of standards still under development.

Surface topography is a 3-D characteristic. Full description of topography of a surface is impractical, so the ASME and ISO surface texture standards provide parameters that describe the measurement of the surface, as illustrated in Figure 1.

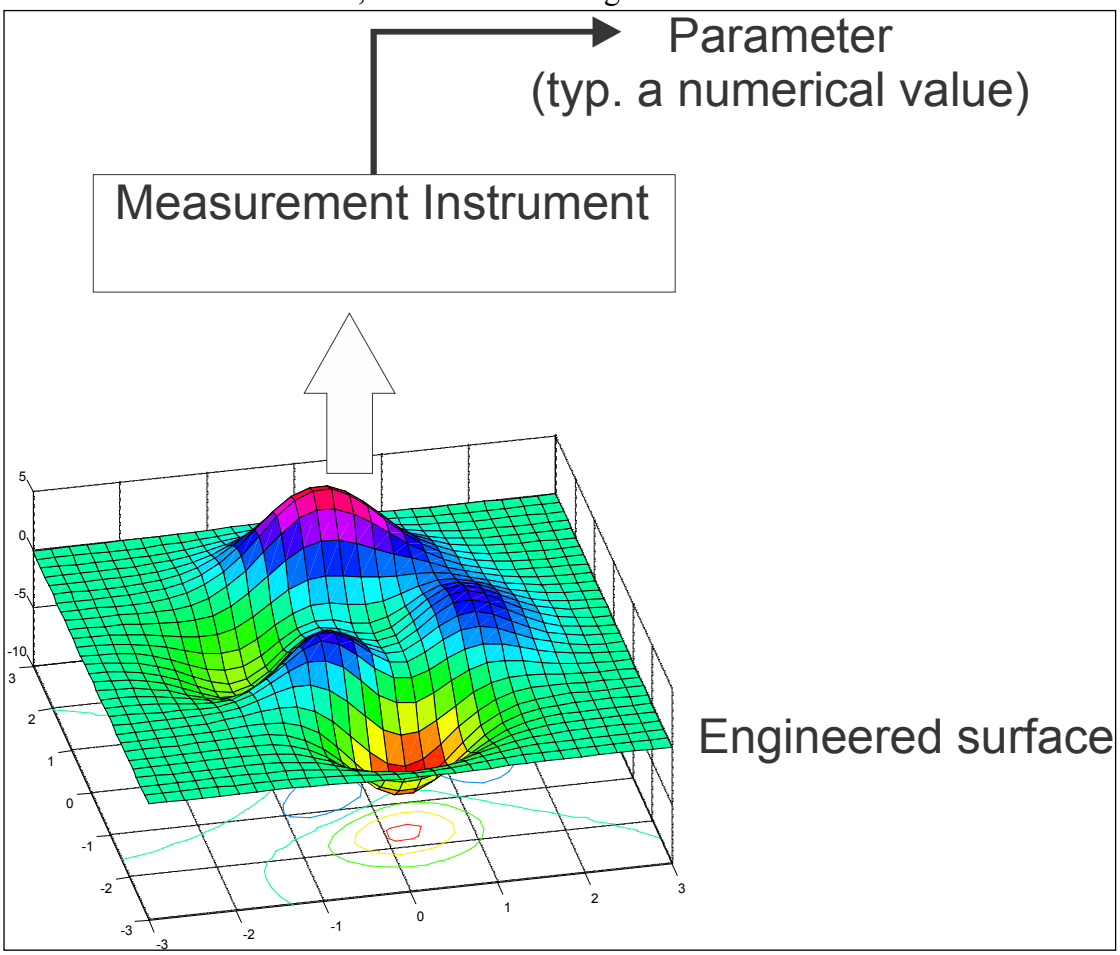

Figure 1. A measurement instrument measures geometric properties of a surface, and outputs a numerical parameter as the measurement result.

The measurement instrument measures dimensional characteristics of the topography. The instrument combines multiple values in mathematical operations (whether the operations are performed by a computer, or by electronics, or by mechanical design, or some combinations), and outputs the result of the operations.

Texture of the surface has several characteristics. A representative surface is shown in Figure 2. This surface illustration shows a texture direction (lay). Normal to the texture direction, a profile of the surface has been plotted underneath the surface. Below the profile, the "waviness" of the surface (long term undulations) is shown, and below the waviness, the roughness profile is shown.

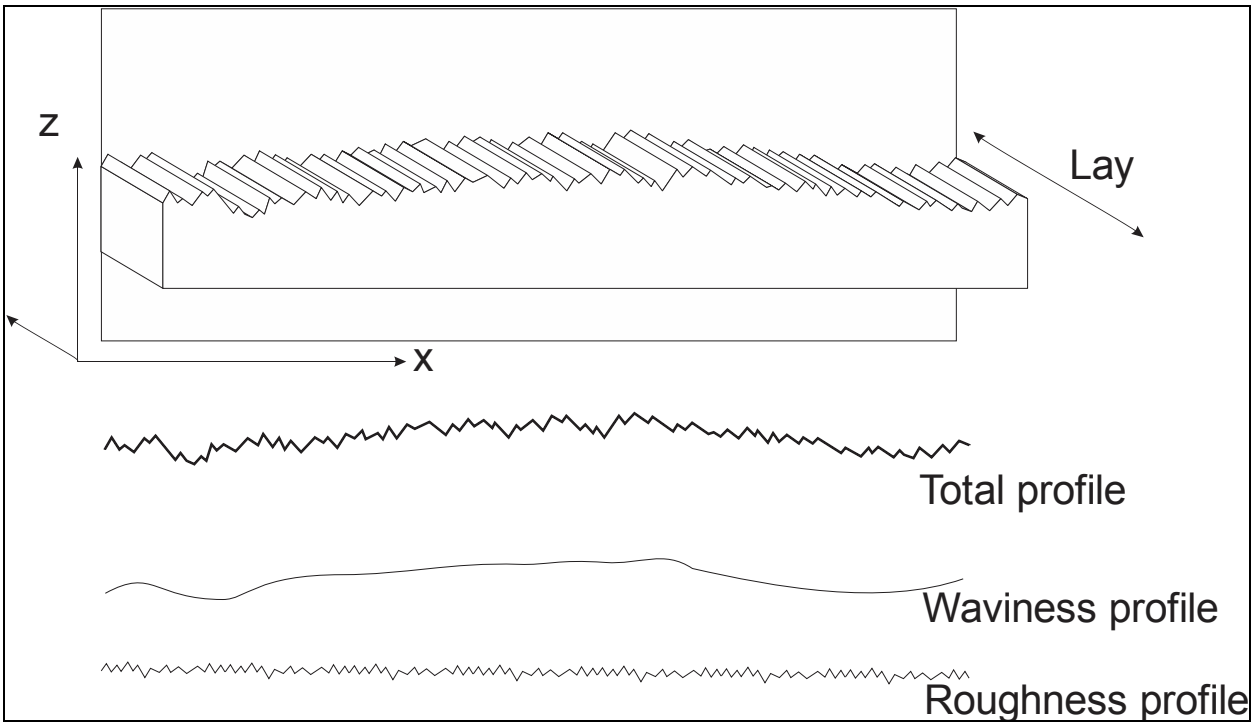

Figure 2. Surface texture, indicating lay on the surface, and a cross-section of the surface showing profile, waviness, and roughness. Adapted from ASME B46.1:2009

Drawing parameters for texture typically specify a single scalar value to represent roughness. A typical mechanical drawing might indicate $\sqrt[1.6]{0.8}$, which would indicate a specification for the maximum acceptable value for a roughness parameter. (In this specific example, R_a=1.6 μm, cutoff length 0.8 mm. These parameters will be described in more detail later.). Roughness parameters are typically measured using profilometers. Some profilometers calculate the parameter from the measurement, and only report the measured parameter. Other profilometers will also plot a profile plot.

A typical roughness profile plot has different scales for the vertical axis and the horizontal axis: the vertical axis is greatly magnified compared to the horizontal axis. This can visually mislead the end user. Figure 3 shows a representative roughness profile plot. Note that the horizontal scale spans 0.026 inch (0.66 mm), while the vertical scale spans 0.00038 inch (0.0097 mm). If the profile plot were done at a 1:1 aspect ratio, the vertical scale would be the thickness of the line around the figure border. It is important to remember that surface profile plots almost always show the vertical scale with several orders of magnitude greater magnification than the horizontal scales; therefore, angles and slopes are visually distorted.

The earliest surface texture (also called surface roughness and surface finish) measurement instruments were based on tracing a stylus over a surface, and plotting the displacement of the stylus (Gustav Schmaltz, about 1929[7]), and later, amplifying the displacement electronically and processing the results (Ernest Abbott, about 1933[1]). Vladimir Linnik developed a microscope objective interferometer (microinterferometer) for measuring surface finish in the

early 1930s[8]. However, most commercial surface texture and surface roughness instruments until the 1980s were based on stylus instruments. Non-contact instruments, specifically, the type commonly known as "white light interferometers," have proliferated over the past 3 decades[9].

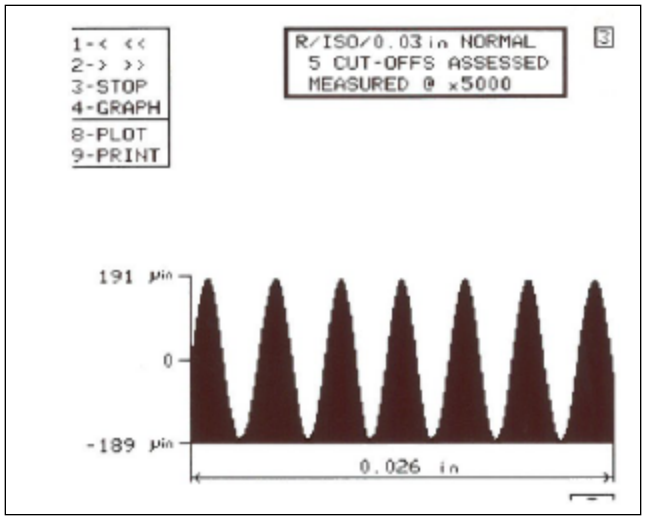

Figure 3. Surface profile plot from a Taylor-Hobson Talysurf 6 surface texture measuring system.

Optical instruments for measuring surface topography can be roughly classified into three types of devices:

1. Instruments which use an optical stylus, for example, a laser triangulation sensor, a confocal chromatic probe, or a point autofocus sensor for detecting a point on the surface
2. Instruments which capture an areal image by scanning either the optical objective or the sample surface vertically. Focus variations are detected, and the surface topography is generated from the focus of each point in the image.
3. Instruments which capture an areal image by forming interference fringes through the optical system, and scanning either the optical objective or the sample surface vertically. Interferograms are processed to generate surface topography.

For this paper, we will focus on the third type of optical instrument.

Measuring and Computing Surface Parameters

Consider a machined surface, such as illustrated in Figure 2. The topography of the surface generally represents deviations from perfect geometry. This combines irregularities due to the machining process, such as tool marks or grinding marks, irregularities due to manufacturing, such as induced by machine vibration, and irregularities in form due to geometric errors in the machine, such as thermally induced distortion or non-straightness in slideways[10]. Each type of deviation from perfect geometry has characteristic wavelengths. The surface texture parameters typically look at shorter spatial wavelengths (texture wavelengths on the order of mm or shorter). A profile with multiple wavelengths is illustrated in Figure 4.

Prior to analysis, the profiles are filtered. The use of a stylus introduces a mechanical filtering effect. The radius of the stylus prevents the stylus from measuring topography with a wavelength shorter than approximately the diameter of the stylus, as illustrated in Figure 5. In

electronics, filter characteristics are typically described with a frequency response plot, which is a log/log relative magnitude/frequency plot, with the vertical axis plotting the relative magnitude of the output versus the input, and the horizontal axis showing the frequency. The ASME B46.1 standard illustrates the transmission characteristics of the filter using a linear vertical axis (% transmitted) and a logarithmic ***wavelength*** axis—so short wavelengths (high frequencies) are on the left, and long wavelengths (low frequencies) are on the right. Characteristics of the gaussian filter are shown in Figure 6. The important point to remember is that surface roughness filters are bandpass—they block very short spatial wavelengths, and they block very long spatial wavelengths. Typically, two filters are applied to the profile, prior to analysis: These are the λ_s filter, which *removes* wavelengths shorter than λ_s, and the λ_c filter, which *keeps* wavelengths shorter than λ_c.

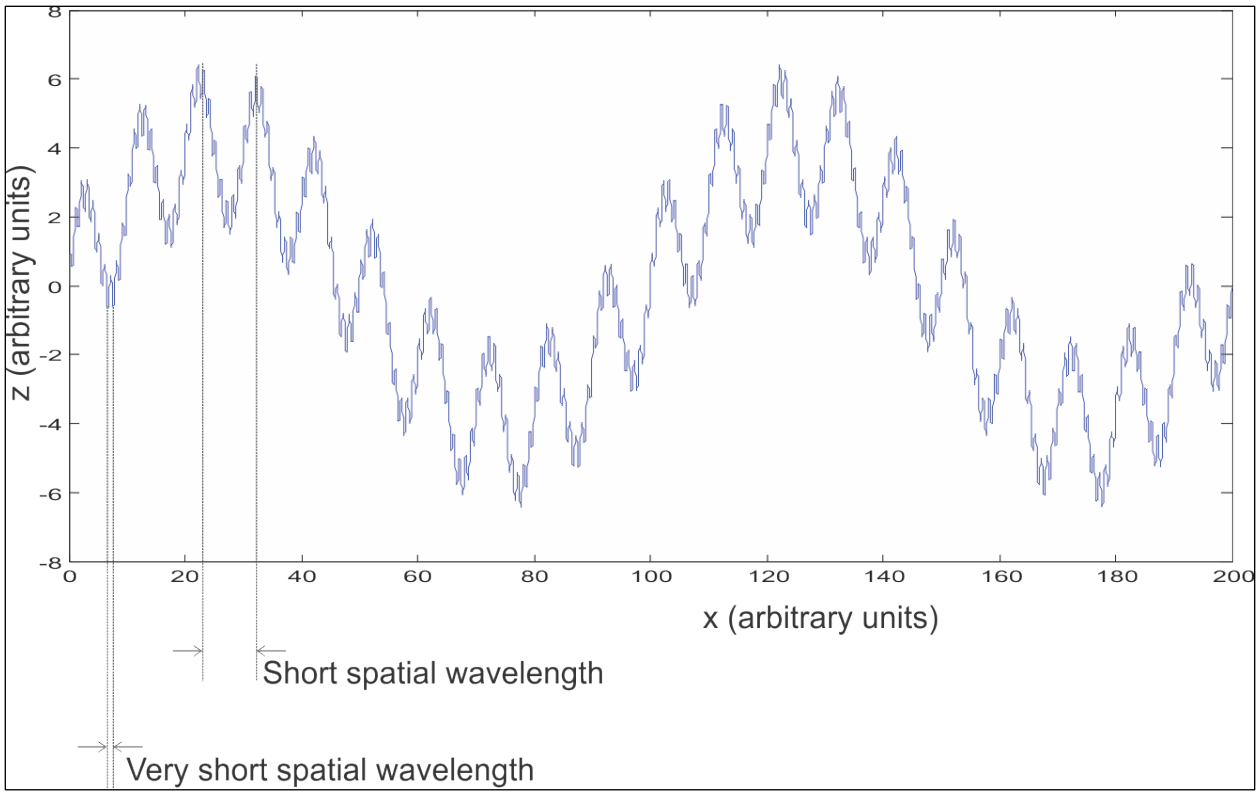

Figure 4. Illustration of a profile with multiple wavelengths. The very short and the short spatial wavelengths are identified. Axes scales are in arbitrary length units. A short spatial wavelength corresponds to a high spatial frequency.

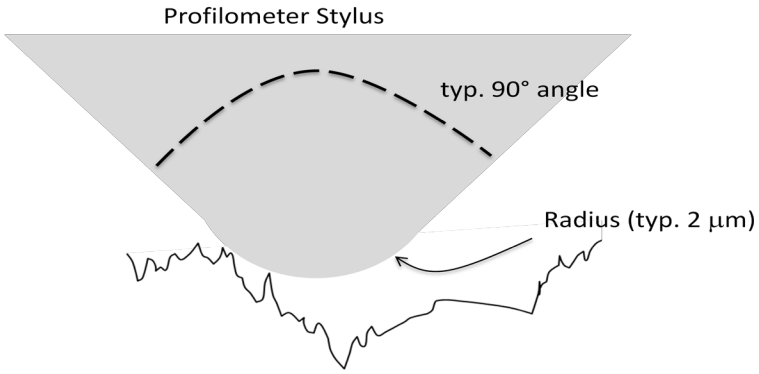

Figure 5. Illustration (not to scale) of a mechanical stylus tracing over a surface. The finite stylus radius of curvature acts like a mechanical filter that removes very short wavelengths. This is typically the λs short wavelength cutoff.

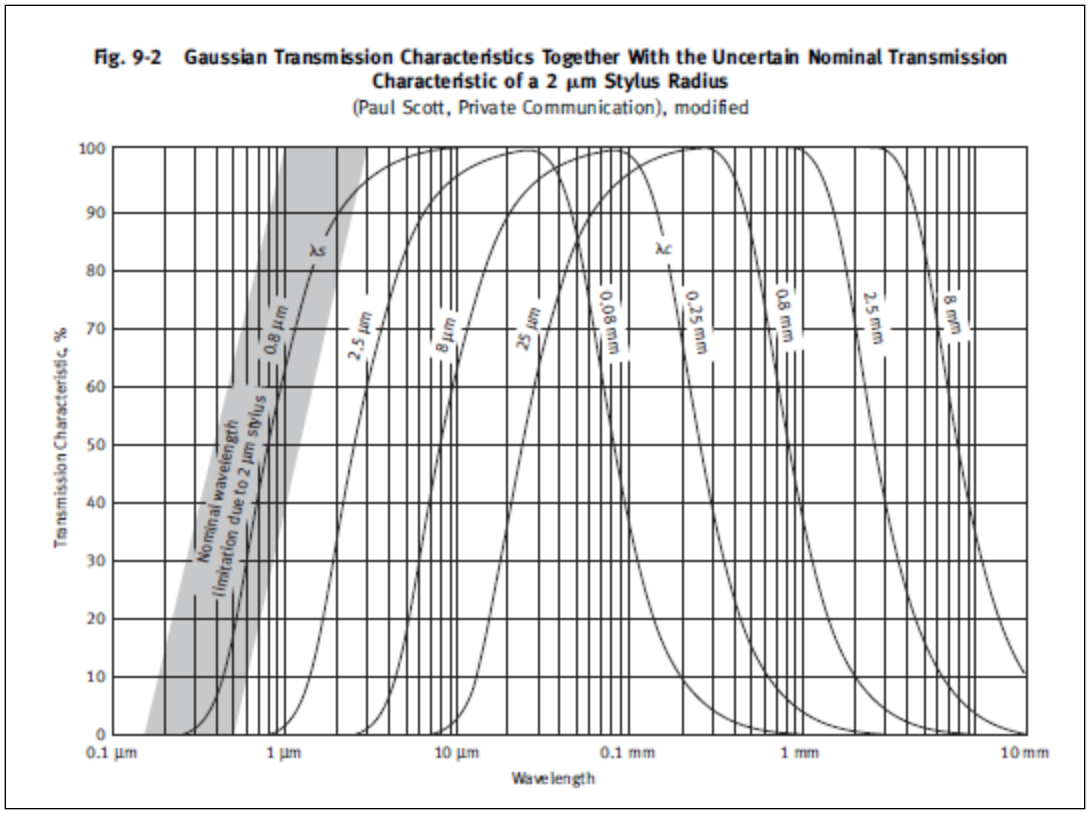

Figure 6. Figure 9-2 reprinted from ASME B46.1:2009, by permission of the American Society of Mechanical Engineers. All rights reserved. Note that the filter characteristics' horizontal axis is in log(wavelength), not log(frequency), and transmission is plotted as a linear percent scale.

Two filters are applied to the profile prior to analysis: These are the λ_s filter, which *removes* wavelengths shorter than λ_s, and the λ_c filter, which *keeps* wavelengths shorter than λ_c. Figure 7 illustrates the application of λ_s and λ_c filters.

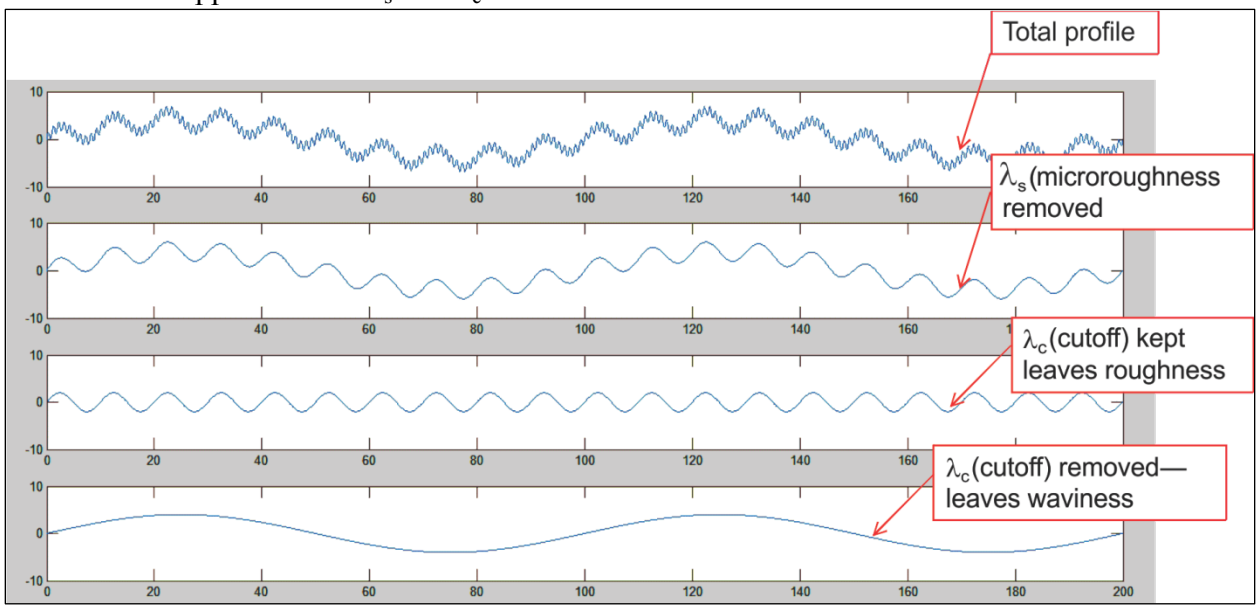

Figure 7. Illustration of the effects of filtering a profile. The total profile is the raw measured profile. A stylus instrument will remove wavelengths shorter than λ_s by mechanical interactions (optical resolution and software would remove λ_s with an optical areal instrument). Software removes wavelengths longer than λ_c, then, the profile is analyzed.

Historically, based on the development of the stylus instrument, stylus electronics, and methods to compute average, "roughness average," or R_a, became one of the most popular methods to measure the surface texture of an engineered (machined) surface. One can express R_a mathematically as:

$$Ra = \frac{1}{L}\int_0^L |z(x)|\,dx \tag{1}$$

Where L is the length over which the R_a parameter is evaluated. The "R" parameters, such as R_a, R_q, R_t, etc. are usually considered 1-dimensional—that is, z is only a function of x. When evaluating areal surfaces, S parameters, such as S_a, S_q, S_t have been defined by ASME and ISO standards. These are analogous to the R parameters, but are based on the areal topography z(x,y). For example, S_a is:

$$S_a = \frac{1}{A}\iint |z(x,y)|\,dy\,dx \tag{2}$$

Where A is the area being evaluated. An areal instrument, since it measures topography z(x,y), is also capable of evaluating 1-dimensional R parameters, in addition to evaluating areal S parameters. Profilometers, which typically only measure z(x), typically have difficulty in measuring z(x,y) and evaluating areal S parameters.

Coherence Scanning Interferometers

A coherence scanning interferometer (CSI) is a type of white light interferometer. It is an areal topography instrument. The working principles are typically based on a Mirau interferometer, with a microscope objective that includes a reference mirror. Figure 8 illustrates the typical coherence scanning interferometer design[11]. In operation, the sample is translated in z relative to the microscope objective (this may be accomplished by moving either the sample or the microscope objective). Because the light source is short coherence, fringes are visible only when the path lengths to the reference mirror and to the surface are nearly equal. The fringes reach maximum intensity when the path lengths are equal. As the sample is translated, the camera captures fringes. Each camera pixel captures an intensity $I_{xy}(z)$. Based on the measured $I_{xy}(z)$ intensities, the fringe peaks are correlated by signal processing in the instrument, and an areal topography map of z(x,y) is generated.

The areal topography map can then be analyzed, and parameters of interest can be extracted. The areal topography map is sent to a software analysis program. Figure 9 shows a typical areal image from a coherence scanning interferometer after the topography map has been generated.

Because a CSI captures the entire areal topography in a single measurement cycle, operation tends to be faster than with a stylus-based instrument (especially if the stylus instrument is used to scan an areal topography). In addition, as a non-contact instrument, the CSI can be used on fragile or soft surfaces. However, the CSI also has some limitations, including:

- Heterogeneous surfaces, that is, surfaces with different materials may give different measurements compared to a contacting instrument, due to both changes in reflectivity and changes in phase upon reflection.
- The image at the camera is a combination of the point spread function from every point at the sample. Diffraction can cause unexpected images, for example, at edges.

- The image at the camera has spatial (lateral) resolution limitations associated with the microscope optics, and slope limitations associated with the objective numerical aperture.

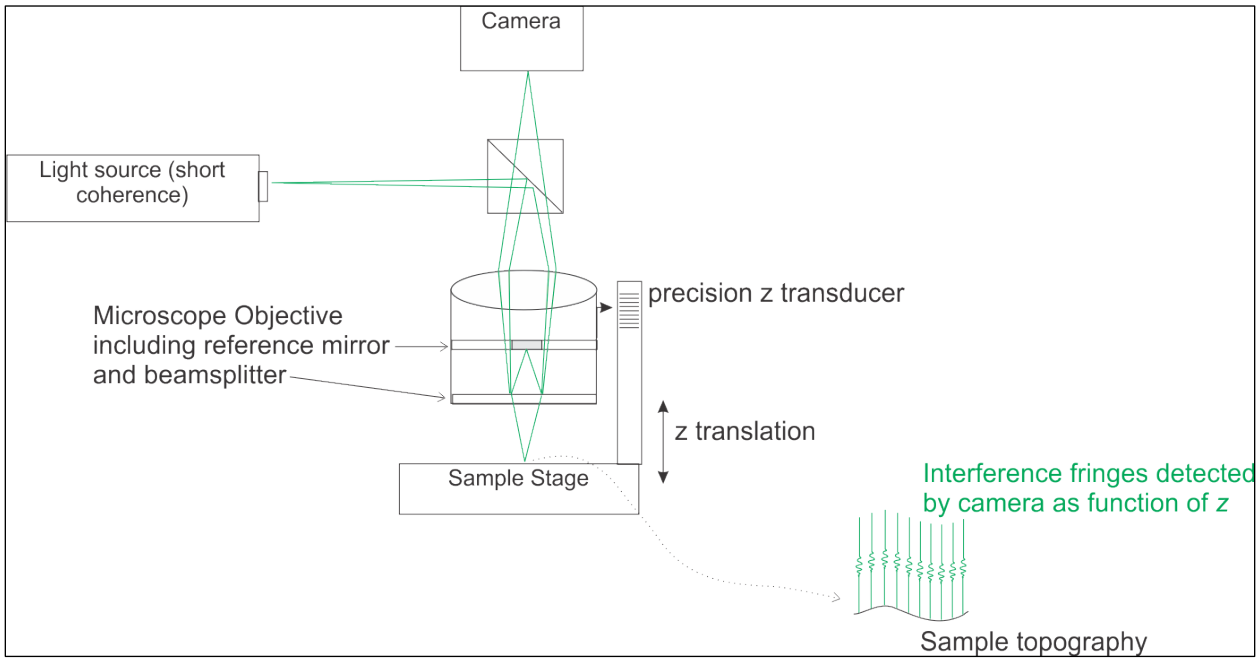

Figure 8. Schematic diagram of a coherence scanning interferometer. The light source illuminates the sample through a microscope objective, which also contains a reference mirror. Interference fringes are formed when the sample topography and the reference mirror have equal path lengths. As the sample stage is scanned vertically with respect to the microscope objectives, an areal map of the topography is formed.

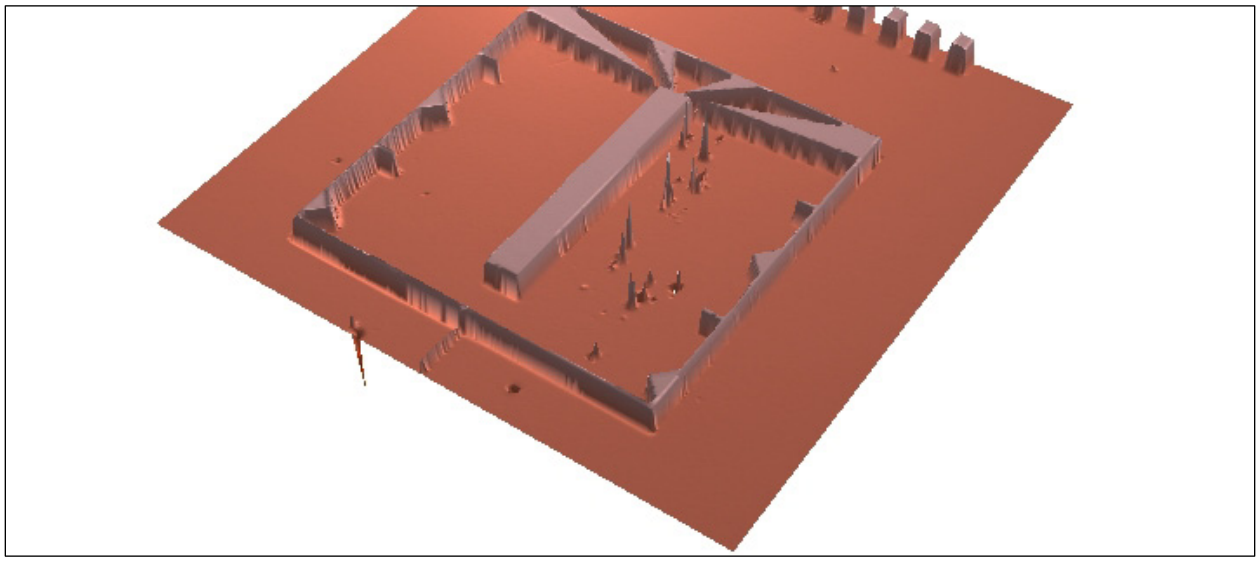

Figure 9. Sample areal image of a retired VLSI 180 nm step height standard. This is measured using a Taylor-Hobson CCI-Lite coherence scanning interferometer, and the topography displayed and analyzed with Talymap Platinum v6.2 software.

Instrument Calibration

The coherence scanning interferometer is a complex instrument, but basically measures a map of z(x,y). The manufacturer's installation and calibration, and end user instrument recalibrations are intended to assure the metrological performance of the instrument. Measurements in the x and y direction are governed by the microscope and imaging optics. The pixels in the instrument camera map to (x,y) locations in the microscope field of view, and this is straightforward to calibrate with a calibrated reticle. Calibration of z measurements is more difficult, as the z measurements are a combination of the software correlation of the fringes, and of the z motion transducer. Manufacturer calibration of the z direction is typically performed using optical flats (to establish the reference z in the field of view, or the reference mirror in the objective) and step height standards to calibrate the z position transducer.

Note that the manufacturer's calibration is only a validation that the instrument performs as desired under specific conditions, and does not ensure valid results under all conditions. The end user must be aware of the limitations of the areal instrument, and take efforts to only use the instrument appropriately (in fact, this is a good general rule for using any instrument!).

Procedure for Calibrating a Step Height Standard and Uncertainty

A step height standard is one of four types of standards[3] commonly used to calibrate surface texture instruments[4]. These are:

A. Depth measurement, or amplification (step height). Typically a positive or negative groove or family of grooves with a well characterized depth.
B. Stylus condition. Typically a set of grooves with different widths, or triangular profile grooves.
C. Parameter calibration. Typically a sine wave profile set of grooves, although other defined periodic geometries, such as triangular or trapezoid, are available.
D. Overall instrument performance. Typically an irregular profile, but with a well-defined lay.

These are known as Type A, Type B, etc. reference specimens. When calibrating a stylus instrument, it is generally recommended to use all four types of reference specimens[12]. The topography of interest of a Type A (step height) is illustrated in Figure 10.

[3] If you are calibrating an instrument that measures surface texture *and* form, a fifth type of standard is also used.

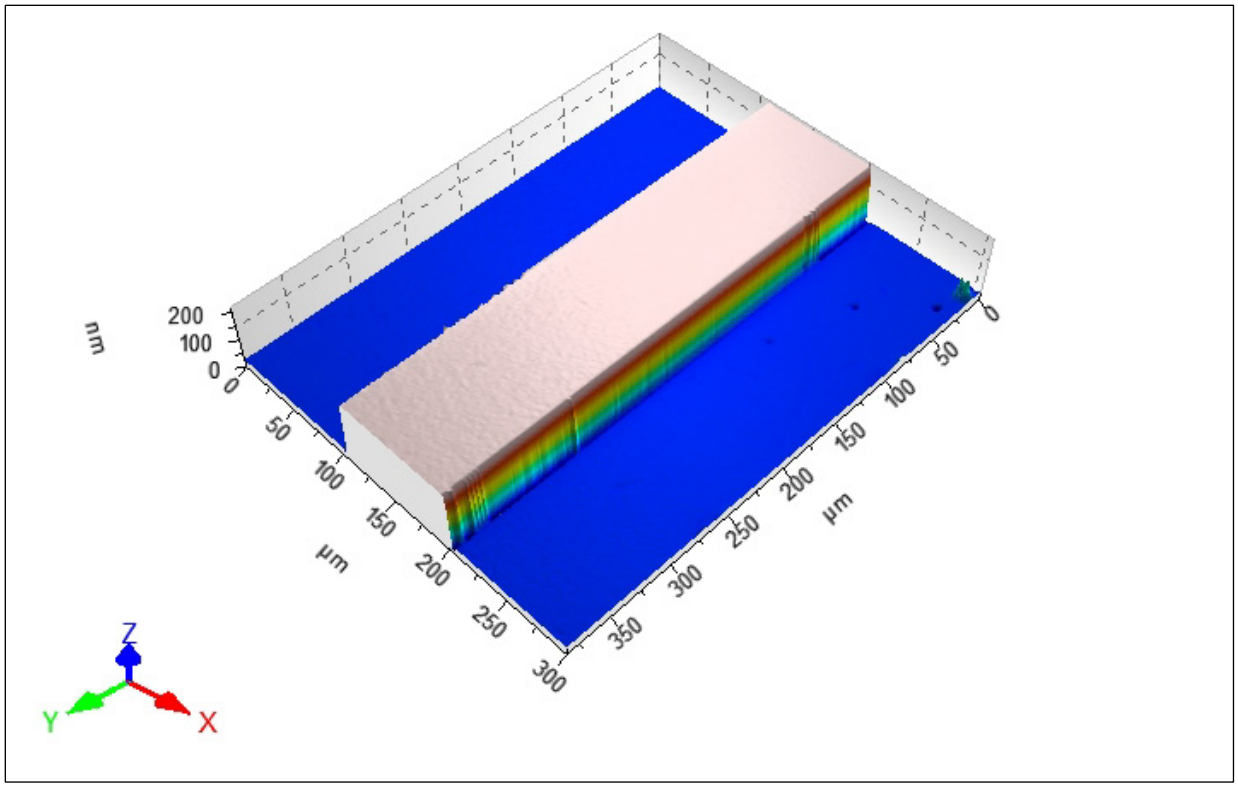

Figure 10. Areal topography of a step height standard. This is a segment of the step height standard illustrated in Figure 9; the calibrated topography is the "z" height.

When measuring roughness (R_a) and step height standards, the components of measurement uncertainty in step heights measurements include[13]:

i. Geometric nonuniformity and surface finish of the step-height master
ii. Variations in the calibration constant due to noise in the instrument, including digitizing and software
iii. Variations in the measured value due to nonlinearity in the instrument transducer
iv. Uncertainty in the average height of the step-height master
v. Uncertainty in the horizontal resolution of the instrument, including stylus effects
vi. Uncertainty in the vertical resolution of the instrument

Components v and vi are only applicable for measurements of R_a.

We will go through the steps in calibrating a customer step height standard (customer unit under test or UUT). We need a calibrated master step height, and we need to verify that the CSI can be used (personnel, procedures, environment, etc.). We would measure the calibrated master step height first, to establish a scale correction factor *SF*:

$$SF = \frac{CV}{MV} \tag{3}$$

Where *CV* is the certified value of the master step, and *MV* is the measured value. We would then put in and measure the UUT. The raw UUT measurement is *m*, and the calibrated UUT value is *y*:

$$y = SF \times m \tag{4}$$

Measurements may be repeated to obtain the statistical evaluations for uncertainty per the ISO GUM[14]. Applying the influence factors to Equation (3), we obtain the standard uncertainty for the scale factor correction as u_{SF}:

$$u_{SF} = \left[\left(\frac{\partial SF}{\partial CV} \cdot u_{CV} \right)^2 + \left(\frac{\partial SF}{\partial MV} \cdot u_{MV} \right)^2 \right]^{1/2} \tag{5}$$

u_{CV} is the standard uncertainty of the master (obtained from the calibration certificate; this is component iv); u_{MV} is the standard uncertainty of the measured value of the master (obtained statistically). When evaluating u_{MV}, you should also include associated geometric uncertainties. This gives you uncertainty components i and ii. Evaluating the derivatives in Equation (5), we get:

$$u_{SF} = \left[\left(\frac{1}{MV} \cdot u_{CV} \right)^2 + \left(\frac{-CV}{MV^2} \cdot u_{MV} \right)^2 \right]^{1/2} \tag{6}$$

When evaluating the influence factors for Equation (4), we obtain:

$$u_y = \left[\left(\frac{\partial y}{\partial SF} \cdot u_{SF} \right)^2 + \left(\frac{\partial y}{\partial m} \cdot u_m \right)^2 \right]^{1/2} \tag{7}$$

Where u_{SF} is the previously evaluated standard uncertainty for the scale factor correction, and u_m is the standard uncertainty for the measurement of the UUT. We also need to include the transducer nonlinearity in evaluating u_m:

$$u_m = \sqrt{s_m + u_z} \tag{8}$$

Where s_m is the result of statistical evaluations of measuring the UUT, and u_z is a type B evaluation of the nonlinearities of the z transducer. Figure 11 shows the deviation of the z transducer response from a straight line over a range of motion of approximately 15 µm.

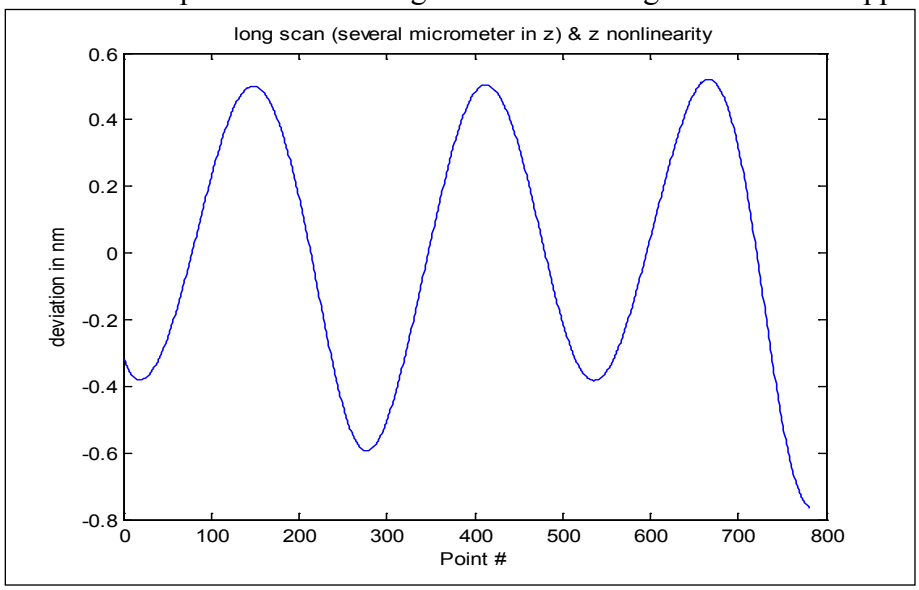

Figure 11. Evaluation of z-transducer linearity over a 15 µm range.. This is done by measuring a flat surface (level), then, tilting the surface, and re-measuring. Tilting the surface is just a straight line change, so the difference from a straight line is due to nonlinearity in the transducer.

Evaluating the derivatives for Equation (7), we get:

$$u_y = \left[\left(m \cdot u_{SF} \right)^2 + \left(SF \cdot u_m \right)^2 \right]^{1/2} \tag{9}$$

The workflow of analyzing step heights in software is very straightforward, and is shown in Figure 12.

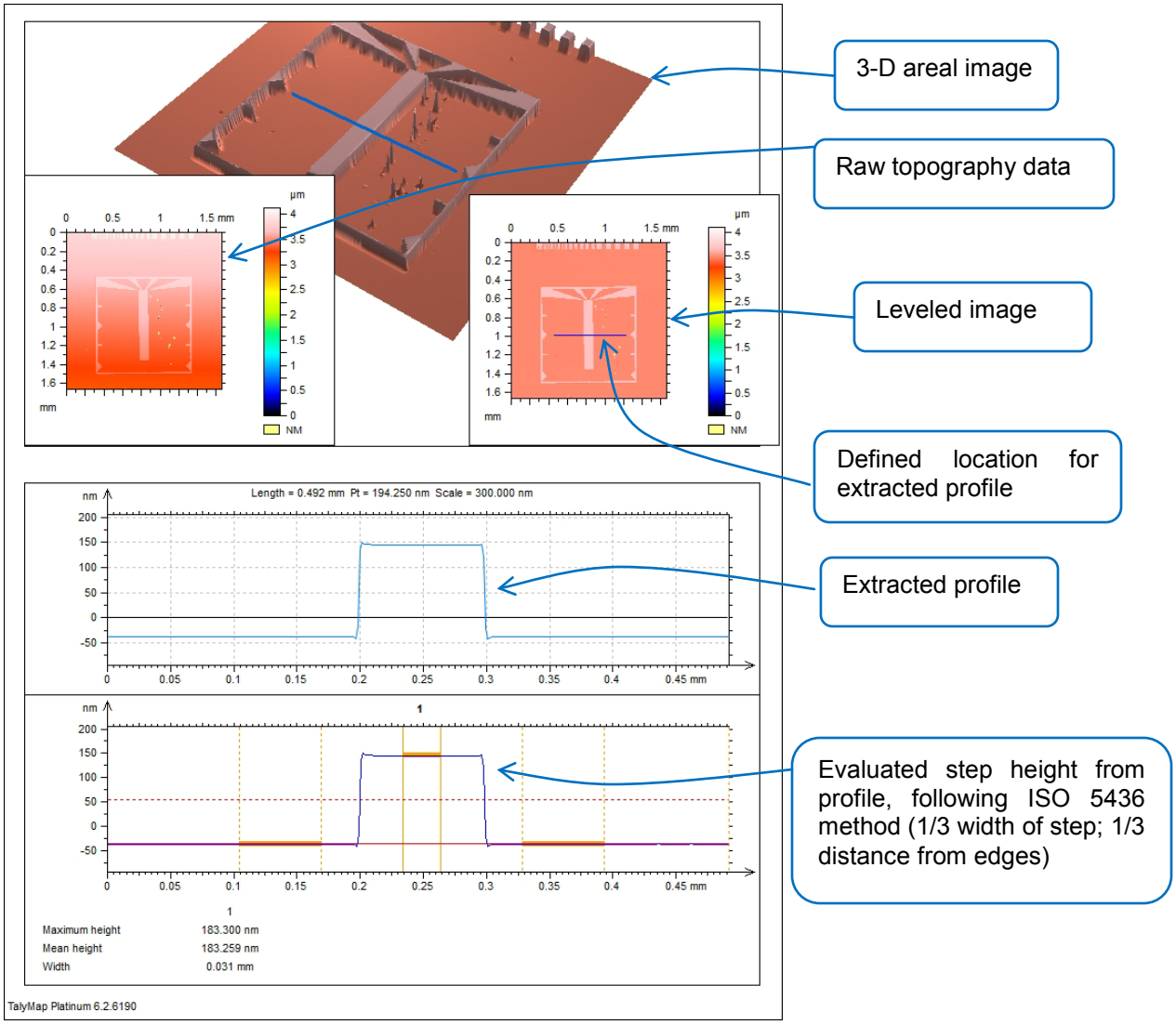

Figure 12. Workflow for analyzing a step height, after the CSI instrument has sent the topography data to the analysis software. For this example, the CSI instrument is a Taylor-Hobson CCI-Lite, and the analysis is performed using Talymap Platinum v6.2.

We can now evaluate the derivatives, and develop the uncertainty budget. This is shown in the following example.

We have a nominally 4.5 μm step height that we wish to calibrate (not illustrated here). Our master step has a nominal value of 4.835 μm with a standard uncertainty (from the certificate) of 0.0086 μm. After collecting measurements and evaluating uncertainties, we obtain:

Table 2. Experimental measurement of a nominal 4.5 μm step height, and evaluation of standard and expanded (coverage factor k=2) measurement uncertainty. The reported value would be 4330 nm with an expanded uncertainty (coverage factor k=2) of 16 nm.

Component	Value	Units	Notes
CV	4835	nm	From cert
MV	4829.841	nm	Avg of 8 rdgs
SF	1.00106812	dim'less	
m=	4324.946	nm	Avg of 8 rdgs
UUT y=	4329.56557	nm	Calculated from Eqn 4
u CV	8.6	nm	From cert
u MV	1.66	nm	Statistical; includes geometry statistics
s_m	1.89	nm	Statistical; includes geometry statistics
u_z	0.35	nm	From linearity study; half-width/sqrt(3)
u_m	2.25	nm	RSS u_z, s_m
u_SF	0.00181363	dim'less	Calculated from Eqn 6
u_y	**8.16**	**nm**	Calculated from Eqn 7
U_y (k=2)	**16**	**nm**	

It is interesting to note that the measurement uncertainty of the UUT is actually slightly smaller than the certificate uncertainty of the master step height. This is because the master step height is used to establish a scale factor correction for the CSI, and the CSI is assumed to be generally linear over the measurement span. Because the UUT is smaller than the master step height being used, the UUT's uncertainty is close to being proportionally smaller.

Measurement of different types of reference specimens, such as Type B, Type C, or Type D, would follow the same general logic, but the evaluation of measurement uncertainty becomes more complicated. This will be addressed in further work.

It is important to ensure that the reference specimens being calibrated do not have features that would cause problems for a CSI instrument, especially coatings, dissimilar materials, high surface slopes, or short pitch. Intercomparisons with other instruments, such as stylus instruments, is important, as the optical system and signal processing can introduce unexpected errors, especially with more complex topography[15],[16],[17]. In addition, it is important to verify the software used to calculate parameters[18].

Summary

Areal surface metrology instruments, such as coherence scanning interferometers, have become popular in industry. They can also be used to calibrate reference standards, such as Type A height (or depth, or amplification) standards commonly used to calibrate profile instruments. Because of the large number of options and features in these instruments, calibration and evaluation of measurement uncertainty can be complicated. We have illustrated the calibration of a step height standard using a CSI, including an evaluation of uncertainty. Calibration of other types of reference standards will require more research.

Acknowlegments

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