

REPORT

3D Topography Measurement of Ceramics

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ABSTRACT

Three different methods for measuring the topography of a set of alumina samples were compared. The methods that were used were conventional stylus measurements, scanning optical microscopy, and laser profilometry. The alumina samples were prepared using different common industrial finishing techniques.

Different methods for presenting and visualising the results were explored. 3D roughness parameters were calculated which included the RMS deviation, skewness and kurtosis of the surfaces. Bearing area curves were also calculated.

It was found that the non-contact optical methods normally gave higher roughness values than the stylus measurements. However, the variability in results was quite large, making it difficult to make a good comparison between the different methods.

The relative merits of the three different measurement methods were discussed and contrasted with the performance of an AFM on the basis of an amplitude-wavelength (A-W map).

Initial results of a feasibility study to develop graphics workstation based methods for modelling and visualising the interaction of the styli of measurement systems with sample surfaces are presented.

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Approved on behalf of Managing Director, NPL, by Dr M K Hossain,
Director, Centre for Materials Measurement and Technology

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1 INTRODUCTION

This report describes the results of a comparison of measurements of the topography and roughness of ceramic samples by a number of different techniques. The main aim was to check to see how the results that were obtained were dependent on the measurement method used. A secondary purpose was to evaluate different algorithms for the determination of the roughness parameters for 3D roughness data sets.

The different methods that were evaluated were traditional stylus profilometry (SP), non-contact optical laser profilometry (LP), and confocal scanning optical microscopy (SOM). In addition, some work was also performed with an atomic force microscope (AFM).

2 EXPERIMENTAL

Measurement Methods

Stylus

Two stylus instruments were used. The first was a 2D profilometer which incorporated an internal reference flat, and used a 2 μm tip stylus. The second instrument was a Talysurf 3D instrument which also incorporated an internal reference plane, and also incorporated a 2 μm tip. The use of an internal reference plane as an alternative to the common skid system ensures that the height measurements are absolute and are not affected by the locally averaging process that is caused by the use of a skid.

The scanned area was 0.2 mm x 0.3 mm with 256 scans of 256 points, with each scan carried out in the 0.3 mm direction.

Scanning Optical Microscope

The scanning optical microscope has been described before [1,2]. It uses confocal imaging to provide optical sectioning resulting in point-to-point height information. The instrument used in this work employed a device called a Nipkow disc to provide the pinholes for the confocal imaging (Figure 1). A transputer computer array was used to process the optical sections obtained and to calculate the height maps. The area measured was limited by the field of view of the microscope, and in this case a 40 x objective lens was used giving a field of view of 0.2 mm x 0.3 mm, with a pixel resolution of 720 x 512.

Laser Profilometer

The laser profilometer that was employed was the Rodenstock RM600 system. This instrument is based on the disc height following system of a CD player with a lens employing focus positional feedback to determine surface height (Figure 2). The system has a focused spot size of 2 μm . Again a 0.2 mm x 0.3 mm area of the samples was measured. The vertical measurement range was set to $\pm 30 \mu\text{m}$ for all samples except the SA and the LE samples where $\pm 3 \mu\text{m}$ was used.

Atomic Force Microscope

The main set of samples were not examined with an AFM as the maximum height range of the instrument that was available was not large enough to allow the measurement to be carried out. However, experience on the use of an AFM to measure the topography of ceramic surfaces was gained during a high resolution examination of worn alumina surfaces [3].

Materials

Seven samples were chosen from a 95 % alumina ceramic. These samples had been previously used in a study of the effect of different finishing techniques on the strength of ceramics [4]. The surface finishes that were used were chosen to give a range of different roughness scales and types of finish typical of different application areas for ceramics. The different finishing techniques and strength results are given in Table 2. Scanning electron micrographs of the sample surfaces are shown in Figure 3. The surface finishes that were obtained appeared to have a range of roughness, and also varied considerably in type, from the LE sample which consisted of a very flat surface with a number of angular holes, to the RG sample which showed a very disrupted surface.

The strength of flexure samples varied considerable with the preparation technique, with the lowest strength for the lapped and etched sample at 157 MPa, and the highest value for the fine ground samples at 300 MPa. At least two competing mechanisms which affect the strength were contributing to this variation. These were firstly the presence of residual stresses in the surface of the ceramic, which cause the flexure strength of the ceramic to increase. These residual stresses are caused by the grinding process, and are largely eliminated by annealing. The second mechanism is the presence of damage such as cracks or holes in the surface of the ceramic.

Analysis Procedures

Visualisation of the 3D datasets was carried out by a number of different computer/software systems. These were

- A Silicon Graphics workstation using the Explorer data visualisation system to perform the normalisation of the datasets, and the rendering of the surface plots.
- Spyglass Transform running on a Pentium PC.
- The RTH Talysurf analysis software.
- The Rodenstock laser profilometer software.
- NPL written software to analyse and display the results of SOM examinations.

The different visualisation techniques were compared and contrasted, and the most convenient and effective technique used for the rest of the study.

Roughness parameters were calculated by a number of different algorithms. Some of these were the conventional 2D methods [5] which were applied to 2D profiles extracted from the 3D data set. It should be noted that the effectiveness of these algorithms was reduced by the low number of measurement points available in the extracted profiles (the measurements were optimised for 3D and not 2D measurements).

A simple 3D roughness average measurement was also defined in analogy to the 2D parameters.

The main set of analysis algorithms that was used were those defined in an EC funded collaborative research project [6]. These new parameters have been proposed as a good basis

for standardisation of 3D topography measurements within Europe. The parameters that were used in this study are given in the appendix.

Some results are also given of a preliminary investigation of the feasibility of using a graphical simulation technique to model the interaction of styli with example surfaces. This has the potential to give information on the confidence that can be given to the accuracy of height measurements.

3 RESULTS

Different Visualisation Methods

The surface of the LE sample are shown in Figure 4. For the visualisation of 3D data there are clearly a number of different approaches which can be taken in terms of the choice of colour, the use of isometric views, and whether a net plot is used. All of the different methods have different strengths and weaknesses; for example the net plot used by the Rodenstock enables a reasonably effective representation of the data to be made on a modest PC. By contrast, the high resolution colour representation that can be made with the Silicon Graphics workstation is very effective, but needs relatively expensive hardware to process and to print out the results.

Comparison of Different Methods - Surface Topography

The results of the main set of 3D measurements are shown in Figures 5-12, and Figures 13-20. Contour plots or height maps are used as it was felt that this method gave the most immediate comparison between the different test methods for these types of surfaces. Two sets of figures are presented in the comparison. In the first set the limits for the colour range are set by the maximum and minimum heights encountered in the different datasets. In the second set, constant maximum and minimum values were used for the height range.

All the three measurement methods reveal the characteristic differences between the samples, ranging from the relatively smooth LE sample to the rougher sawn sample. However, some differences were apparent.

The stylus instruments gave height maps with a blocky appearance as though some feature in the measurement process was giving some dominance to the horizontal and vertical direction. The SOM gave height maps with noticeably better spatial resolution, and no hint of the blockiness associated with the stylus results. The laser profilometer gave height maps that seemed to be the lowest quality with evident pixelation and an apparent low resolution.

Some errors in the different measurement methods were evident. Thus the roughly diagonal markings in some of the SOM height maps are due to artefacts caused by the scanning of the Nipkow disc, and result in a small error in the height information at these points.

The laser profilometer suffers from the fact that it cannot measure a surface which has a surface slope at the point of measurement of more than 7 degrees; this results in some points on the height maps that were acquired being marked as unmeasurable, so that some of the apparent gaps or holes in the LP maps are simply due to this large slope error.

Comparison of Different Methods - Roughness Calculations

The results of the preliminary comparison between the simple roughness average values calculated from the SOM examination and a 2D stylus profilometer are given in Table 2 and Figure 21. It is immediately obvious that the 1D roughness measurements calculated on profiles extracted from the 3D datasets give higher roughness average values than those for the profilometer. However, when the calculation is repeated using a 3D formulation, the results are very close in most cases.

The main set of roughness calculations followed the following steps.

1. Scaling of height.
2. Calculation of bearing area curve.
3. Reset values at unmeasurable points to minimum value of height determined by bearing area curve.
4. Fitting least mean squares plane to data.
5. Subtraction of least mean squares plane from data.
6. Calculation of height range, RMS deviation, skewness and kurtosis.
7. Recalculation of bearing area curves.
8. Calculation of the $3\sigma_{50}$ parameter [9], which is calculated as 99.87% of the bearing ratio.

The values of the different parameters are given in Tables 4-8. The two optical techniques give results of height measurements with a larger range than the stylus measurements. This is also reflected in the RMS deviation results. The height plots are all negatively skewed, indicating that the surface has a significant percentage of the surface below the mean level, i.e. the height distribution is skewed to the lower height values. The kurtosis of the height maps vary considerably from sample to sample and also with the measurement technique. The values are nearly always greater than 3 (the value for a gaussian curve), showing that the height distributions are not normally gaussian in shape. It is perhaps significant that the LE sample has a very high kurtosis consistently for all three measurement techniques.

The values of the $3\sigma_{50}$ parameter also vary considerably from sample to sample, with higher values for the optical non-contact measurement methods in most cases except for the SA sample where the stylus measurement gave the highest value (Figure 23). One reason for the variability of this parameter may be that as it is very close to the top of the height distribution at 99.87 %, with only a handful of data points with higher height, the variability in results can be expected to be quite high. Also the adoption of the 3σ terminology implies a gaussian height distribution for height which is not necessarily true. It is likely that another point near the top of the height distribution, say 98%, would give more consistent results.

Bearing area curves

The bearing area curves reflect the numerical results obtained for the roughness parameters (Figure 24). Thus the stylus measurements give sharper bearing area curves than the optical measurement methods, and there is a long tail of points at the low height side of the average

height reflecting the negative skew of the results. In only two cases were unexpectedly high disagreement between the bearing area curves for the different measurement methods obtained (Figures 24f and 24g).

4 DISCUSSION

Different techniques

The different techniques show different results for the different materials, and apart from the fact that the non-contact optical methods give higher values for the roughness of the surface (to be discussed in the context of A-W maps below), there does not seem to be a consistent trend between the different techniques.

One of the major difficulties in performing this work has been the fact that the different measurement instruments all produced data files with a different syntax. Although reading these files into the required format for the analysis was not that difficult, it nevertheless took considerable effort for the 21 sets of data that were being processed. A common data format, which has in fact been suggested by the work on the EC project, would eliminate this problem.

There is also perhaps a need to define agreed methods of visualising 3D data, as it is certainly difficult to compare and contrast results when different methods are used, perhaps leading to incorrect interpretation of the relative merits of different routes for surface preparation for engineering applications.

One of the main advantages of the non-contact techniques has always been the lack of contact and elimination of damage to surfaces, particularly for soft materials.

The comparison of the different techniques shows that there are perceived differences for the quality of the results when the height maps are examined. Thus the SOM appears to give height maps which have high spatial resolution in comparison to the laser profilometer maps which seem to be "noisy" and pixelated. However, the height maps also pick up the artefacts in the SOM data that are caused by the rotation of the Nipkow disc, and the blocky structure observed in the stylus measurements also give cause for concern, particularly since their source has not been identified.

One reason for the variability in results may be that different areas of the surfaces were measured for each instrument, and that some variability in the values of roughness parameters and local topography will occur on any surface from one position to another. This source of variability could have theoretically been removed by the use of techniques to ensure that exactly the same area was measured in every case, this however is very difficult and could not be done in this study.

A-W maps

A useful device for the comparison of different measurement techniques is the use of the amplitude-wavelength or A-W map. This map shows how the different measurement devices interact with surfaces by considering their interaction with surfaces that have a sine wave profile [7,8]. For each instrument, a region is defined which shows the combination of

amplitudes and wavelengths that each different instrument can measure. A-W maps have been calculated for the instruments used in this study, and are given in Figure 25.

The right hand upper wavelength limit is defined by instrumental parameters such as the range of stage traverse, or in the case of the SOM, the size of a single field of view. The left hand wavelength limit is given by the spatial resolution of the stage or data processing system. The high amplitude limit is normally due to some type of physical constraint on the measurement system, and the low amplitude limit is given by physical limitations on the vertical resolution of the measurement device. The higher portion of the diagonally sloping upper bound is due to the included angle of the probe (optical or physical) that is used by the instrument, with the lower portion due to the radius of curvature of the probe tip.

It can be seen that the achievable region of use for the non-contact laser instrument and the tradition stylus instruments are nearly identical (with a slightly smaller spatial resolution for the stylus instrument), showing the design success of the laser profilometer manufacturers in designing an instrument that matches the stylus instrument so closely. High resolution stylus instruments, and of course the AFM provide atomic height resolution. However, it should be realised that achieving traceable calibration of the AFM (which is necessary before measurements of surface topography can be made), restrict the useful range of the AFM to a much smaller region.

An important point is that the finite included angle for the probes means that high amplitude low wavelength surface features cannot be easily measured with any instrument. This gives errors in the measurement of sharp edges and spikes, so that even the AFM cannot physically measure features which are less than about 30 nm in size if the height varies from point-to-point by more than about 10 nm.

Stylus interactions

The feasibility study to develop ways of visualising the interaction of probe tips with surfaces resulted in a software system which can be used to interactively move a model probe over the visualised surface. Figure shows one frame from a session of this type where a model tip is shown in contact with a notch on the surface of the test sample. The graininess of the foreground of the visualised surface is due to the advanced techniques that are employed to provide video rate performance for the test system. This software is in an early state of development, and with suitable controls built into the system, will allow for the exact modelling of real instrument tip geometry.

The feasibility study has also started to address the inverse problem of trying to extract as much information as possible from datasets where limitations on the tip geometry create uncertainties in the measurements.

Figures 26,27 and 28 demonstrate the utility of the approach. In Figure 27 a rectangular block is defined as the real test object, and the results of a measurement with a large tip radius probe calculated. Use of the knowledge of the tip geometry, and an inverse calculation technique allow the most accurate form of the data to be extracted and identification of areas where large measurement uncertainty exists.

5 CONCLUSIONS

1. A comparison between different topography measurement techniques examining the surface topography of a set of alumina samples. The non-contact techniques of scanning optical microscopy and laser profilometry gave higher roughness values than the stylus measurements, but there was such high variability in results that it difficult comparing results from different instruments.
2. The Scanning Optical Microscope is able to measure high amplitude features with a higher spatial resolution than conventional stylus instruments.
3. Care is needed in the interpretation of AFM images where the size of features on the surface approaches the AFM tip radius dimensions (normally about 10 nm).
4. The feasibility of using workstation technology to provide methods of studying the size of probe-surface interactions has been successfully demonstrated.

Acknowledgements

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Table 1, Materials

Specimen Designation	Preparation Method	Strength, Mpa
LE	Lapped to polish etched 5.5 hrs HCl	157
FG	Fine ground	300
RU	Rough ground and rumbled	217
6L	Rough ground and partly lapped with 6 μ m diamond	-
SA	Sawn and annealed	215
RG	Rough ground	194
SW	Sawn	278
A	Rough Ground and annealed	-

Table 2, Comparison of 2D stylus measurements with scanning optical microscope. Measurements are roughness averages in μ m.

Specimen Designation	Profilometer		Scanning Optical Microscope		SOM 2D
	Mean 1	Mean 2	Mean V	Mean H	
LE	0.06	0.04	0.41	0.53	0.12
FG	0.19	0.22	0.53	0.64	0.13
RU	0.37	0.52	0.89	1.3	0.21
6L	0.22	0.28	1.42	1.24	0.21
SA	0.19	0.25	1.43	0.95	0.19
RG	0.25	0.3	2.03	1.07	0.25
SW	0.11	0.14	2.16	2.82	0.36

Table 3, Stylus roughness parameters

Sample Designation	Minimum	Maximum	RMS Deviation	Skewness	Kurtosis	$3\sigma_{50}$
LE	-4.82	2.38	0.49	-2.94	14.58	0.71
FG	-4.17	1.4	0.58	-1.28	5.44	0.89
RU	-5.62	3.65	1.4	-0.72	3.62	3.09
-	-	-	-	-	-	-
SA	-7.88	5.39	1.26	-0.76	5.00	4.86
RG	-7.58	4.5	1.55	-0.96	3.86	2.45
SW	-7.57	3.74	1.27	-0.77	4.27	2.72
A	-11.91	3.66	1.5	-1.56	8.39	3.04

Table 4, Laser profilometer roughness parameters

Sample Designation	Minimum	Maximum	RMS Deviation	Skewness	Kurtosis	$3\sigma_{50}$
LE	-4.81	3.07	0.76	-2.65	11.99	1.89
FG	-10.07	4.27	1.16	-1.56	10.85	2.41
RU	-10.85	6.48	1.76	-1.62	10.51	3.88
6L	-	-	-	-	-	-
SA	-4.27	2.48	1.49	-0.94	3.54	2.35
RG	-13.2	9.39	2.75	-2.26	10.11	4.12
SW	-12.45	6.27	2.15	-3.37	17.39	3.09
A	-12.46	12.05	2.51	-0.86	4.37	6.90

Table 5, Scanning optical microscope roughness parameters

Sample Designation	Minimum	Maximum	RMS Deviation	Skewness	Kurtosis	$3\sigma_{50}$
LE	-7.82	4.65	1.44	-2.99	13.1	3.03
FG	-7.27	2.7	1.39	-2.43	9.67	1.9
RU	-7.54	4.22	1.64	-1.38	6.44	2.93
6L	-5.2	2.86	1.39	-1.73	5.64	2.92
SA	-7.06	3.26	1.91	-1.39	5.12	3.05
RG	-10.13	3.91	2.29	-1.86	6.93	3.07
SW	-46.23	7.22	5.66	-3.55	19.9	5.08

Table 6, RMS Deviation values

Sample Designation	Stylus	SOM	LP
LE	0.49	1.44	0.76
FG	0.58	1.39	1.16
RU	1.4	1.64	1.76
6L	-	1.39	-
SA	1.26	1.91	1.49
RG	1.55	2.29	2.75
SW	1.27	5.66	2.15
A	1.5	-	2.51

Table 7, $3\sigma_{50}$ values

Sample Designation	Stylus	SOM	LP
LE	0.71	3.03	1.89
FG	0.89	1.90	2.41
RU	3.09	2.93	3.88
6L	-	2.92	-
SA	4.86	3.05	2.35
RG	2.45	3.07	4.12
SW	2.72	5.08	3.09
A	3.04	-	6.90

Appendix: Roughness Parameters [5,6]

In all the formulae below M and N are the dimensions of the array of measurements z_{ij} (N only for 2D), the summations are for all M,N,

Arithmetic mean deviation of surface or roughness average for 2D data, R_a

$$R_a = \frac{1}{N} \sum |z_i|$$

Arithmetic mean deviation of surface for 3D data, S_a

$$S_a = \frac{1}{NM} \sum |z_{ij}|$$

Root-mean-square deviation of the surface for 3D data, S_q

$$S_q = \sqrt{\frac{1}{NM} \sum \sum z_{ij}^2}$$

Skewness of the surface, S_{sk}

$$S_{sk} = \frac{1}{MNS_q^3} \sum \sum z_{ij}^3$$

Kurtosis of the surface, S_{ku}

$$S_{ku} = \frac{1}{MNS_q^4} \sum \sum z_{ij}^4$$



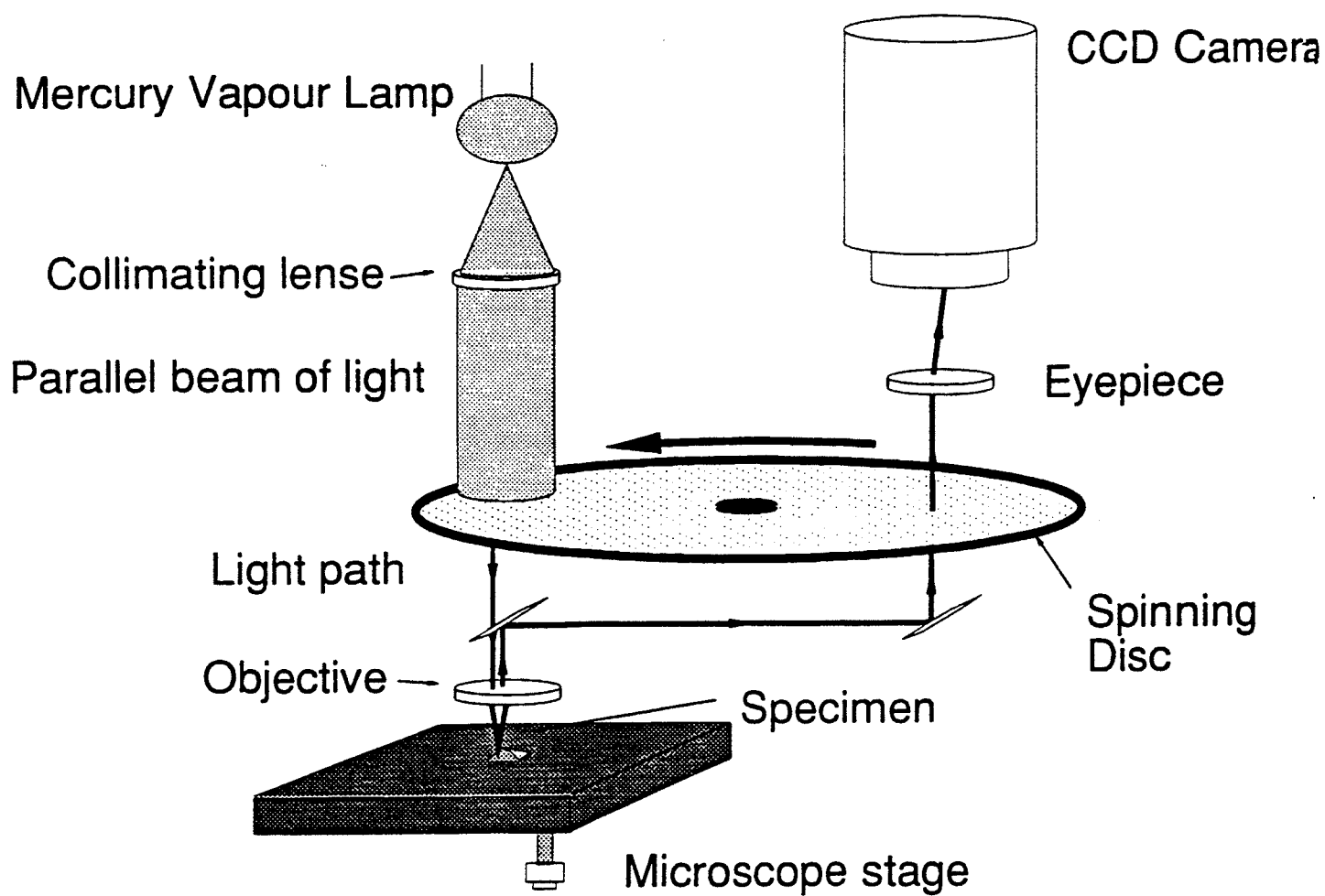


Figure 1, Schematic diagram of scanning optical microscope

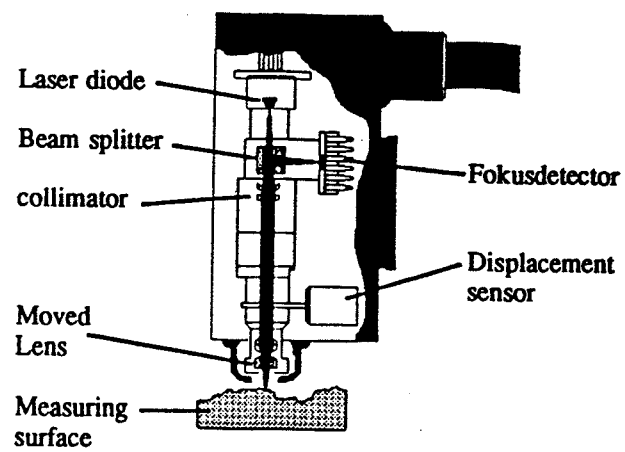
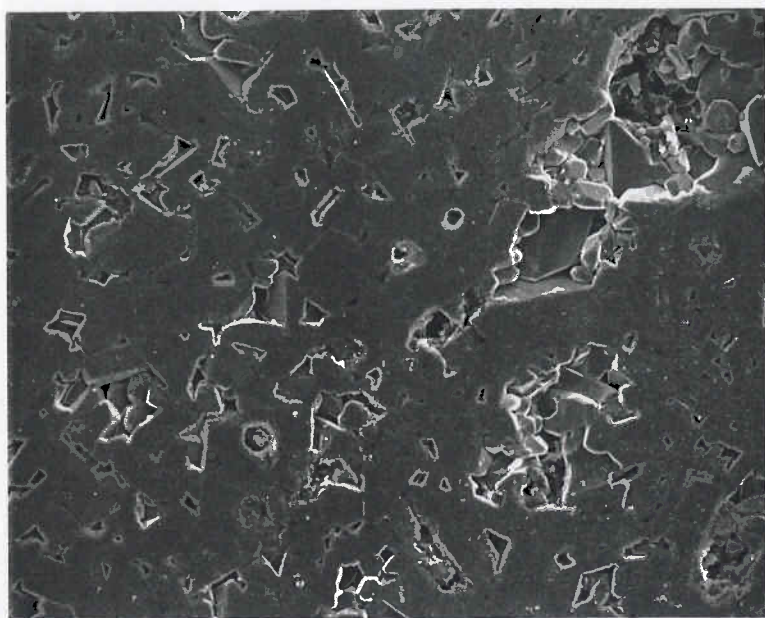
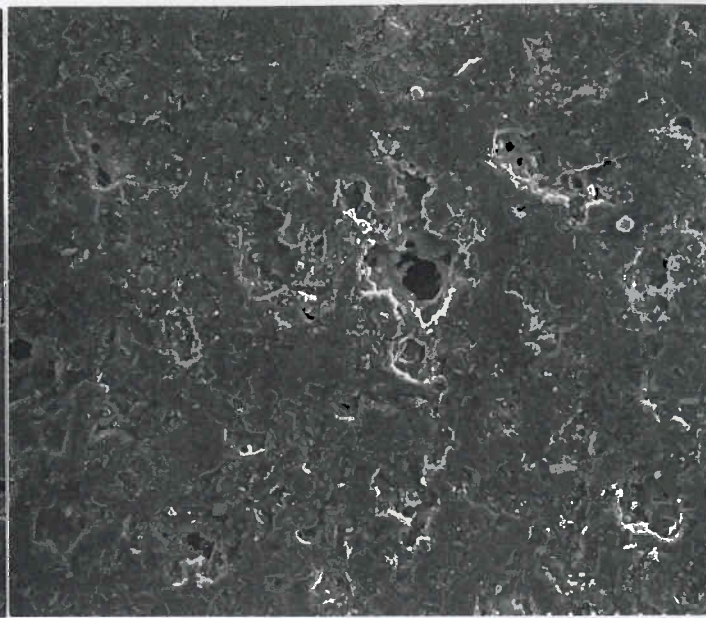


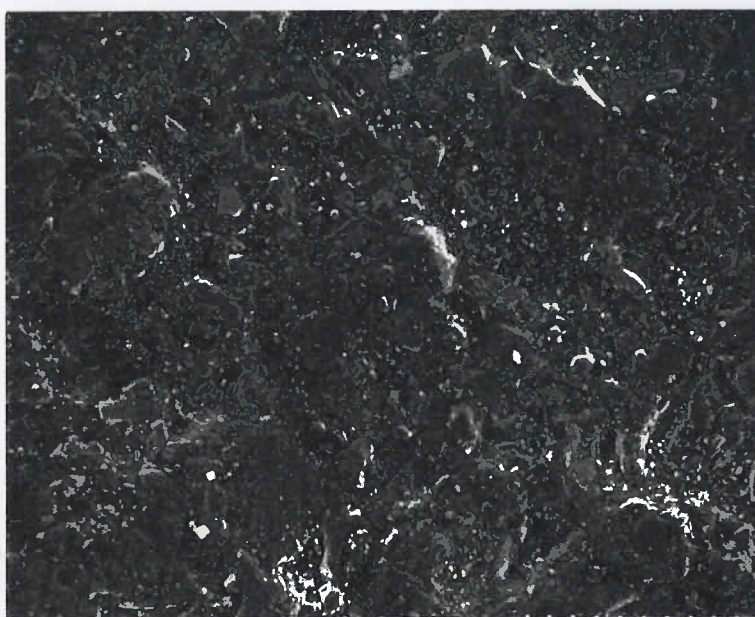
Figure 2, Schematic diagram of laser profilometer probe



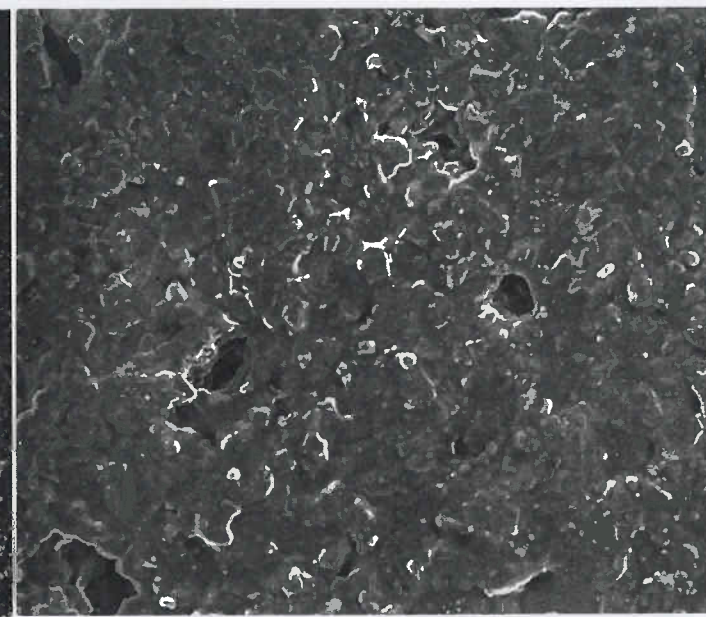
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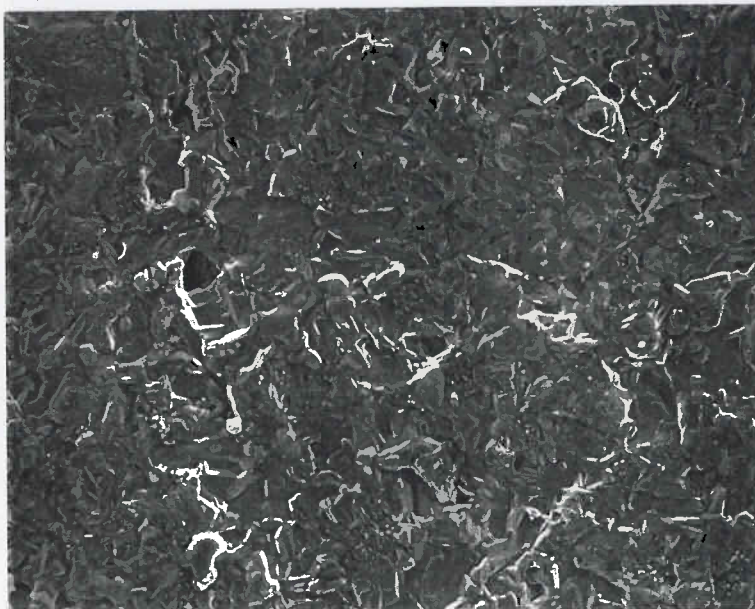
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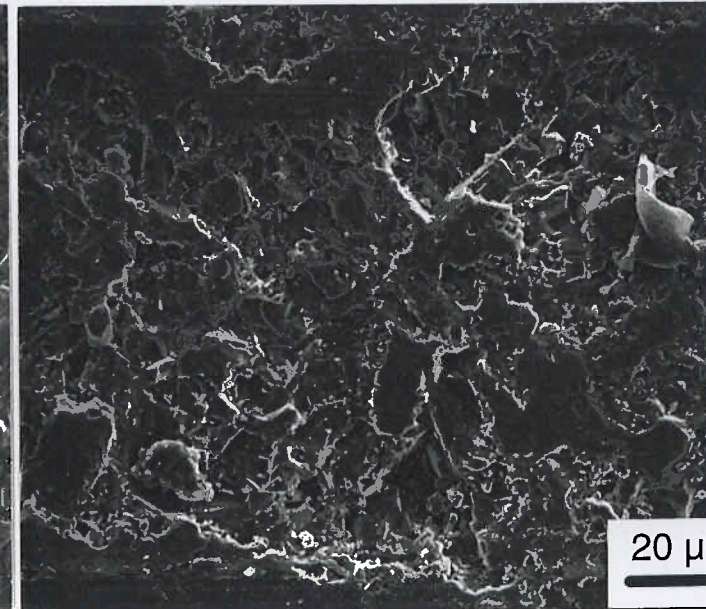
c)



d)



e)

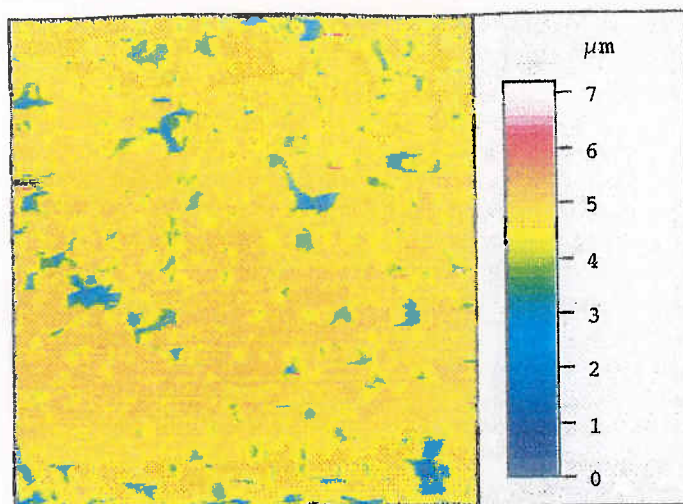


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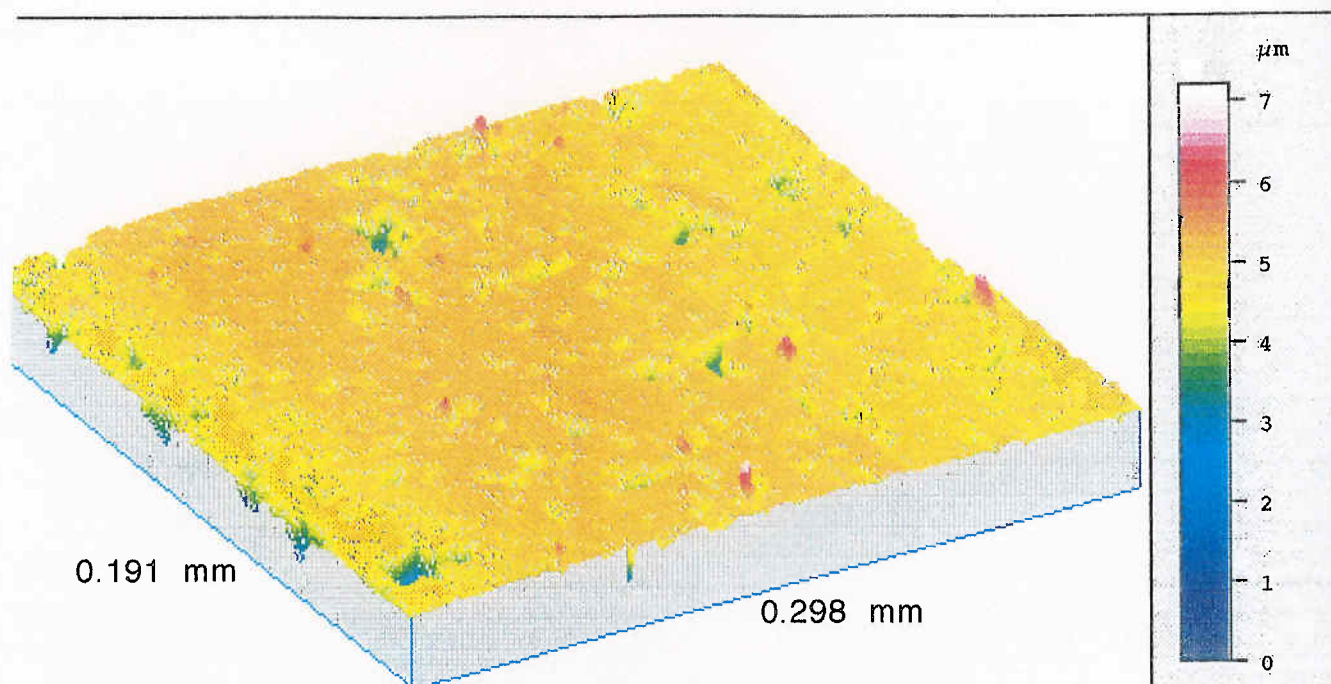
Figure 3, Scanning electron micrographs of alumina samples, a) LE, b) FG, c) RU, d) 6L, e) SA, f) RG

a)

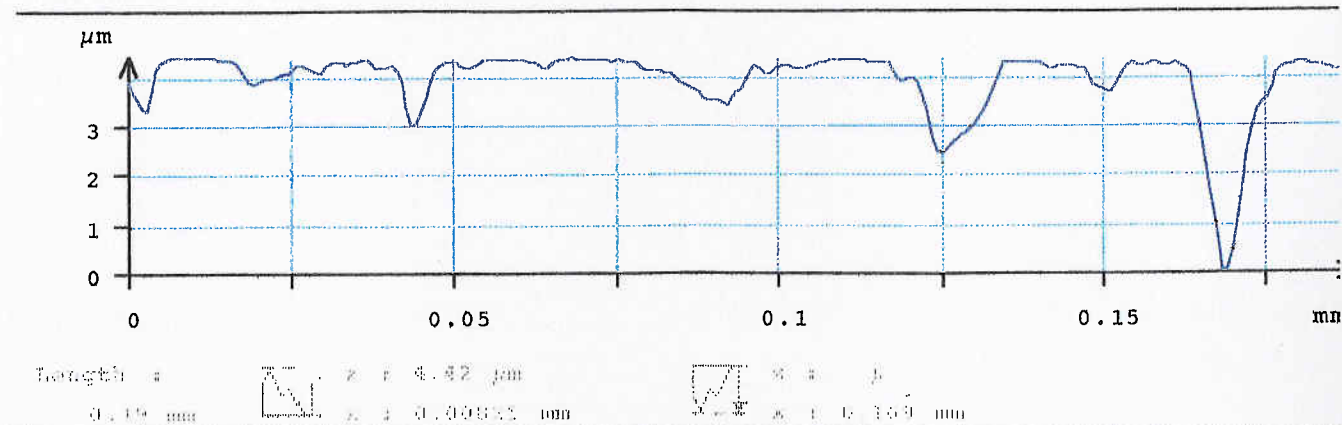
Simtex FA
Lapped & Etched



LS Plane Removed : Pseudo-colour image : heights are coded using colours.



S Plane Removed : Three-dimensional representation of the surface. Heights are colour-coded.



Profile extracted < LS Plane Removed : Profile curve

Figure 4, Different methods for visualisation of 3D roughness data, a) RTH stylus instrument software, b) silicon graphics explorer package, c) Rodenstock laser profilometer package, d) scanning optical microscope software.

b)

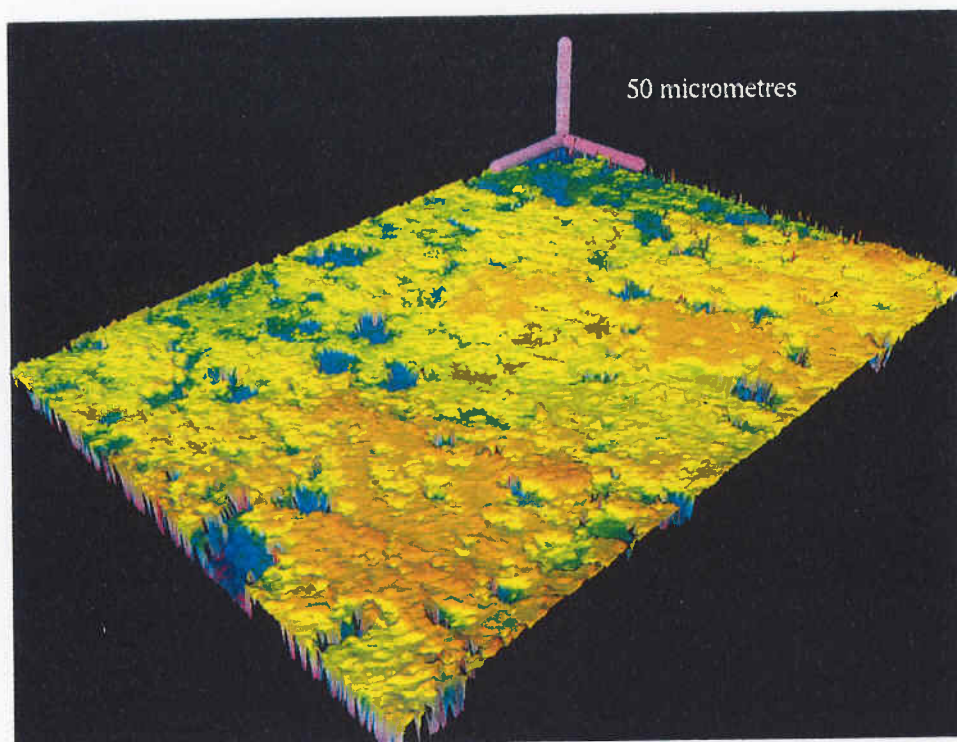


Figure 4, Different methods for visualisation of 3D roughness data, a) RTH stylus instrument software, b) silicon graphics explorer package, c) Rodenstock laser profilometer package, d) scanning optical microscope software.

c)

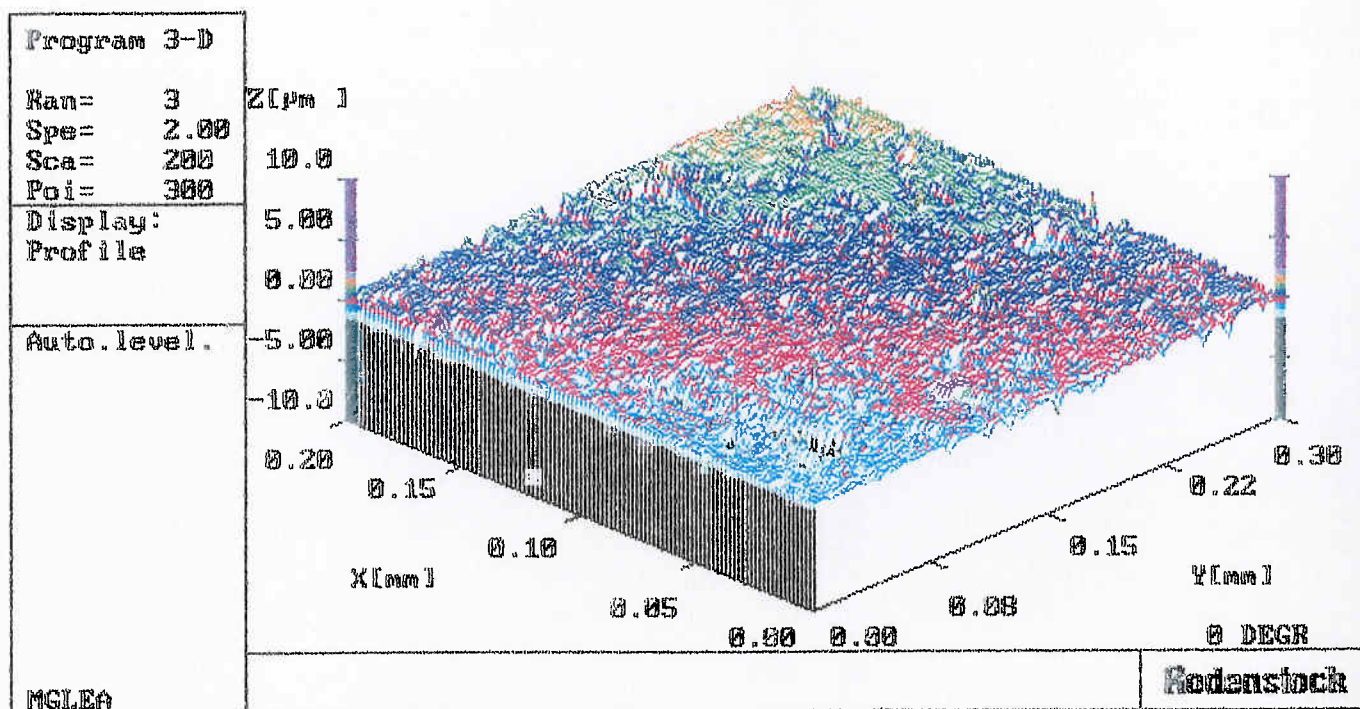
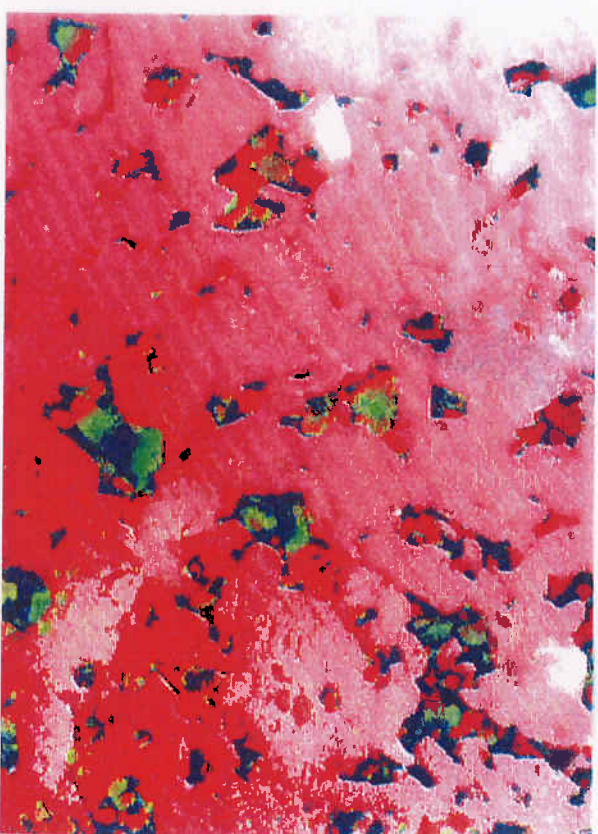


Figure 4, Different methods for visualisation of 3D roughness data, a) RTH stylus instrument software, b) silicon graphics explorer package, c) Rodenstock laser profilometer package, d) scanning optical microscope software.



d)

Figure 4, Different methods for visualisation of 3D roughness data, a) RTH stylus instrument software, b) silicon graphics explorer package, c) Rodenstock laser profilometer package, d) scanning optical microscope software.

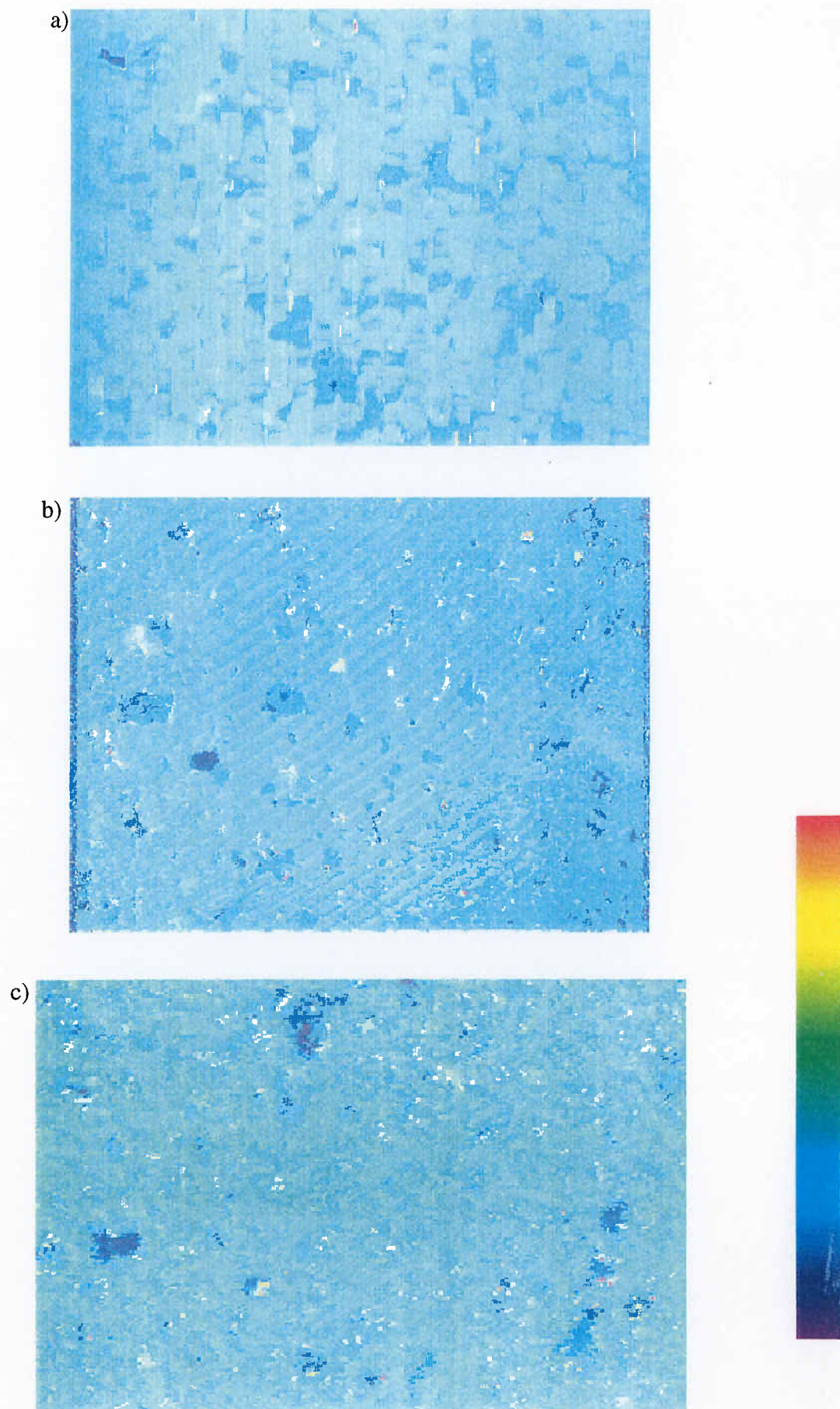


Figure 5, Height maps for sample LE drawn with colour scale covering full range of data listed in Tables 3-6, a) stylus map, b) SOM map, c) laser profilometer map.

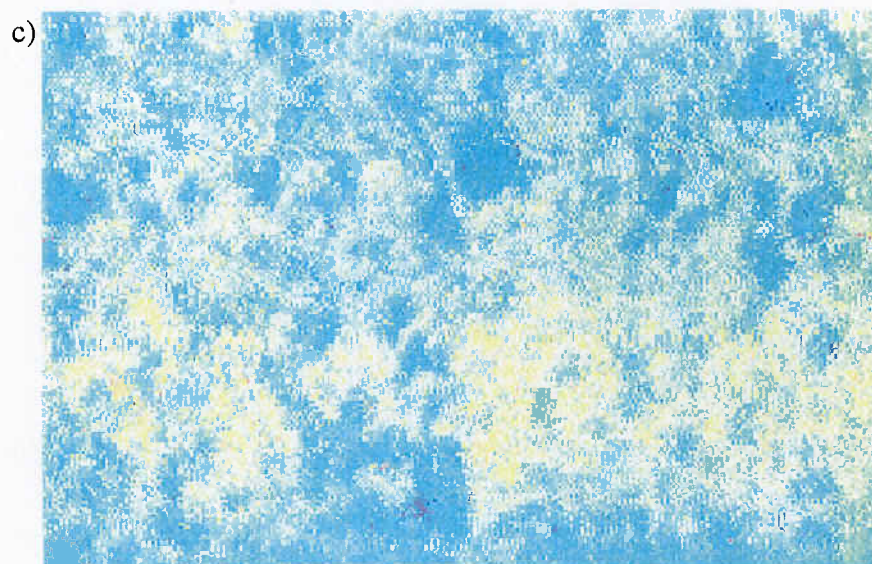
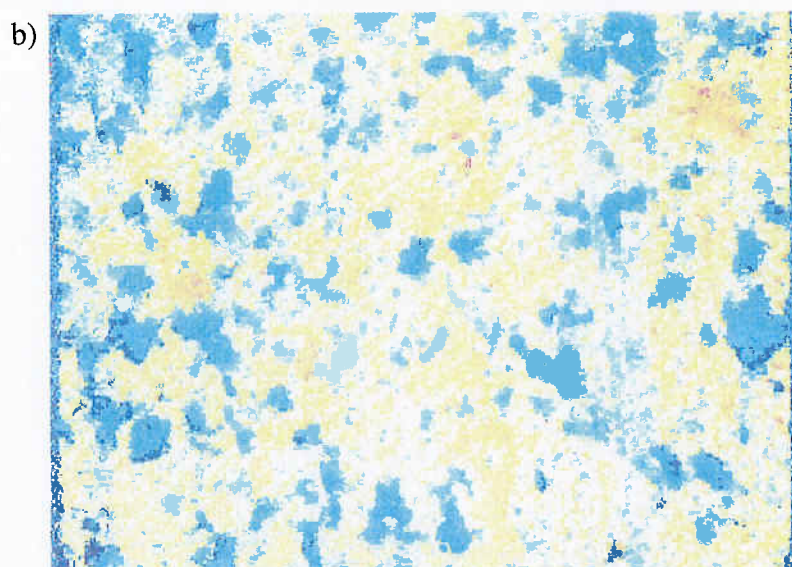
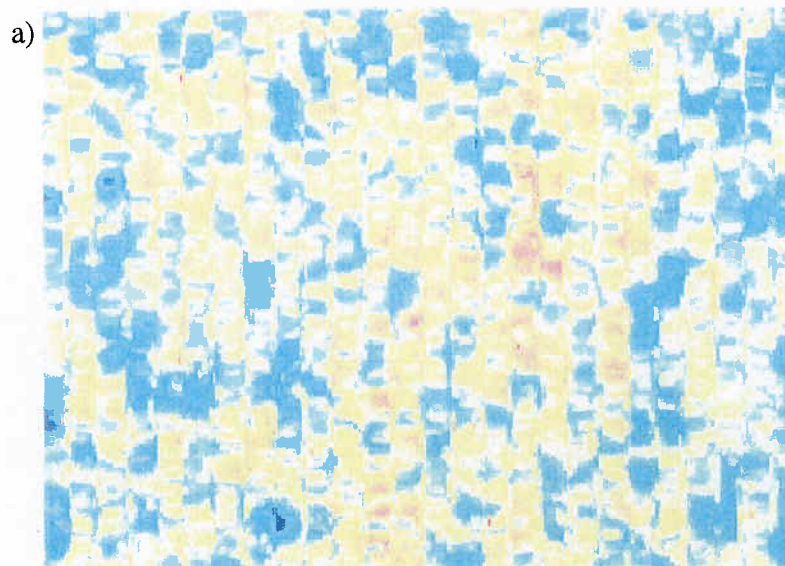
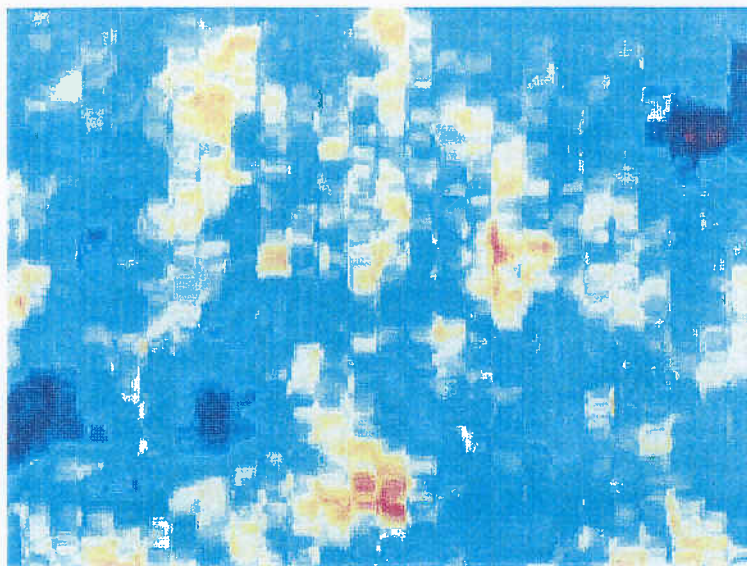
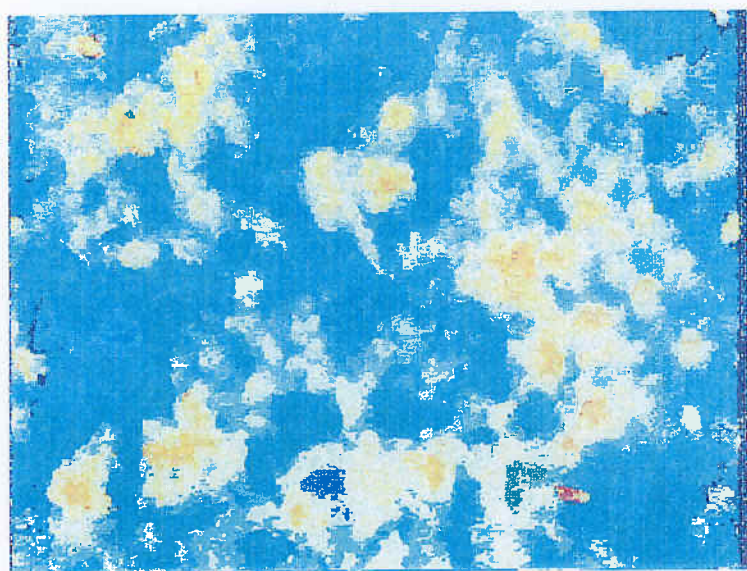


Figure 6, Height maps for sample FG drawn with colour scale covering full range of data listed in Tables 3-6, a) stylus map, b) SOM map, c) laser profilometer map.

a)



b)



c)

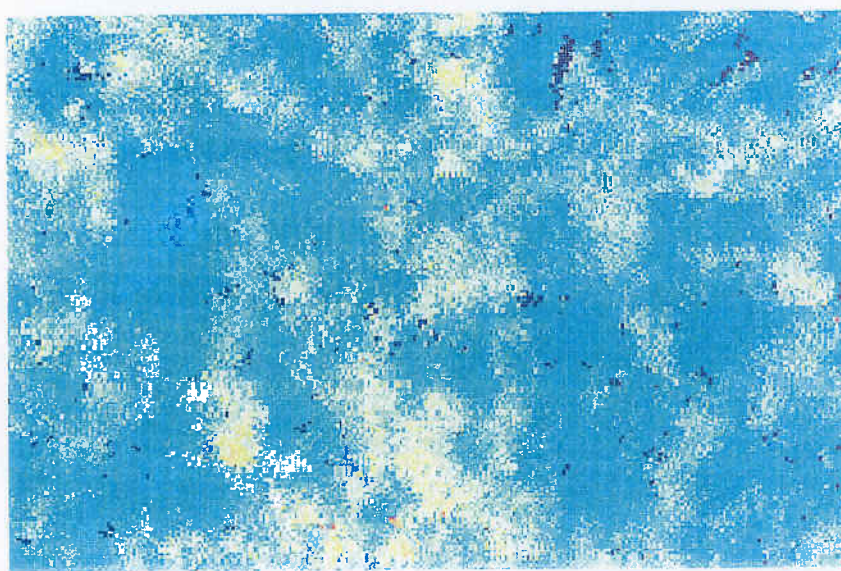


Figure 7, Height maps for sample RU drawn with colour scale covering full range of data listed in Tables 3-6, a) stylus map, b) SOM map, c) laser profilometer map.

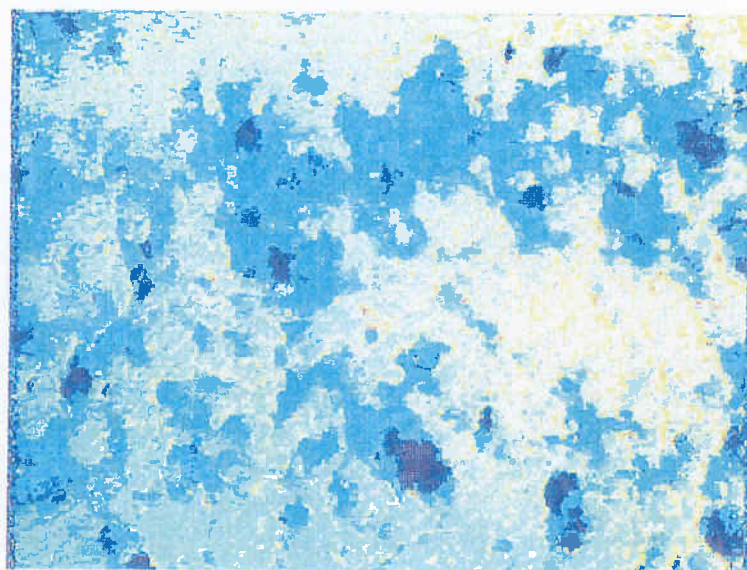


Figure 8, SOM height maps for sample 6L drawn with colour scale covering full range of data listed in Tables 3-6

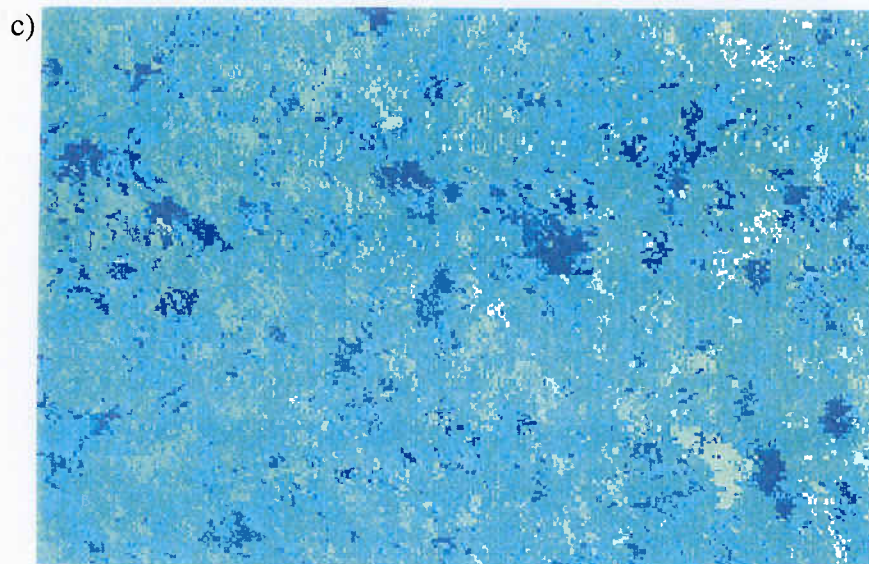
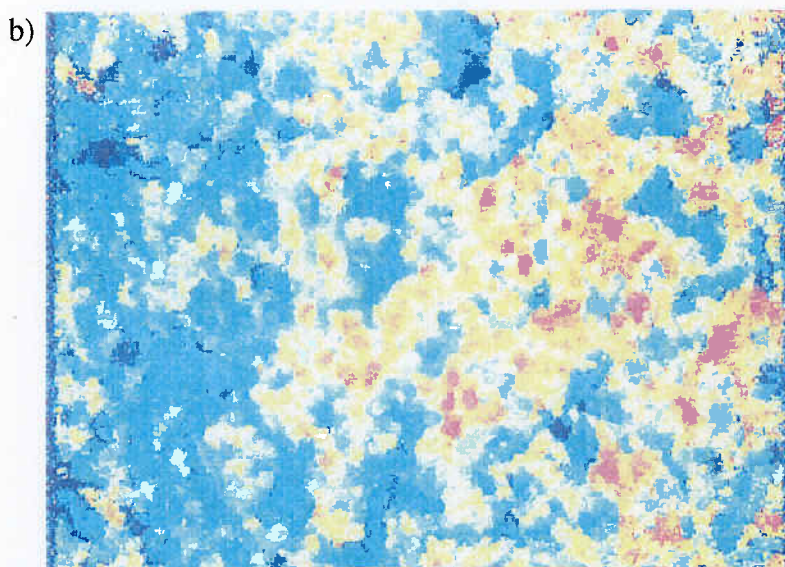
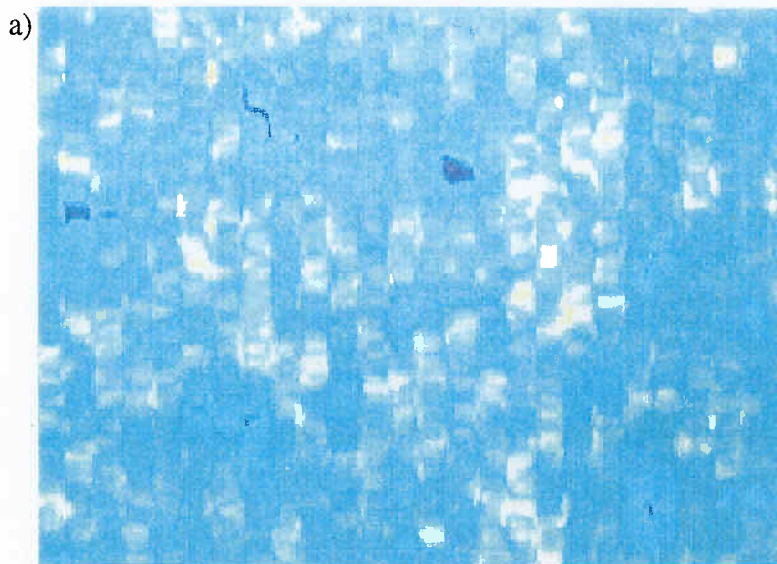


Figure 9, Height maps for sample SA drawn with colour scale covering full range of data listed in Tables 3-6, a) stylus map, b) SOM map, c) laser profilometer map.

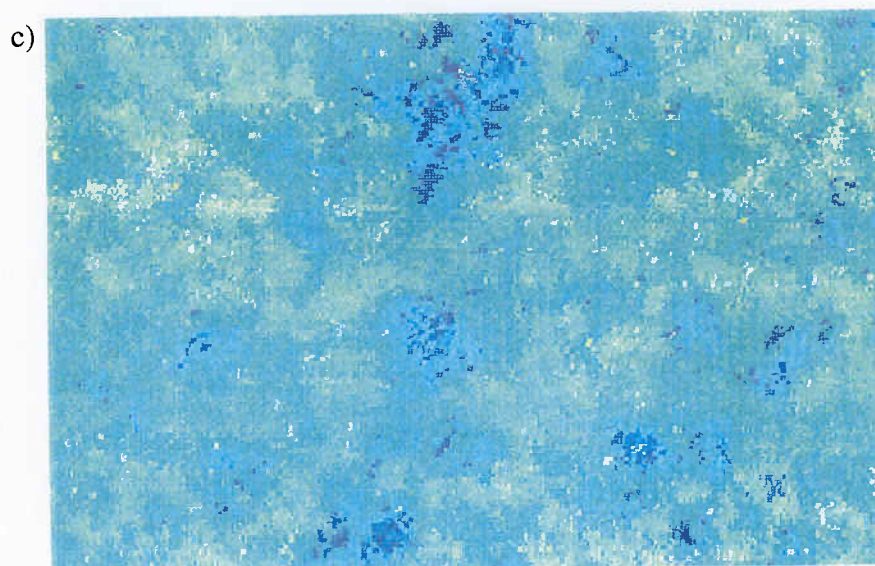
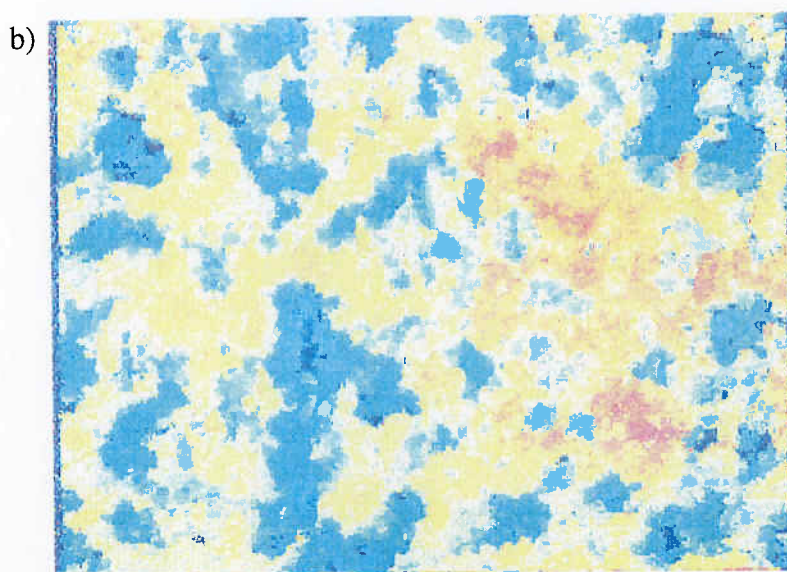
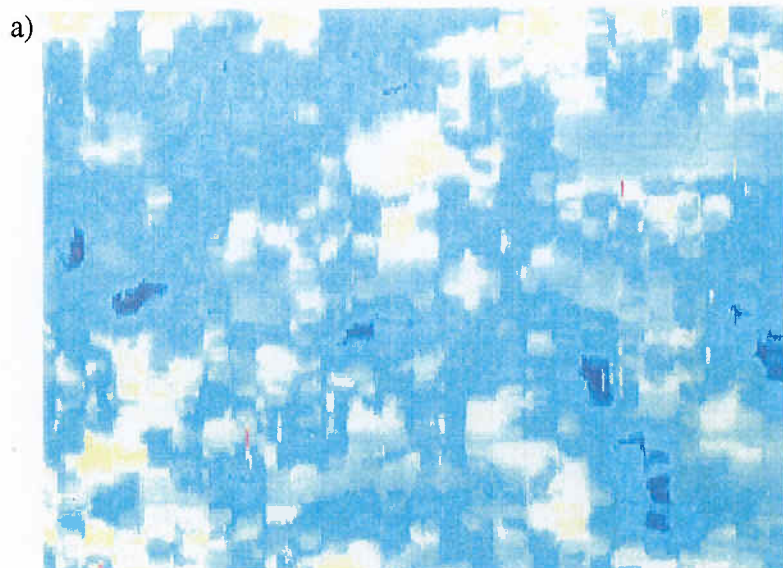


Figure 10, Height maps for sample RG drawn with colour scale covering full range of data listed in Tables 3-6, a) stylus map, b) SOM map, c) laser profilometer map.

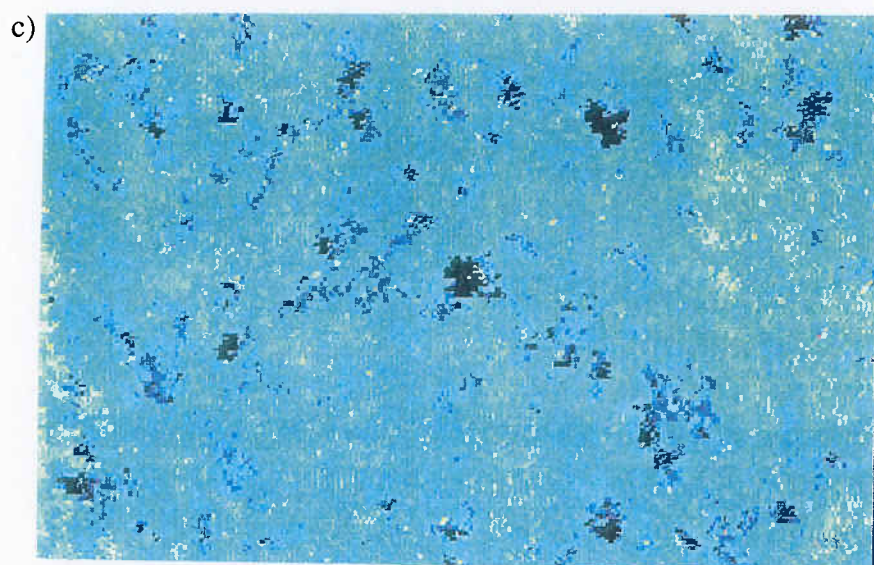
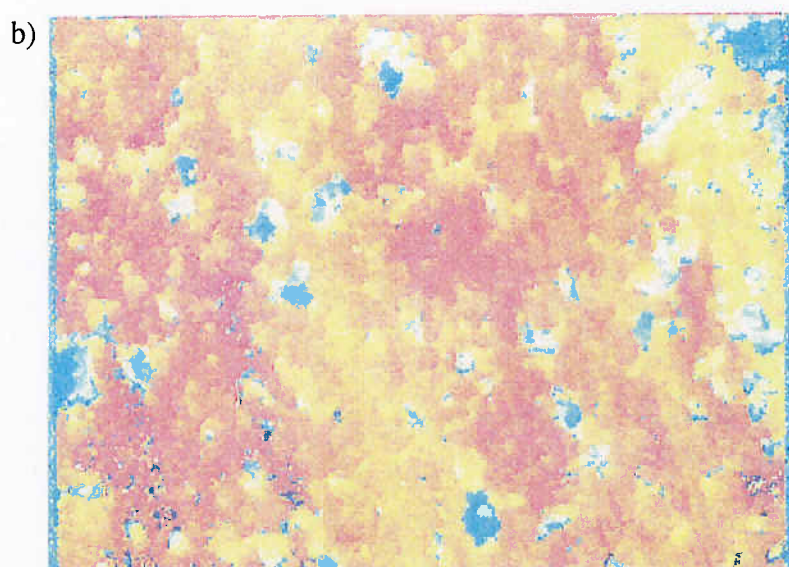
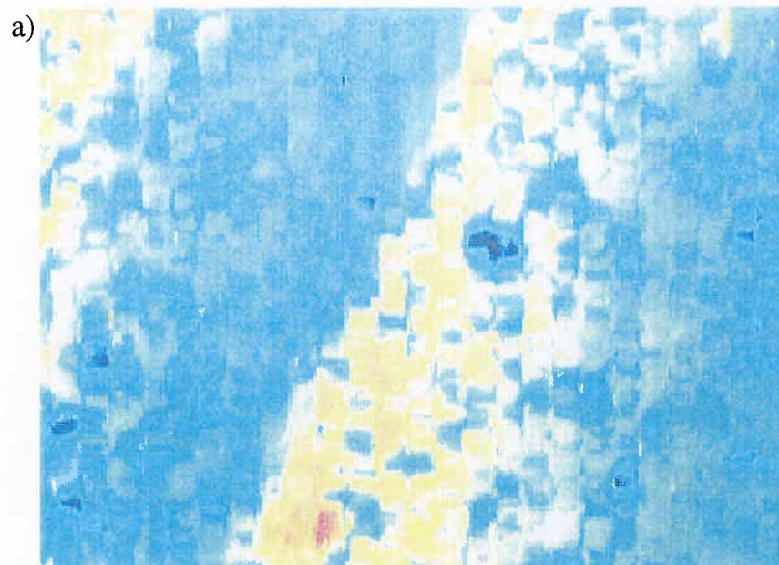


Figure 11, Height maps for sample SW drawn with colour scale covering full range of data listed in Tables 3-6, a) stylus map, b) SOM map, c) laser profilometer map.

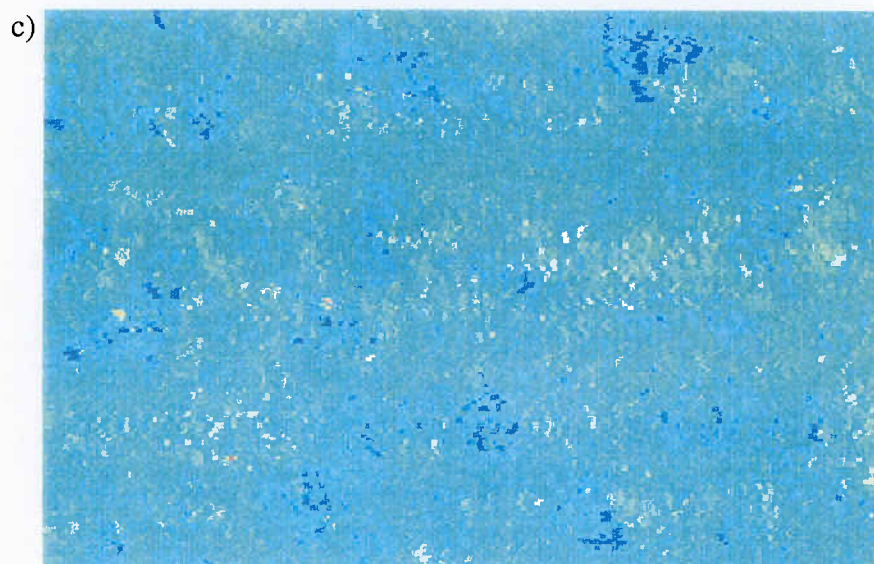
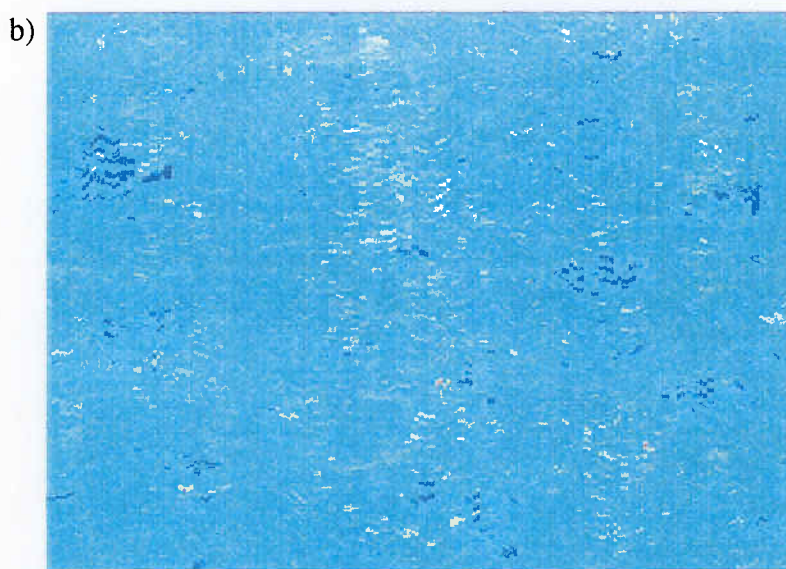
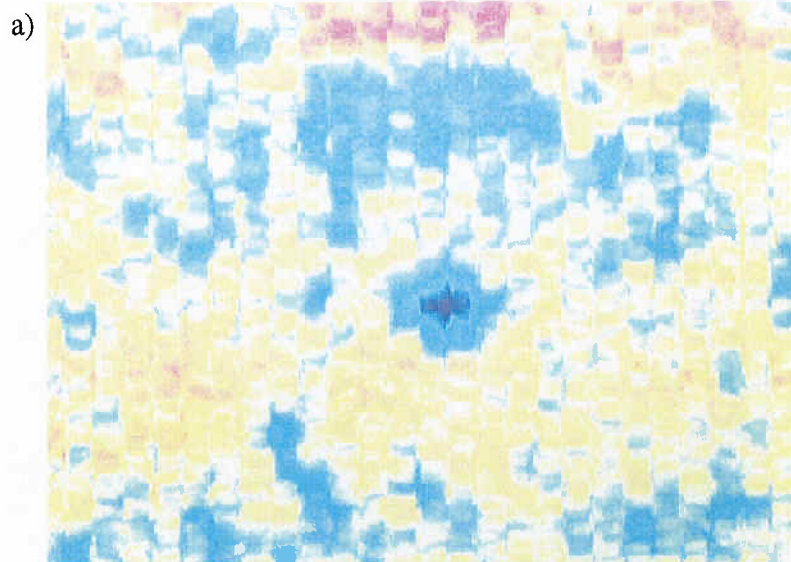
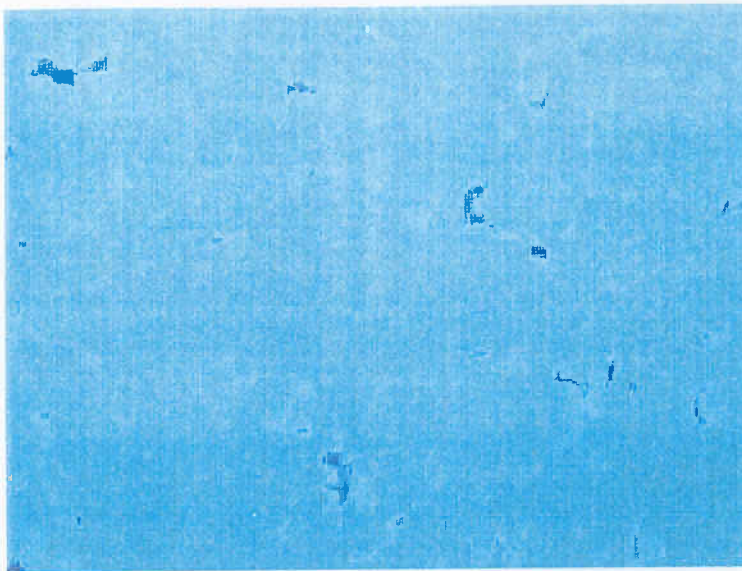
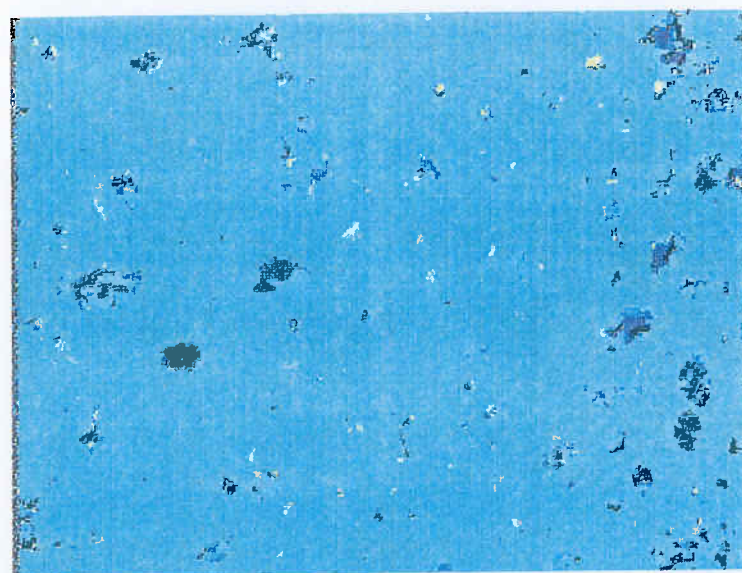


Figure 12, Height maps for sample A drawn with colour scale covering full range of data listed in Tables 3-6, a) stylus map, b) laser profilometer map.

a)



b)



c)

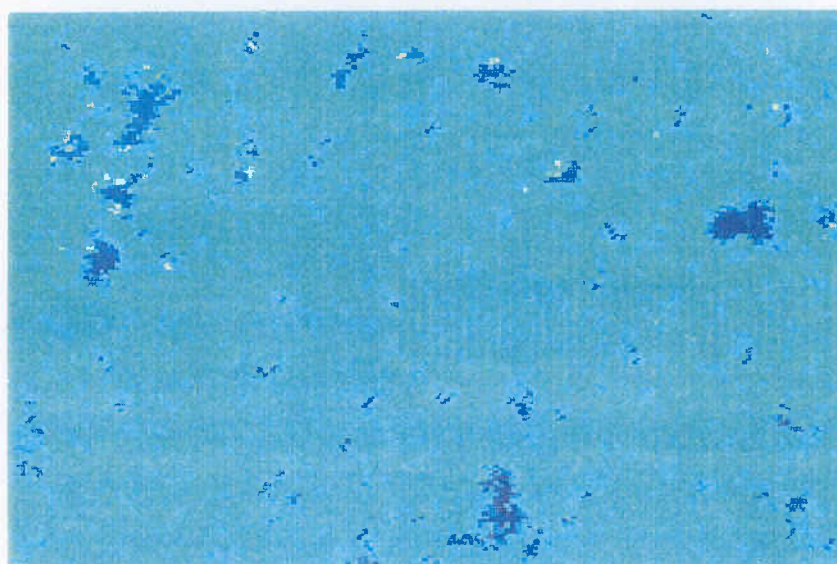
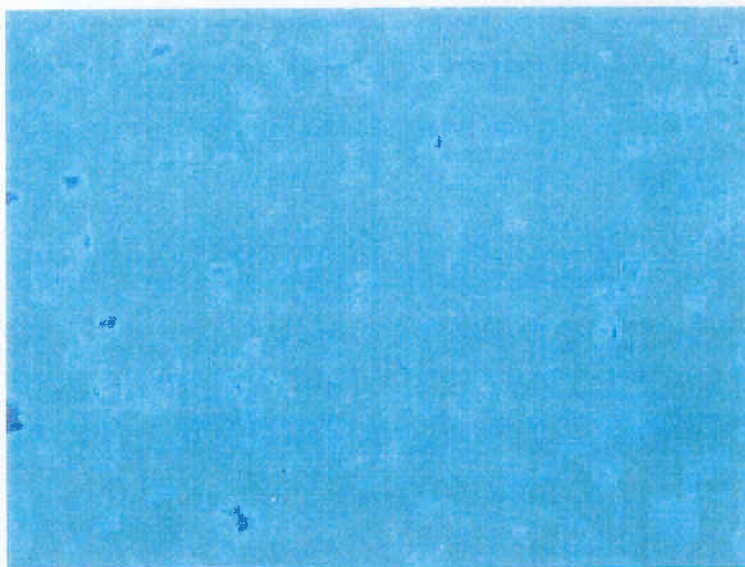


Figure 13, Height maps for sample LE drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value, a) stylus map, b) SOM map, c) laser profilometer map.

a)



b)



c)

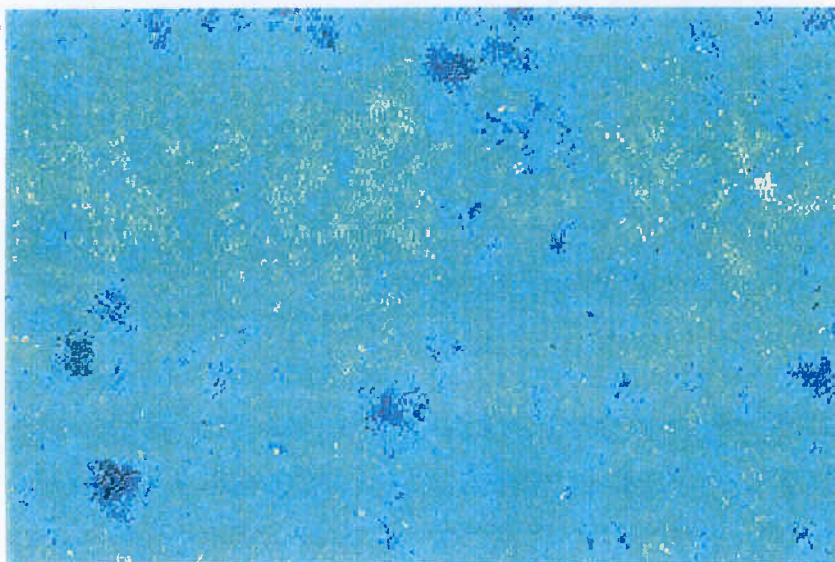


Figure 14, Height maps for sample FG drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value, a) stylus map, b) SOM map, c) laser profilometer map.

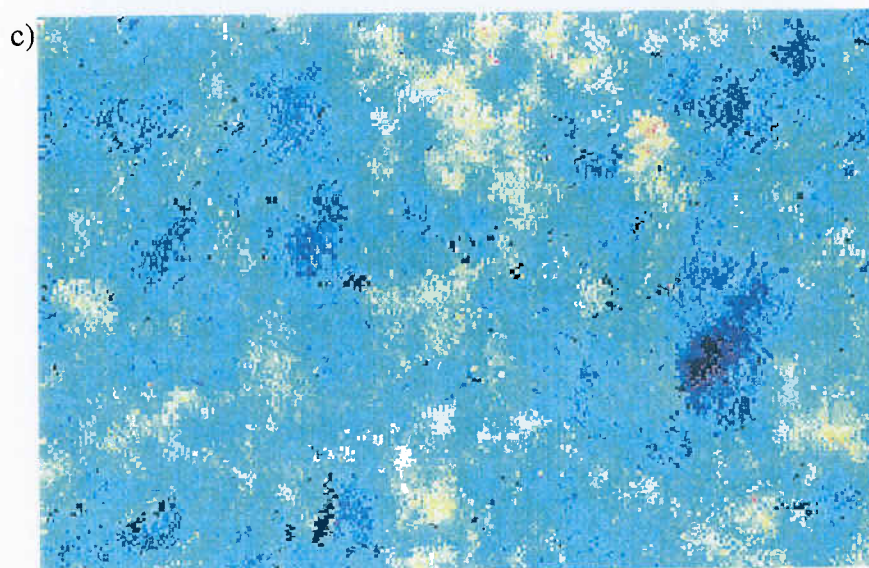
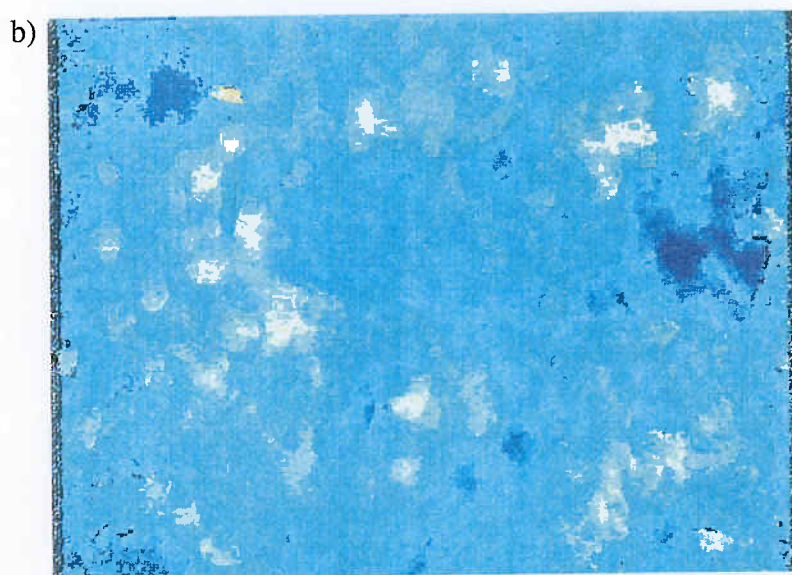
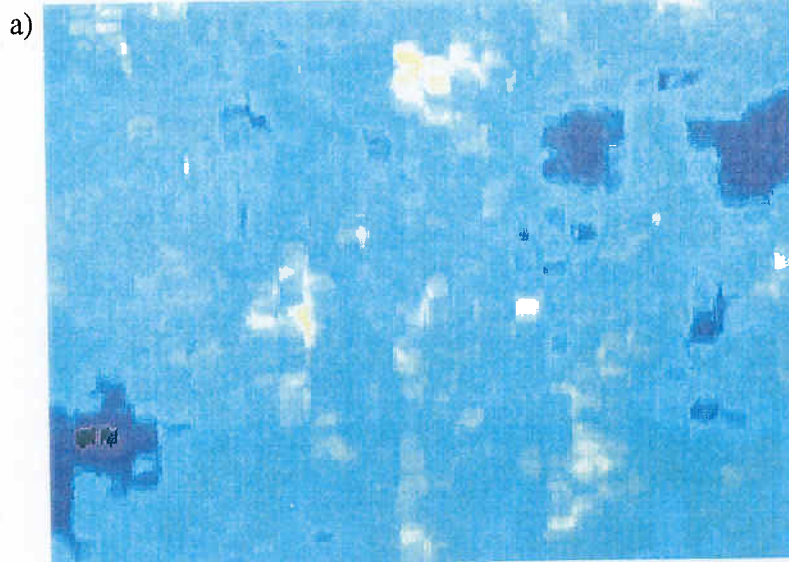


Figure 15, Height maps for sample RU drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value, a) stylus map, b) SOM map, c) laser profilometer map.

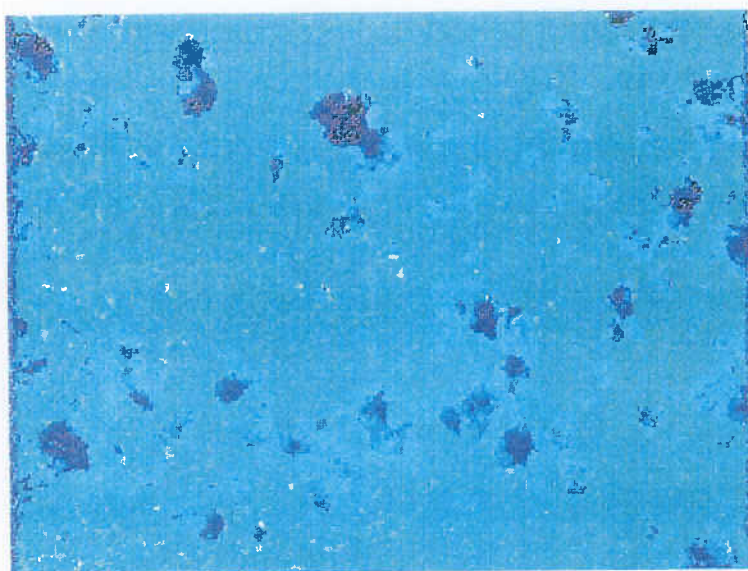


Figure 16, SOM height maps for sample 6L drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value

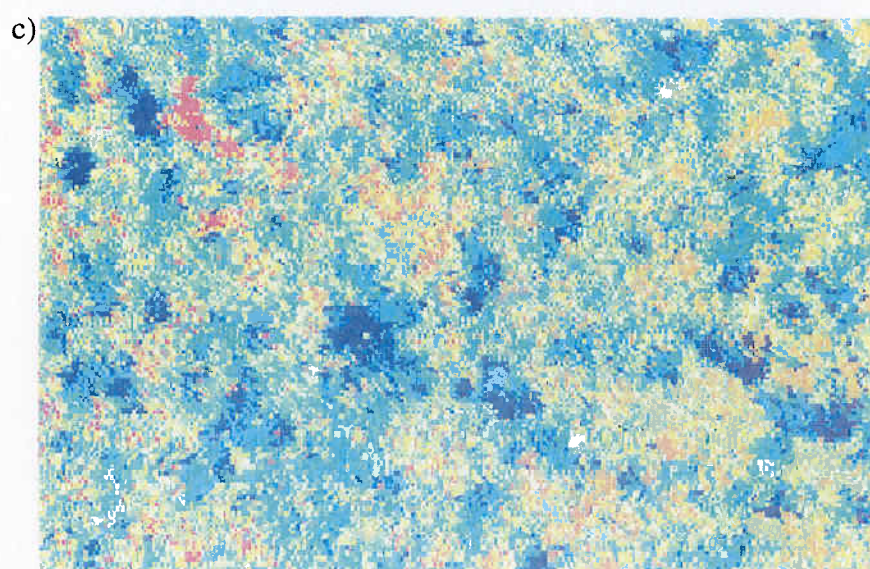
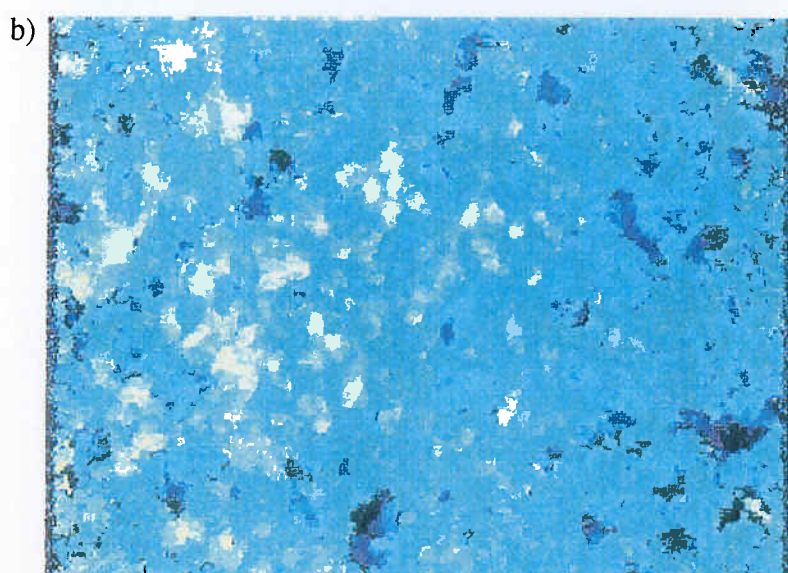
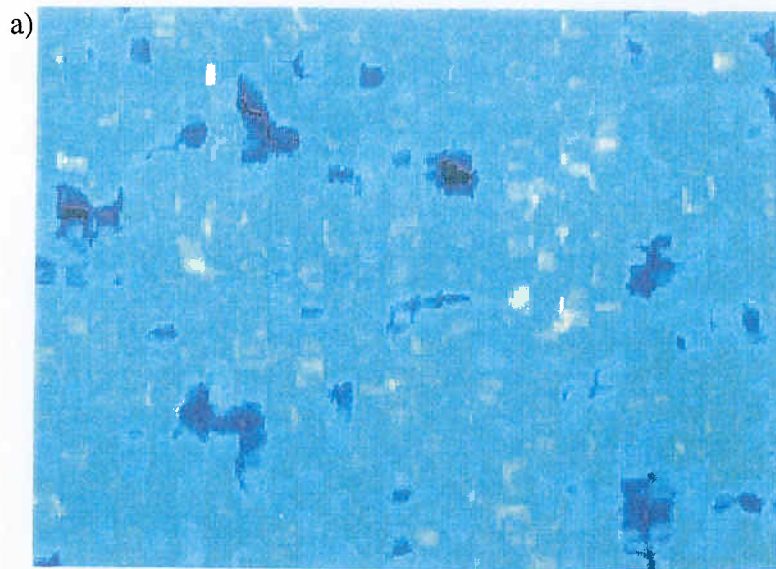


Figure 17, Height maps for sample SA drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value, a) stylus map, b) SOM map, c) laser profilometer map.

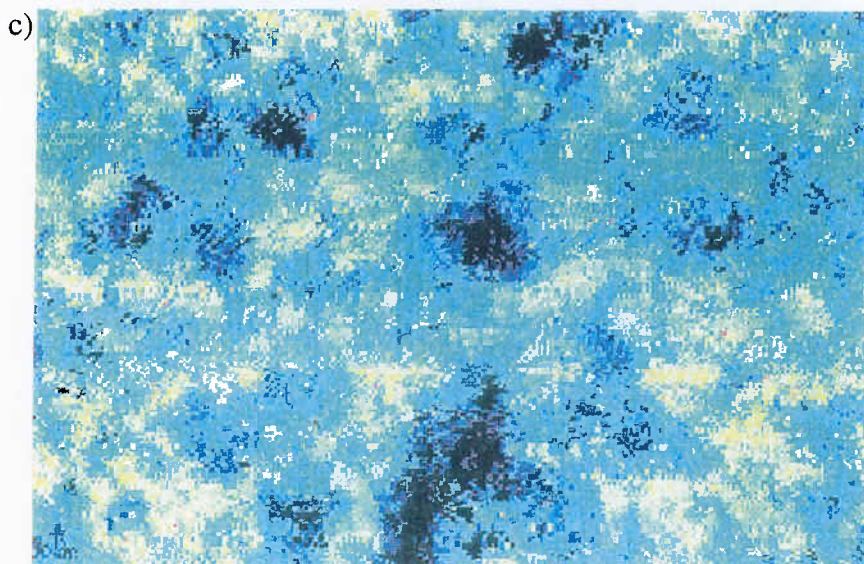
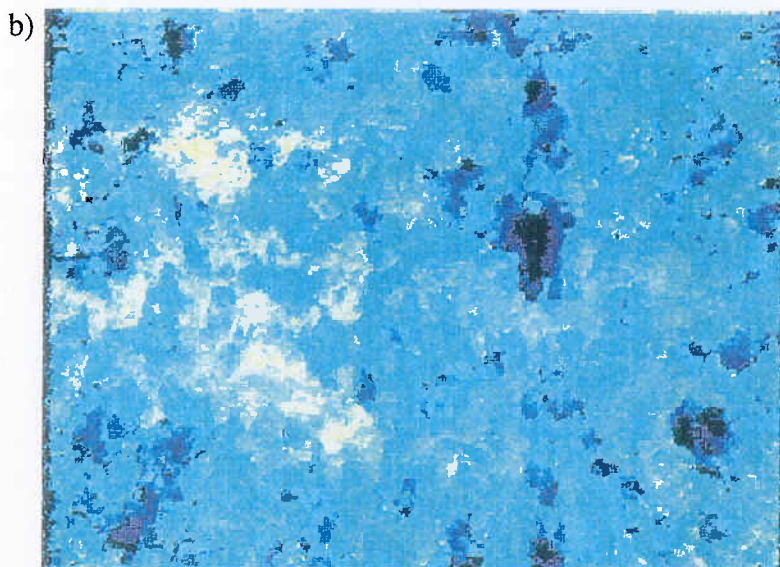
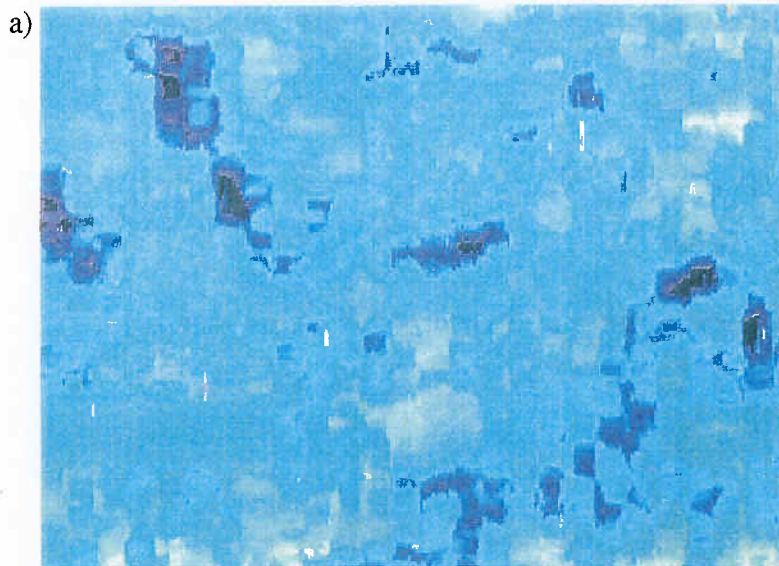


Figure 18, Height maps for sample RG drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value, a) stylus map, b) SOM map, c) laser profilometer map.

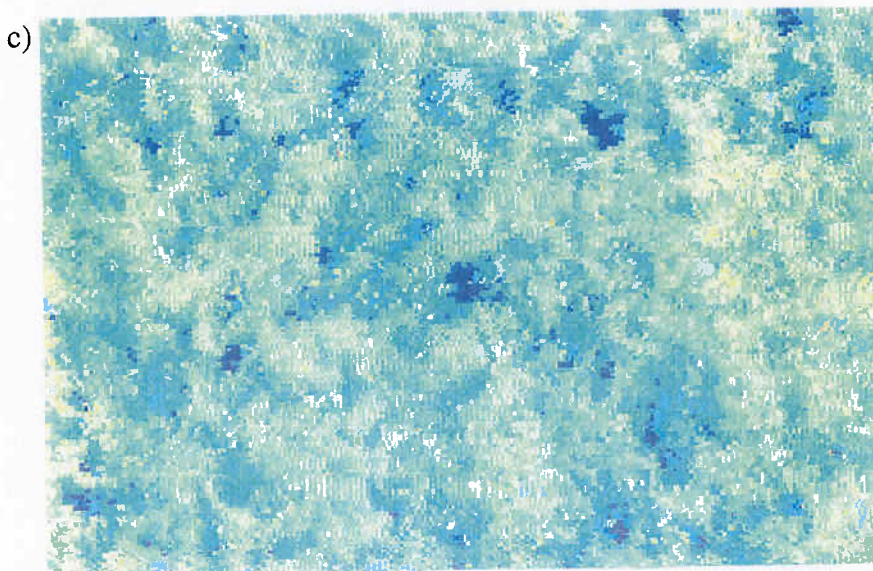
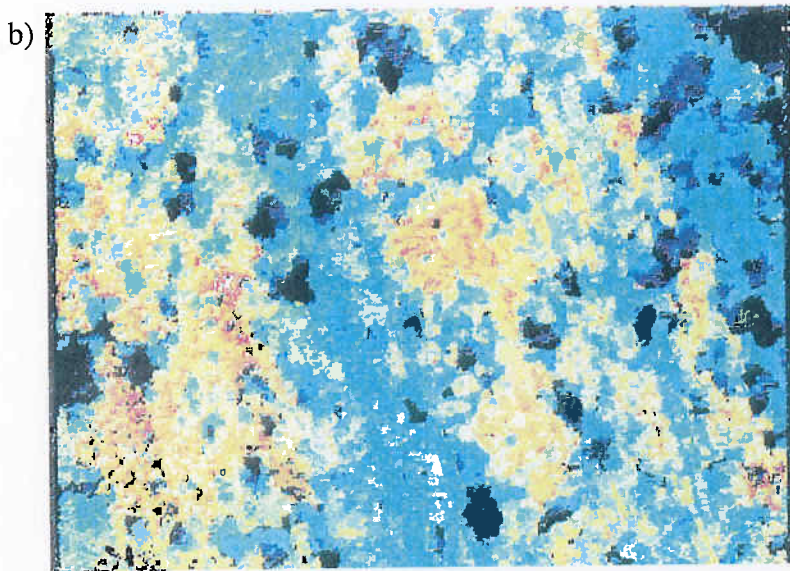
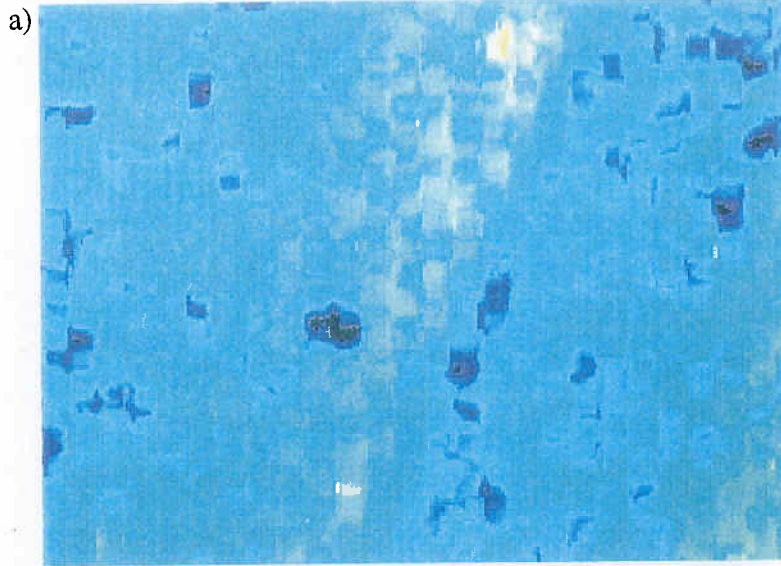
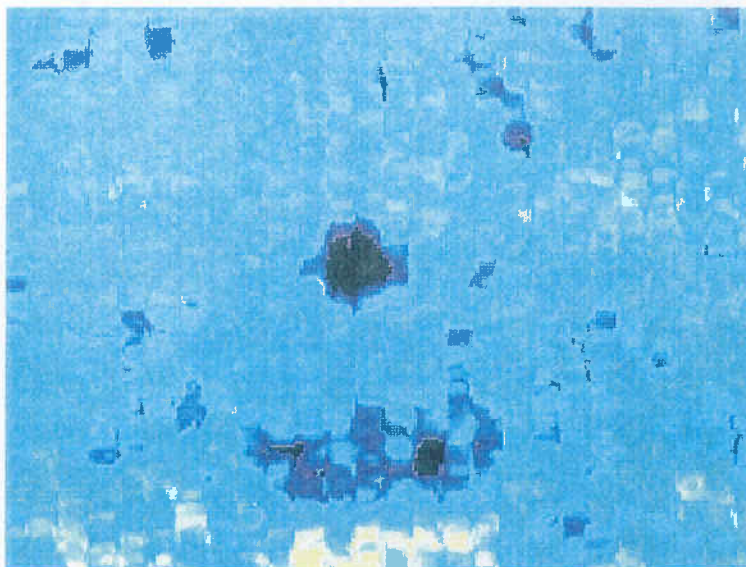


Figure 19, Height maps for sample SW drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value, a) stylus map, b) SOM map, c) laser profilometer map.

a)



b)

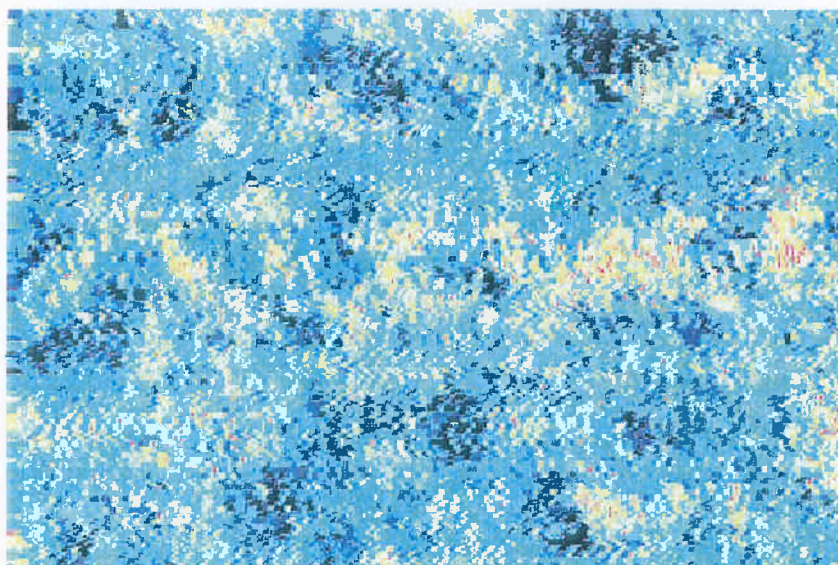


Figure 20, Height maps for sample A drawn with colour scale covering range of 5 micrometres below to 5 micrometres above mean value, a) stylus map, b) laser profilometer map.

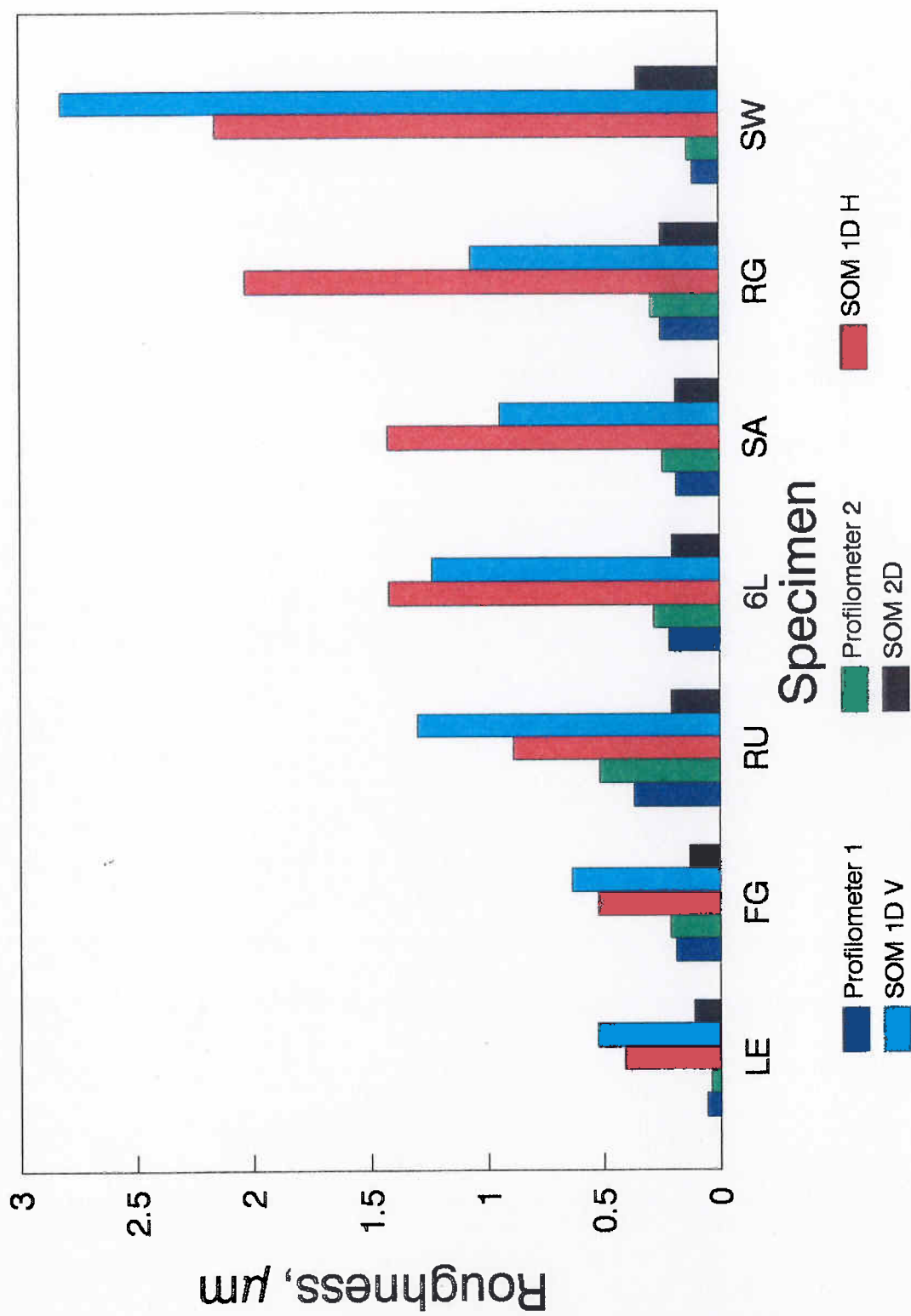


Figure 21, Roughness parameter comparison for profilometer and SOM. Note that Profilometer 1 and Profilometer 2, and SOM 1D V and SOM 1D H are R_a values for profiles extracted for the two orthogonal directions for the profilometer and the SOM respectively. The SOM 2D values are the S_a

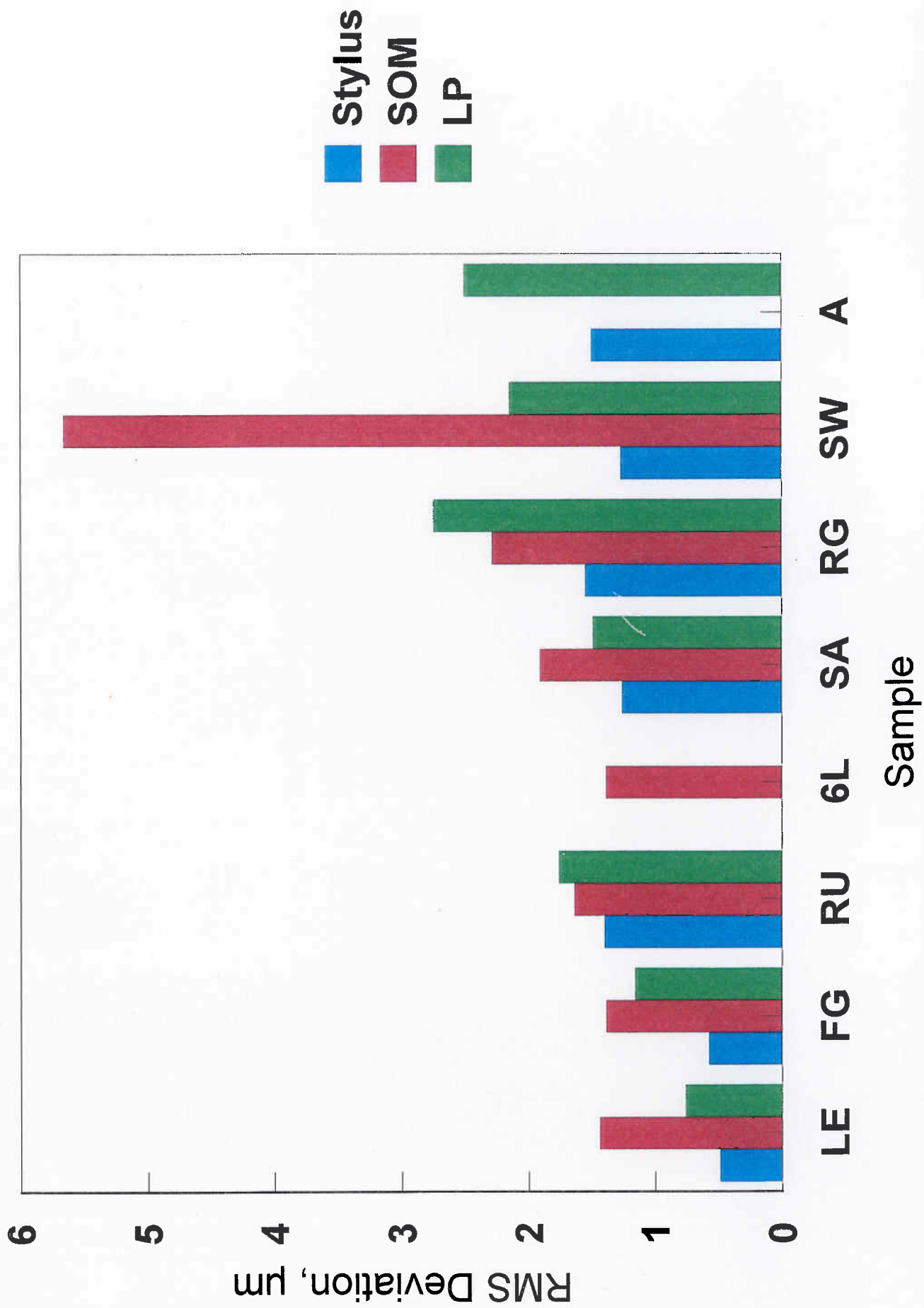


Figure 22, RMS deviation values for different samples and different measurement methods

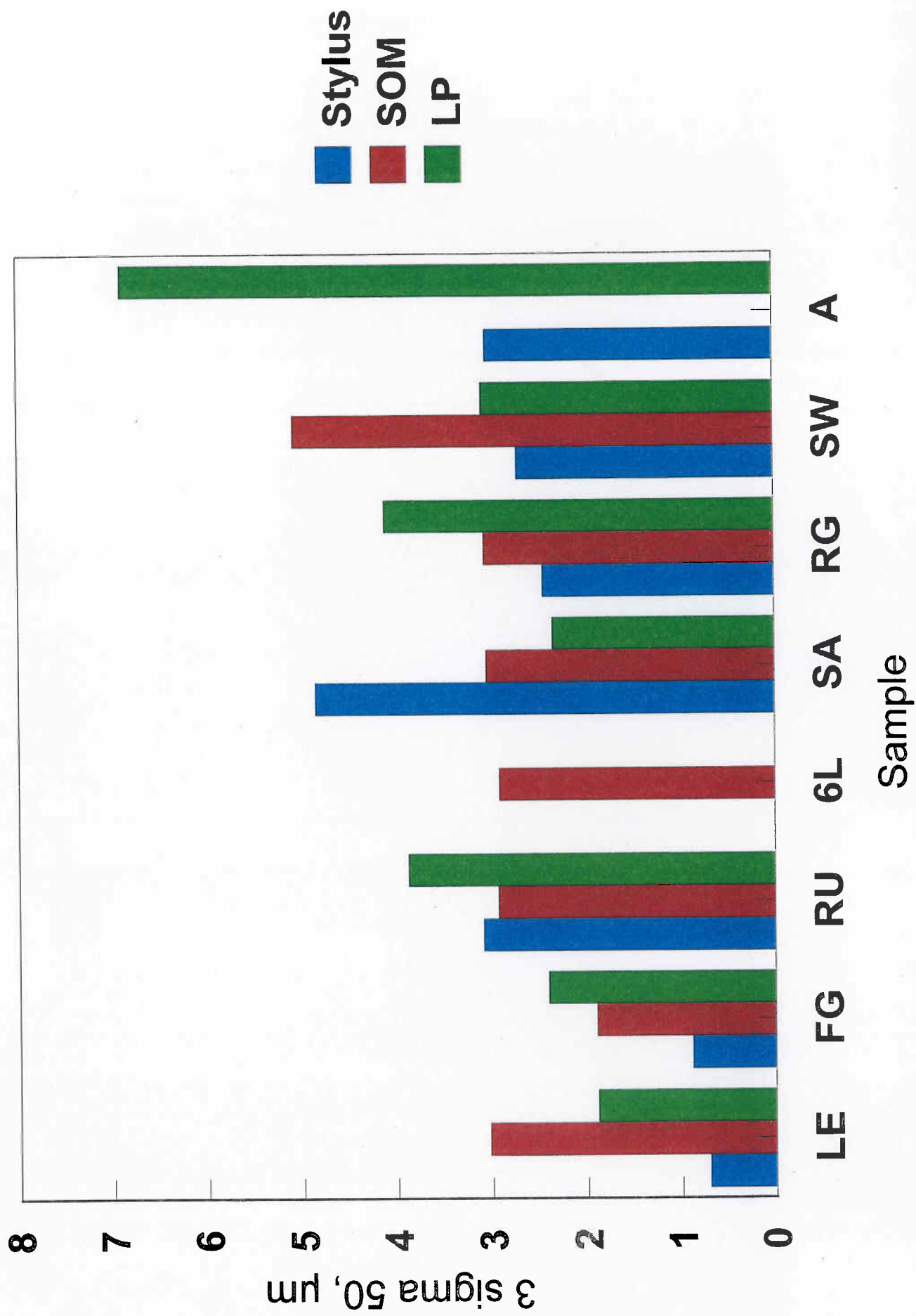


Figure 23, $3\sigma_{50}$ values for different samples and different measurement methods.

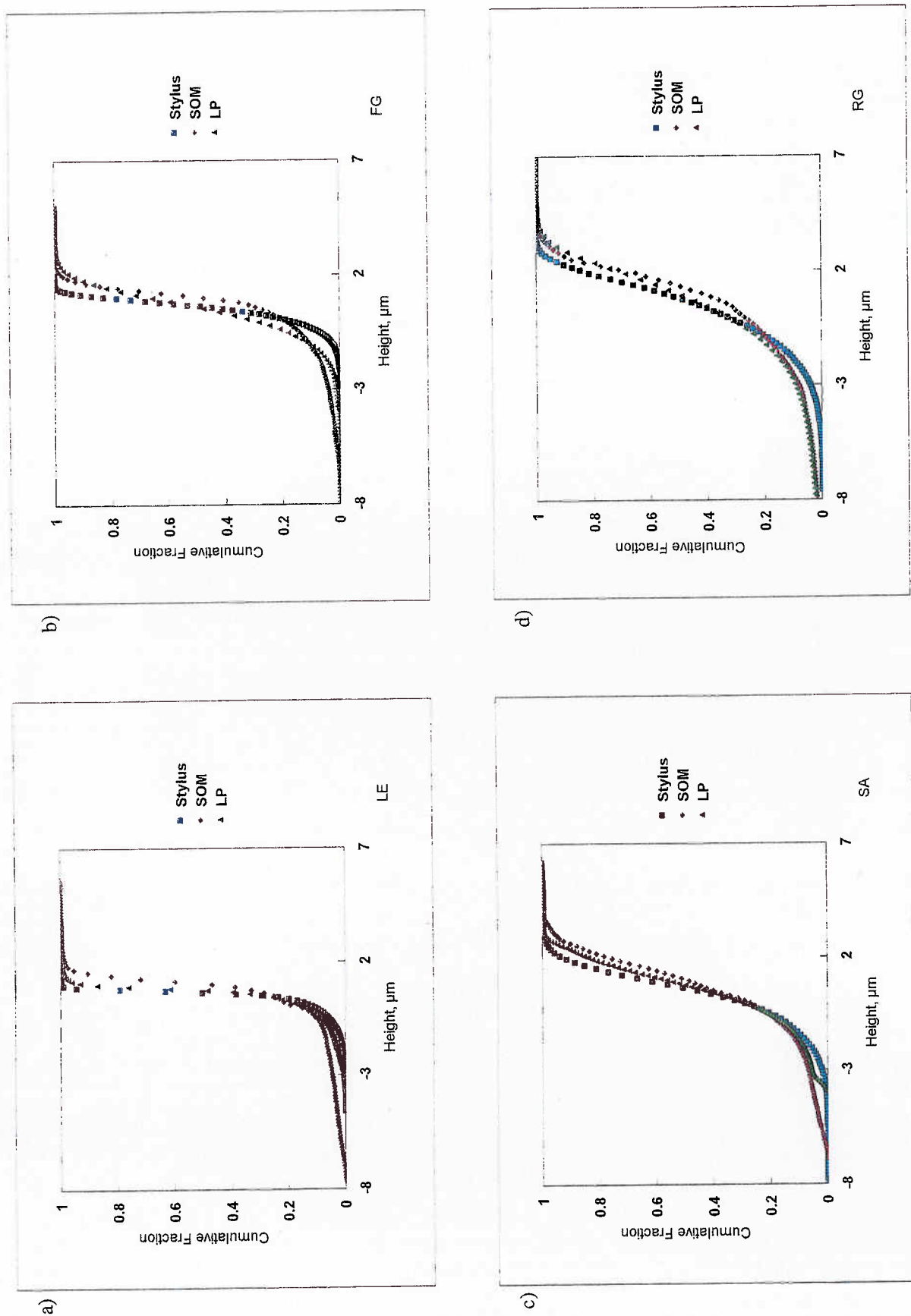


Figure 24, Bearing area curves for different instruments and samples, a) LE, b) FG, c) SA, d) RG, e) RU, f) SW, g) A, h) 6L.

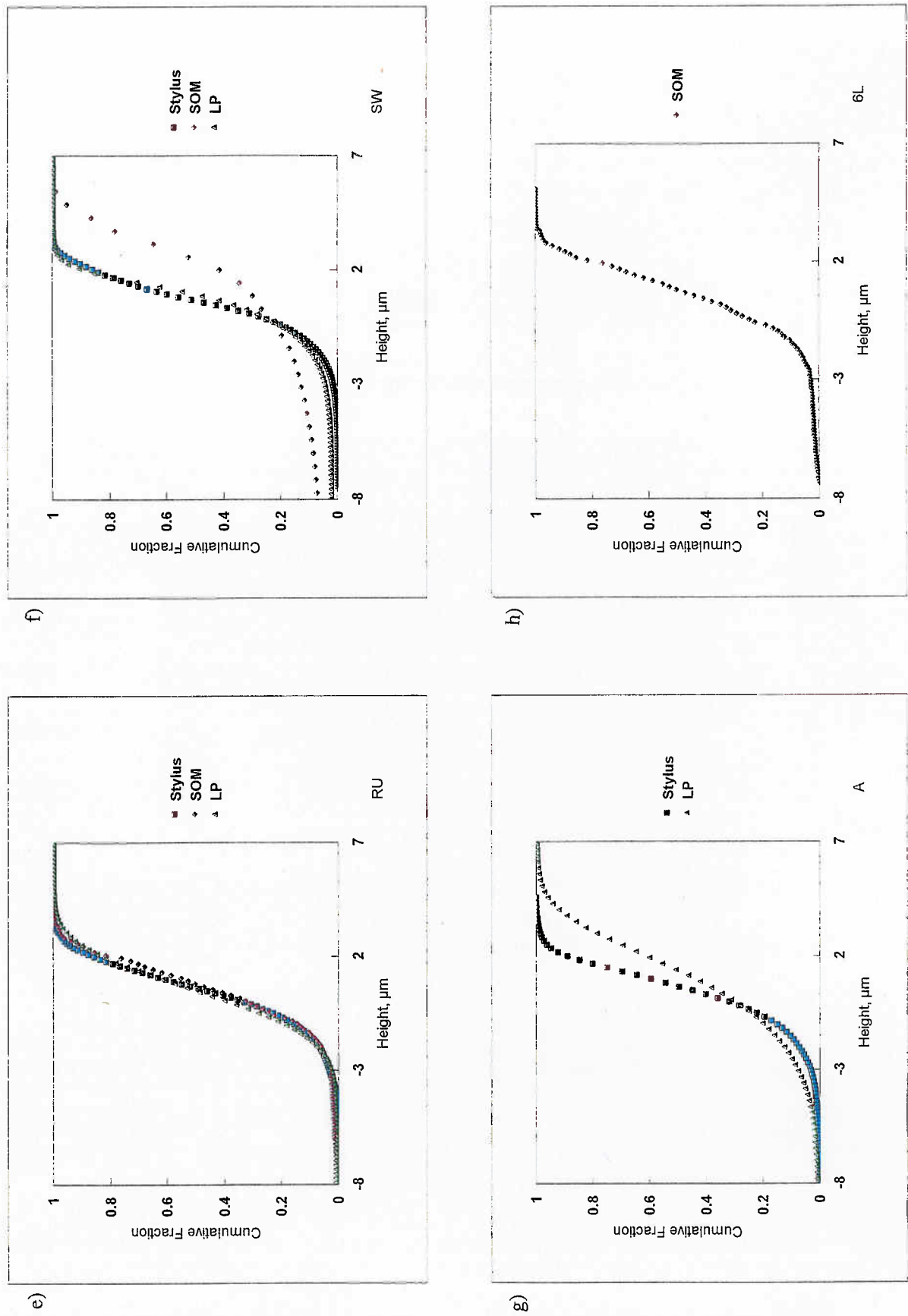


Figure 24, Bearing area curves for different instruments and samples, a) LE, b) FG, c) SA, d) RG, e) RU, f) SW, g) A, h) 6L.

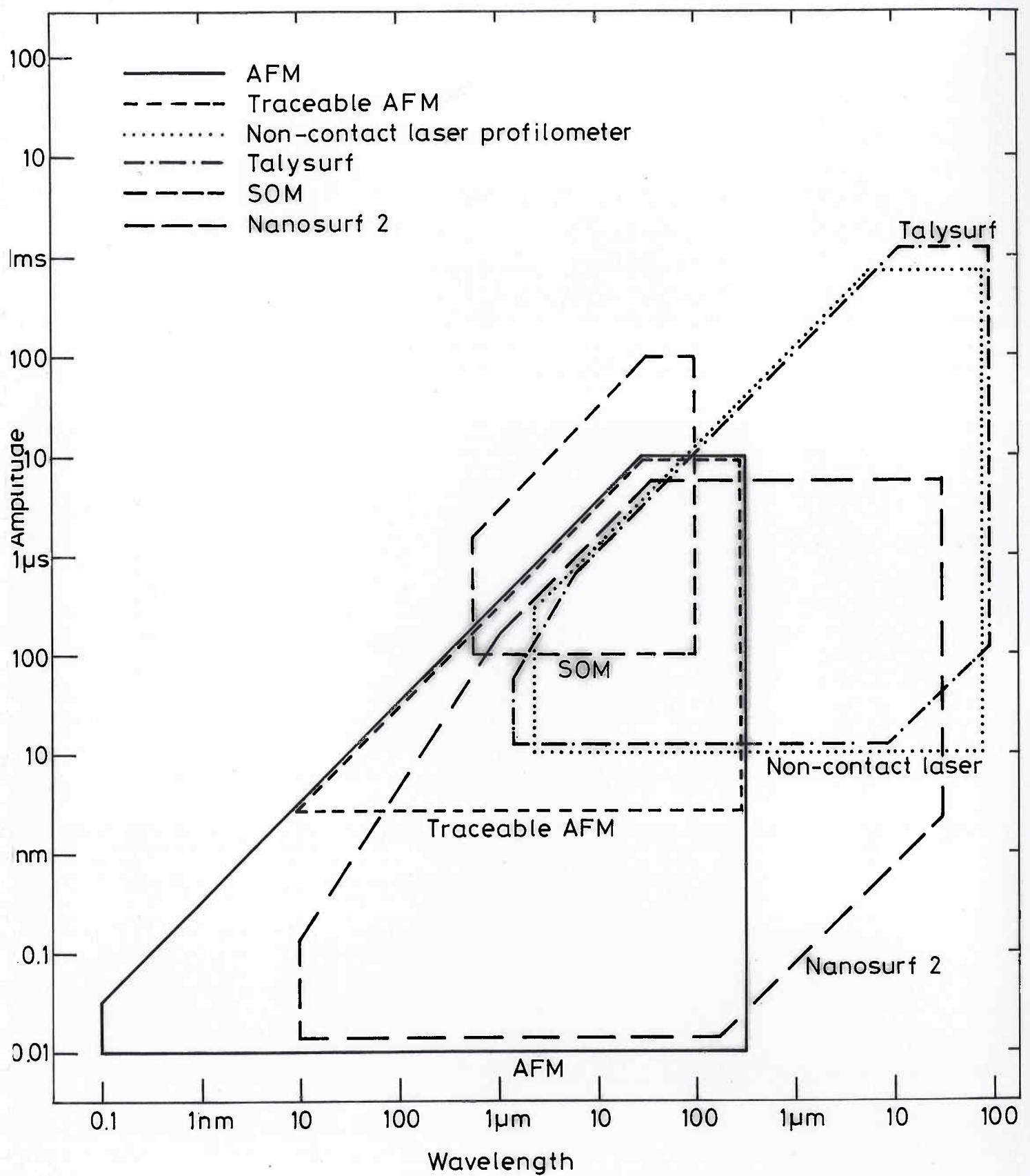


Figure 25, A-W maps for different measurement systems.

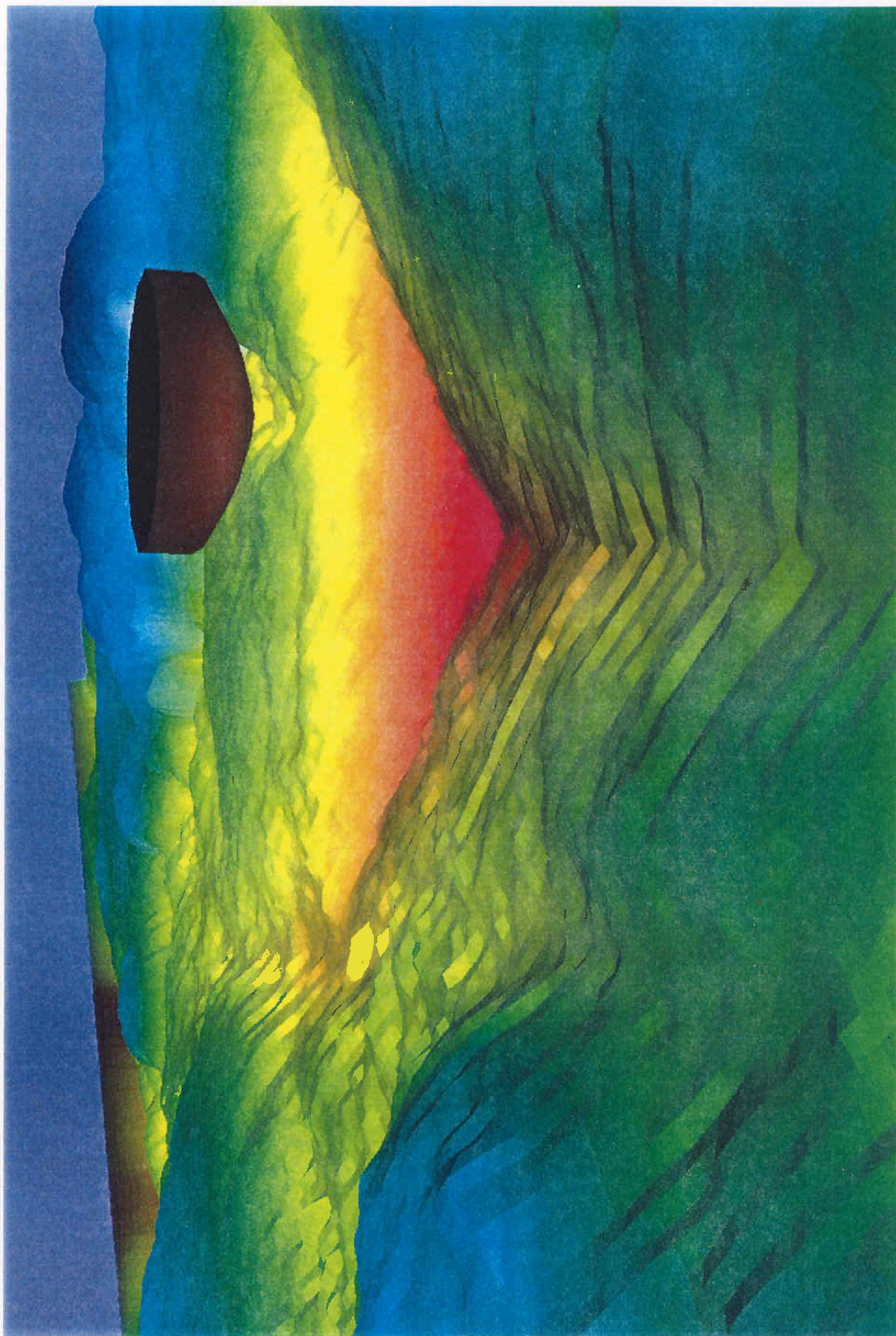


Figure 26, Visualisation of stylus interacting with surface extracted from interactive display.

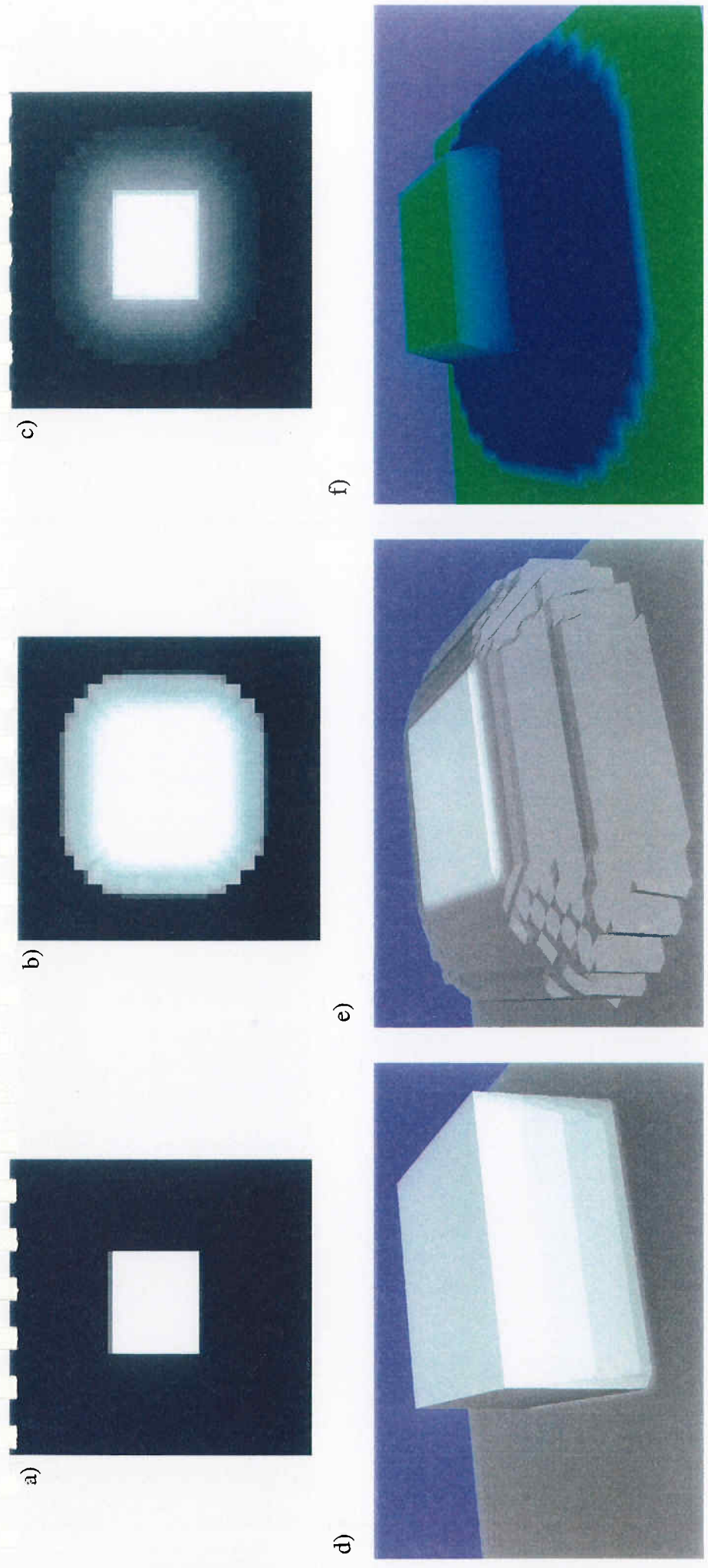


Figure 27, Model of deconvolution of tip shape effect and assessment of measurement errors for rectangular block, a) density scaled height map of block, b) a) simulation of map produced when measured by blunt tip, c) best attempt deconvoluted image, d), e), f) corresponding isometric views to a), b), c);, g) map showing area where real shape of surface is unknown shaded in red.

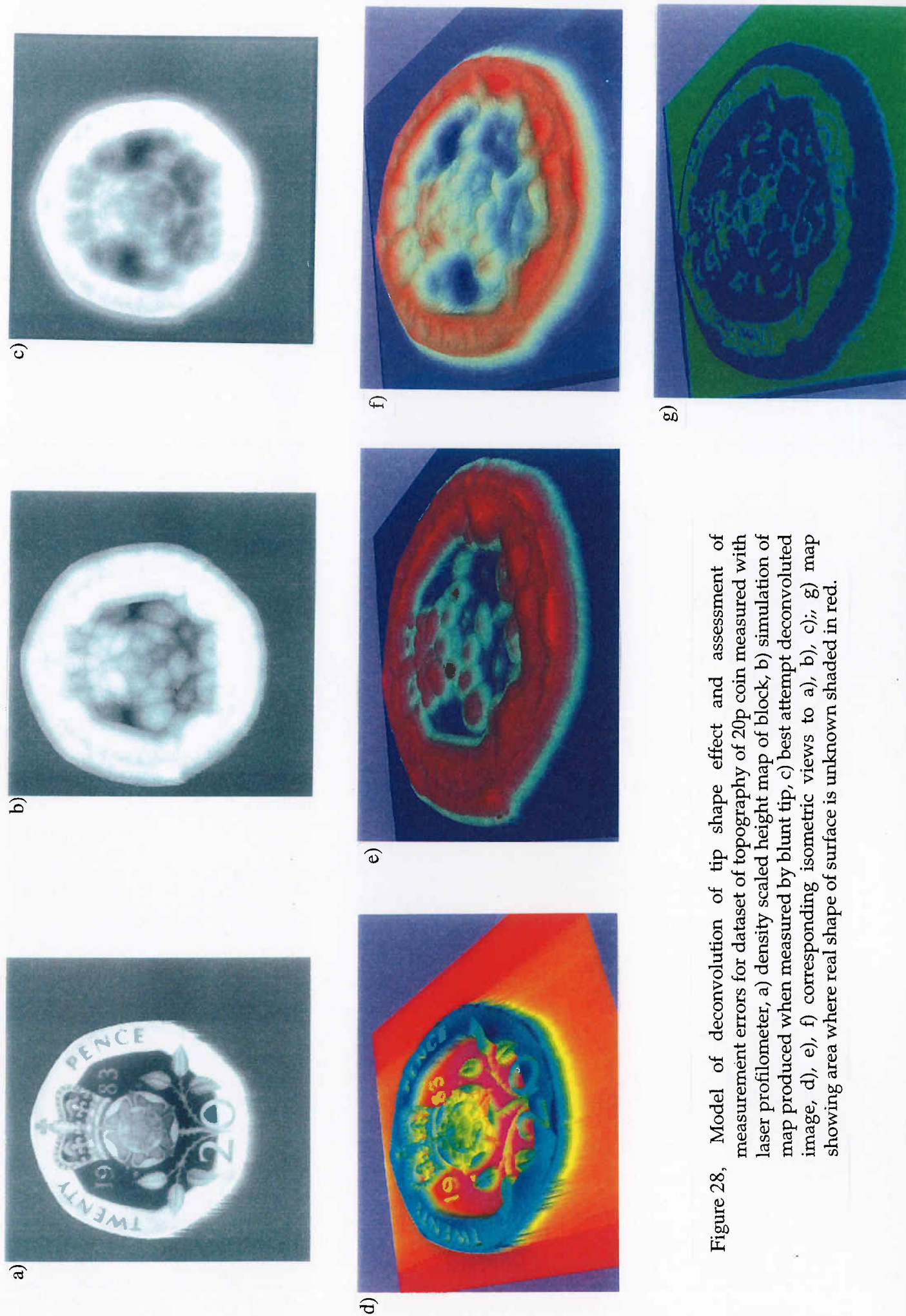


Figure 28, Model of deconvolution of tip shape effect and assessment of measurement errors for dataset of topography of 20p coin measured with laser profilometer, a) density scaled height map of block, b) simulation of map produced when measured by blunt tip, c) best attempt deconvoluted image, d), e), f) corresponding isometric views to a), b), c);, g) map showing area where real shape of surface is unknown shaded in red.

Appendix: Roughness Parameters [5,6]

In all the formulae below M and N are the dimensions of the array of measurements z_{ij} (N only for 2D), the summations are for all M,N,

Arithmetic mean deviation of surface or roughness average for 2D data, R_a

$$R_a = \frac{1}{N} \sum |z_i|$$

Arithmetic mean deviation of surface for 3D data, S_a

$$S_a = \frac{1}{NM} \sum |z_{ij}|$$

Root-mean-square deviation of the surface for 3D data, S_q

$$S_q = \sqrt{\frac{1}{NM} \sum \sum z_{ij}^2}$$

Skewness of the surface, S_{sk}

$$S_{sk} = \frac{1}{MNS_q^3} \sum \sum z_{ij}^3$$

Kurtosis of the surface, S_{ku}

$$S_{ku} = \frac{1}{MNS_q^4} \sum \sum z_{ij}^4$$