# Areal Texture and Angle Measurements of Tilted Surfaces using Focus Variation Methods

**F. Hiersemenzel[1], J.N. Petzing[1], R.K. Leach[2], F.S. Helmli[3], J. Singh[1]**
[1] Wolfson School of Mechanical & Manufacturing Engineering,
Loughborough University Loughborough, Leicestershire, LE11 3TU, UK
f.hiersemenzel@lboro.ac.uk, j.petzing@lboro.ac.uk, j.singh@lboro.ac.uk

[2] National Physical Laboratory,
Hampton Road, Teddington, Middlesex, TW11 0LW, UK
richard.leach@npl.co.uk

[3] Alicona
Alicona Imaging GmbH, Teslastrasse 8, 8074 Grambach, Austria - Graz
franz.helmli@alicona.com

**Abstract**
Optical instruments for areal surface topography measurement have seen significant commercial development in the last five years, along with the ISO 25178 areal standard. Providing the user with confidence in new instruments depends on understanding instrument behavior and sources of error. Focus variation techniques rely on the inherent micro- or nano-scale roughness of a surface to allow acquisition of topography data. The work reported here has been examining the sensitivity of the focus variation technique to surface slope, using areal parameters to characterize surface roughness at extended slope values. The results illustrate links between instrument variables and slope characterization.

**Keywords:**
Focus Variation, Areal parameters, Roughness measurement, Angle measurement

## 1 INTRODUCTION

The development of optical instruments for the measurement of areal surface topography, with techniques such as coherence scanning interferometry, confocal microscopy and focus variation, has seen significant commercial instrument advances in the last five years [1]. In parallel, the ISO 25178 suite of specification standards [2] has started to be published, specifying aspects of areal instrumentation configuration and detailing areal parameters. Providing the user with confidence in these types of instruments depends on understanding the underpinning operating principles and importantly, the relevant sources of error such as those encountered when measuring steep slopes on surfaces.

The majority of the optical instruments, including focus variation (FV) rely on the use of commercial diffraction limited, achromatic microscope objective lenses, with numerical aperture values ranging typically from 0.05 to 1.5 depending on lens manufacturer. The numerical aperture specification (lens half angle) generally determines the ability of the lens to gather light back from a surface, and in particular sets the angular acceptance of each lens. The higher the numerical aperture value, the higher the surface slope angle tolerance (referenced to the horizontal plane). If the surface slope exceeds the lens numerical aperture criterion, then many instruments deteriorate in data acquisition performance, with holes or voids appearing in the three dimensional data sets.

FV [1] relies on the inherent micro- or nano-scale roughness of a surface to provide appropriate surface contrast, leading to the acquisition of surface topography data. A consequence of the physical principle of FV is that it can be demonstrated to measure angled or tilted surfaces that are significantly outside the numerical aperture criterion of the lens being used. Consequently, it is possible to use FV to measure areal surface texture in a non-contact manner, on angled features that cause problems for other non-contact techniques.

The work reported here involved examining the sensitivity of FV to surface slope, considering issues of different lens specifications, surface illumination methods, illumination criteria (intensity, polarization, etc.), fields of view, and lateral and vertical resolution. The research has also investigated the use of areal parameters to characterize the roughness of the surfaces at extended slope values. This work considered whether the aspect ratio of the micro-scale roughness features (when presented at different angles), causes changes to the parameterization and quantification of the surface (in areal terms).

## 2 FOCUS VARIATION DEVELOPMENT

FV, both as a concept and a name was initially developed for use with high resolution electron microscopes (HREM), to retrieve the wave function at the object, and from this the projected structure of the object [3,4]. This involved capturing a series of closely spaced focus values or images and then processing the whole three dimensional (3D) data set.

The natural extension of these HREM methods is to consider application to optics and optical images. Large image views were demonstrated in terms of 'depth from focus' during the mid to late 1980s [5,6], whereby a series of images at various focus positions were acquired. Each individual image was then partitioned and sharpness maps developed using Gaussian and Laplacian mathematical techniques.

Further work [7,8] developed the concept in terms of 'shape from focus' (SFF). The important difference here is that the method was restricted to visibly rough surfaces that produced images with high frequency intensity variations. The practical aspect of the SFF method was to translate the object vertically with respect to fixed optics. The translation of the object was completed in known increments, with each image point on the object surface passing from a defocussed state, to a focused state, and back again into a defocussed state. Again, the key to devolving the SFF 3D data set from the finite number of object plane image slices, was to develop and implement focus measure operators, which operated as high-pass filters. In this case a modified Laplacian algorithm was developed to calculate the second order derivatives, linked to Gaussian distributions.

The opto-mechanics of FV has always been in essence straightforward as demonstrated by existing literature, with little change in the optical design occurring during this period. However, early proof of principle experiments utilized vertical movement of the inspected object because this required less experimental design and control over the apparatus. Subsequent development of FV has resulted in a fixed object and movement of the optical system, in recognition that this provides better control over image acquisition, and reduces system error terms.

The majority of subsequent research has, therefore, concentrated on novel and more robust image processing techniques to define the 3D structure from the captured image stacks. Authors have departed from originally proposed Laplacian/Gaussian based focus assessment algorithms, to define and explore second and fourth order central moments of an image [9], mean method and curvature focus measures [10], and multilayer feed-forward neural networks [11].

A direct consequence of much of this theoretical development and experimentation, has been the innovation and use of commercial instruments [12], and the embodiment of the working principles of FV in a new element (currently under development via ISO/TC 213, WG 16) of the recently part published ISO 25178 set of standards, that detail areal measurement and associated instrumentation [13].

## 3 AREAL MEASUREMENTS OF SLOPED SURFACES

This section presents the initial findings of the investigation of surface roughness measurements using an Alicona InfiniteFocus G4 FV instrument. The research was carried out with surfaces inclined at different angles, with two types of light settings, and with varying lateral resolutions. For all of the following datasets, the upper angular limit was chosen to be eighty degrees and the lower was zero degrees. The xy-stage provided the horizontal reference plane. The inclination of the measured artefact was established with angle gauges that were placed on the instrument's xy-stage. Each element of work used seventeen increments of 5 degrees to assess angular performance.

The artefact used for these measurements challenges FV because of its inherent surface characteristics - it is a gauge block that has been roughened using grinding processes. The roughening process leaves behind a micro-roughened surface that is randomly rough and inhomogeneous in nature, with some areas specular in nature. The latter reflects the light mirror-like rather than scattering the light in a diffuse manner. Therefore, results were expected to show some variable performance of FV because any surface with specular characteristics tends to produce more limited focus quantification. The value of the study lies in the trends of the graphical data and the comparison between measurement results at different settings. However, it should be recognized that the gauge block surface characteristics cause the FV instrument to operate at the edge of its normal operating regime.

### 3.1 The effect of FV illumination sources

Two types of illumination sources are typically used within FV instruments: coaxial illumination through the optical train and external ring-light illumination, usually a circular arrangement of light emitting diodes (LEDs) that can be attached around an objective lens such that the surface is illuminated diagonally rather than just along the surface normal. Choosing the illumination type may depend on surface topography characteristics and issues such as extent of specular reflection. Using a ring-light can increase the probability of the reflected or scattered light to be within the half aperture angle of the lens and consequently more information from the surface can be acquired by the instrument. The illumination investigation examined the artefact surface using only coaxial illumination, and then a combination of coaxial and ring-light illumination. At each angular increment, illumination intensity was adjusted to 'ideal settings' in response to and as defined by the instrument software. Polarized light was not used during these tests.

Numerical comparison of the measured surfaces at incrementing angles was achieved using the *Sq* ISO 25178-2 areal surface texture parameter [2], this being the root mean square length of the scale limited surface. The value of *Sq* was calculated for all images using the instrument software. All images were leveled followed by generation of the surface roughness component using a L-filter cut-off wavelength of 25 µm. It should be noted that the lateral resolution of the instrument was not adjusted during these tests (to compensate for the changing aspect ratio of the surface) and was set at approximately 1.3 µm. The vertical resolution was set at 20 nm.

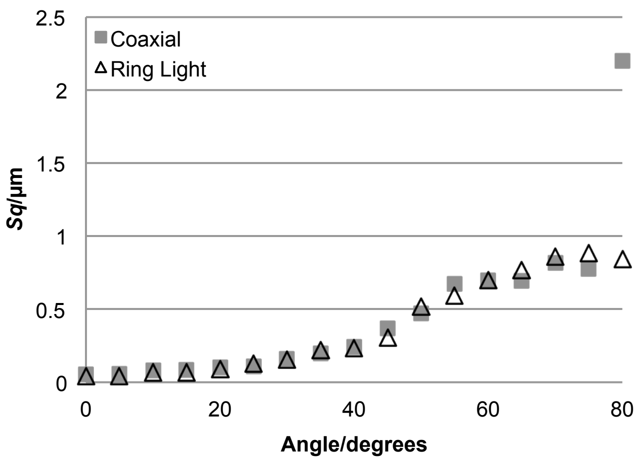


Figure 1: *Sq* measurements of sloped surfaces (100× objective)

The measurement results are presented in Figure 1 and demonstrate changes of instrument behavior as a function of illumination conditions. Each data point is the mean value of three repeated measurements at each angular increment. The trends shown by both sets of results suggest that a FV instrument may measure a larger *Sq* value as the inclination of the surface increases, for an inhomogeneous randomly rough surface.

The use of simultaneous ring-light/coaxial illumination tends not to make any significant difference to the *Sq* values below the half aperture angle (53.1 degrees for the 100× objective). Above the half aperture value, combined illumination results in smaller (more consistent) *Sq* values compared to just using coaxial illumination.

The change of *Sq* value as a function of angle is significant, but strongly influenced by the surface characteristics of the gauge block. Additional work has been started (and is still on-going) to explore the data characteristics, with gauge blocks subjected to more intensive grinding operations, giving a rougher surface (*Sq* = 0.171 µm versus *Sq* = 0.042 µm). Table 1 illustrates the initial results for the *Sq* and the *Sa* parameters up to 40 degrees. Whilst there is a rise in value for each parameter by 98 %, the rise is significantly less than the equivalent angular range shown for the data in Figure 1 (454 %). This helps to further illustrate the potential influence of the surface on the response characteristics of the FV instrument.

| Tilt /degrees | 100× *Sa*/µm | 100× *Sq*/µm |
|---|---|---|
| 0 | 0.136 | 0.171 |
| 10 | 0.129 | 0.164 |
| 20 | 0.155 | 0.206 |
| 30 | 0.177 | 0.226 |
| 40 | 0.269 | 0.339 |

Table 1: Comparative results from an alternative gauge block

### 3.2 The affect of lateral resolution

The lateral resolution of the FVM instrument has a direct effect on quantification of surface roughness parameters from any surface (level or sloped) because the lateral resolution acts as a band pass filter during data acquisition. The instrument lateral resolution should, if possible, be decreased according to the inclination of the surface in order to compensate for the changing aspect ratio of the surface. Theory suggests that the lateral resolution should be decreased when measuring steeper surfaces in order to compensate for the higher aspect ratio.

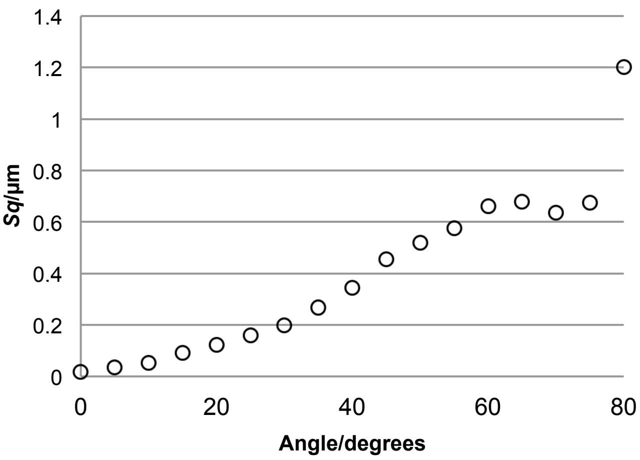


Figure 2: *Sq* measurements of a sloped surface with changing lateral resolution (100× objective)

Experimentation was completed to investigate what effect reducing the instrument lateral resolution has when examining surfaces of increasing tilt. The lateral resolution is related to the cosine of the slope angle as shown in equation (1)

$$LR = LR_0 \cos \alpha \quad (1)$$

Where *LR* is the lateral resolution of the measurement, $LR_0$ is the lateral resolution of the measurement of the surface in a horizontal position, and $\alpha$ is the angle of the sloped surface.

Figure 2 shows the relationship between the measured *Sq* values and the angular increment of the surface whilst the lateral resolution of the FVM instrument is stepwise reduced and compensated. These experiments were completed using simultaneous ring-light/coaxial illumination adjusted to 'ideal settings' in response to, and as defined by, the instrument software. Polarized light was not used during these tests. The vertical resolution was kept constant at 20 nm, whilst the lateral resolution ranged between 2.6 µm and 0.45 µm.

Below the half aperture angle for the 100× objective (53.6 degrees) the *Sq* value slowly increases in relation to the reference $Sq_0$ value (18 nm). $Sq_0$ is the value, which was obtained from the measurement of the surface at zero degrees inclination. Above the half aperture angle of the instrument, the *Sq* values level off and plateau at a value of approximately 0.7 µm. Importantly, the overall trend of the *Sq* data as a function of changing slope and changing lateral resolution, is very similar to the trends shown in Figure 1, with similar peak values for the areal parameter. This provides evidence that the FV system is measuring the sloped surface in a consistent manner irrespective of slight illumination variations, and lateral spacing settings. It is also noticeable when processing the data sets, that the image quality deteriorates more significantly at angles higher than 50 degrees than at the lower angles, with an increase of data holes within the datasets. This may be caused by exceeding the half aperture angle of the lens.

### 3.3 Measurement of surface angle

The secondary aim of assessing the response of FV techniques to angled surfaces is to determine how well the slope geometry can be measured. The angle of each measured surface was calculated within Talymap v5.1 (DigitalSurf MountainsMap v5.1) by using the end points of a profile taken from the 3D surface representation. The results on a five degree incremental basis are shown in Figure 3.

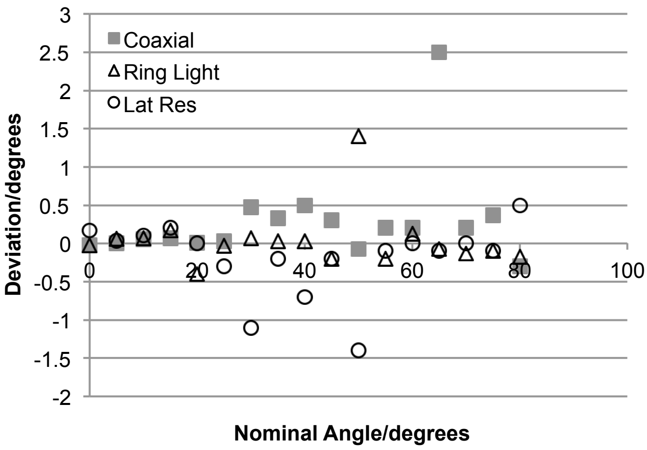


Figure 3: Deviation of measured angle against nominal angle (100× objective)

Illumination augmented with lateral resolution compensation produced the greatest deviation of angle, with a mean deviation of 0.31 degrees, and four data points exceeding 0.5 degrees deviation. Coaxial illumination was more consistent. If the one outlying data point is ignored (as a function of experimental error), then the mean and the maximum deviation was 0.2 degrees and 0.5 degrees respectively, and the data set had a Pearson correlation coefficient value of 0.99974.
Application of simultaneous ring-light/coaxial illumination caused smaller deviation of measured angle (mean and maximum deviation of 0.1 degrees and 0.4 degrees respectively), with a slightly more refined Pearson correlation coefficient value of 0.99989. There does not appear to be any influence of the lens half aperture angle on the ability of the FV technique to assess slope geometry in this manner.

## 4 MEASUREMENT OF DIFFERENT SURFACES

Measurements have been completed to illustrate differences of surface texture measurement on tilted surfaces when using two specimens with fundamentally different surface characteristics, when using two different objective lenses, and when calculating the roughness parameter by averaging over a large number of line profiles.

The first specimen was the roughened flat that was used in the work reported in the previous sections. Viewed with the 100× objective, the surface appears randomly rough and inhomogeneous in nature. The second specimen is a type C sinusoidal profile standard (*Ra* = 0.5 µm, *Pt* = 1.5 µm, *RSm* = 50 µm) supplied by Rubert & Co Ltd, with a micro-roughness superimposed on the larger scale profile to allow the artefact to be suitable for FV measurement. The micro-roughness of the type C artefact differs to the roughness of the gauge block by its method of manufacture. The sinusoidal roughness standard has been chemically etched and thus has a more homogeneous micro-roughness [12].

The measurement procedure for the roughened gauge block follows that described in section 3. For comparability to existing data from the type C artefact, the profile parameter *Ra* was calculated for each of the seventeen increments of angle averaged over five hundred line profiles, to mitigate the effect of voids in the data sets, especially at the higher slope angles.

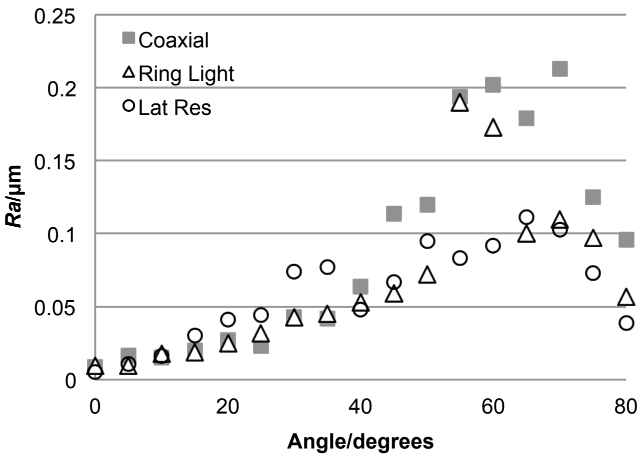


Figure 4: *Ra* measurements of a roughened gauge block (100× objective)

The results are shown in Figure 4. At each angular increment, illumination intensity was adjusted to 'ideal settings' in response to, and as defined by, the instrument software. Polarized light was not used during these tests. The lateral resolution of the instrument was adjusted for the third set of experiments (to compensate for the changing aspect ratio of the surface). During the first two sets of tests (coaxial illumination and ring light/coaxial illumination) the lateral resolution was fixed and set at approximately 1.3 µm. The vertical resolution was set at 20 nm.

In line with the previous experimental results in section 3, all three trends show an increase of surface texture parameter (*Ra*) when the tilt angle of surface increases. In the range of 0 degrees to 20 degrees the *Ra* values show only small differences. Above 45 degrees of slope, the FV results show significant deviations. Again it should be re-emphasized that the gauge block used as the test artefact causes the FV instrument to operate at the edge of its operational capability.

The most noticeable change of behaviour occurs as a function of introducing the compensating lateral resolution. Whereas previously for the *Sq* parameter, compensating lateral resolution did not noticeably affect the results or trends here, the compensating lateral resolution data is noticeably less random within the angular range of 45 degrees to 80 degrees. It should also be noted that all data sets show a significant drop in parameter value at 80 degrees.

Direct comparison is drawn here to *Ra* data obtained from the type C profile standard, shown in Figure 5. It should be noted that in this case a 20× lens was used for inspection with a half aperture angle of 23.6 degrees. As a consequence, measurements have been limited to an upper limit of 55 degrees. This set of measurements demonstrates that it is possible to measure a consistent surface roughness value for a profiled surface, across a range of tilt angles, above the half aperture angle.

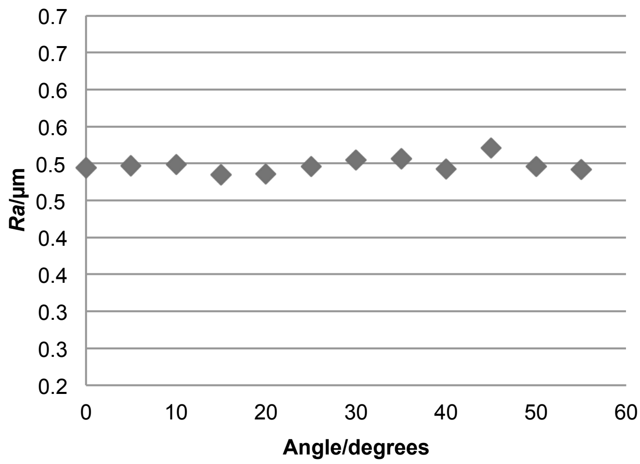


Figure 5: *Ra* measurements of a sinusoidal profile artefact (20× objective)

## 6 CONCLUSIONS

This on-going research is exploring the capabilities and limits of the FV method for generating three dimensional maps of surfaces, both from a texture and geometry viewpoint. As with many other optical metrology systems, the behaviour of a FV instrument, whilst simple in principle, has many different operational variables that influence the final numerical results. In addition, the very surface being measured can also influence the final results.

The key conclusions developed from this work so far can be identified as follows.

- The FV method can acquire datasets from angled surfaces, tilted up to an angle of at least 80 degrees (as demonstrated with a 100× objective lens).
- The geometric angle of the tilted surface can be measured with confidence (as demonstrated with a 100× objective lens). Ring-light illumination improves the quality of the angle measurements
- It is possible to consistently measure the surface roughness of a structured homogenous surface across a range of tilt angles (as demonstrated with the type C artefact using a 20× objective lens).
- The response of an FV instrument to an inhomogeneous surface is less consistent in terms of areal parameter measurement, specifically at angles greater than the half angle of the objective lens (as demonstrated with a 100× objective lens). The response is more consistent using mixed mode lighting (ring-light/coaxial) when compared to just using coaxial illumination. An important reason for these less consistent results for the slightly roughened gauge block ($Sq$ = 0.042 µm) lies in the fact that the sample has a very inhomogeneous surface structure with several regions being very smooth and at the limits of what the FV instrument can measure according to the instrument specifications. Therefore, the increase in areal parameter is not fully representative of the behaviour of FV instruments on samples on which surface texture measurements would be typically performed according to the technical specifications of the instrument.
- Results on a gauge block that is less inhomogeneous and slightly rougher than the first artefact ($Sq$ = 0.171 µm) show a significantly smaller increase of areal parameter with respect to tilt angle. More detailed studies on this rougher gauge block with different parameters (lateral resolution compensation, use of ring light, use of polarizer) are on-going and will be reported at a later point in time.
- Reducing lateral resolution of an FV instrument when measuring higher tilt angles, causes similar data trends to the other two illumination scenarios explored, when measuring the areal $Sq$ parameter. However, it should be noted that when the surfaces are quantified using the profile parameter $Ra$, lateral resolution compensation appears to be advantageous.
- When a user of an FV instrument wishes to measure a line scan over an area that is partly horizontal but includes features or surfaces with changing angles, the user must be aware that illumination characteristics may not be ideal for every part of the surface within the field of view.

It should be noted that further work is on-going as part of this study, to expand experimentation to encompass a larger range of objective lenses, different types of surfaces, and to consider the use of polarized light for the inhomogeneous surfaces. This additional work will be reported at a later point in time.

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