Traceable measurement of areal surface texture

R.K. Leach, C. Giusca

Industry & Innovation Division, National Physical Laboratory, Teddington TW11 0LW, UK

Abstract

There is a clear need in industry and academia for traceable areal surface texture measurements. To address this need traceable transfer artefacts and primary instrumentation are required. The National Physical Laboratory (NPL) is working on two projects – one to develop areal transfer artefacts and one to develop a traceable areal surface texture measuring instrument. The authors describe the development of the artefacts and instrument, and present some of the challenges that are still required to be able to offer an areal traceability measurement service to industry. The instrument has a working volume of 8 mm x 8 mm x 0.1 mm and uses a co-planar air-bearing slideway to move the sample. It also uses a novel vertical displacement measuring probe, incorporating an air-bearing and an electromagnetic force control mechanism. The motions of the slideway and the probe are measured by laser interferometers thus ensuring traceability of the measurements to the definition of the metre. The artefacts were manufactured using a range of machining technologies and in a range of geometries suitable for stylus and optical based instruments.

Keywords: areal, surface texture, measurement, transfer artefacts, areal standards

1. Introduction

Surface texture plays a vital role in the functionality of modern engineered products. Traditionally, surface texture data is used to monitor changes in a manufacturing process. For this form of monitoring, a two-dimensional, profile measurement is sufficient. Industry often has a need to engineer or structure a surface in three dimensions to impart functionality into the surface and the resulting device. Examples include micro-lens arrays for modern displays, MEMS for sensing applications, and glasses that are patterned in such a way as to make them hydrophobic and hence essentially self-cleaning. Three-dimensional or areal surface texture measurements have a number of advantages over profile measurements including:

- The areal approach comes closer to fully describing a real surface and the derived parameters possess greater functional significance.
- The areal approach allows parameters to be derived relating to area for the first time, for example, texture "strength" and direction, material and void volumes, *etc.*
- The areal approach takes data from an area rather than a profile, therefore, the parameters have greater statistical significance and better repeatability between different parts of the same surface.
- Areal measurements are a better visualisation tool.

The control of complex structured surfaces requires an areal measurement of surface texture. There are many instruments on the market that address this need, for example, coherence scanning interferometers (often referred to as vertical scanning white light interferometers) and scanning stylus instruments, but there is currently no definitive, direct route to traceability for such instruments [1]. At present, traceability is inferred from calibrated artefacts and measurement strategies that were originally designed to calibrate profile measuring stylus instruments. Whilst this method of calibration may be adequate in some circumstances, there are characteristics of an areal instrument that cannot be determined from profile measurements alone.

The UK National Measurement System has recently funded two projects that go a long way to establishing traceability of areal surface texture measurement. Firstly, NPL has collaborated with the Atomic Weapons Establishment (AWE), Rubert & Co. and Taylor Hobson to produce a set of prototype artefacts to address verification and calibration of various performance aspects of areal surface texture measuring instruments [2]. Secondly, NPL has developed a traceable areal surface texture measuring instrument [3]. These two projects are described below. We also discuss the current state of standardisation for areal surface texture and discuss some further work that is still required to fully complete the traceability chain.

2. Areal specification standards

In 2002 the International Organization for Standardization (ISO) Technical Committee 213, dealing with Dimensional and Geometrical Product Specifications and Verifications, formed a working group to address standardisation of areal surface texture measurement methods. The working group is developing a number of draft standards encompassing definitions of terms and parameters, calibration methods, file formats and characteristics of instruments. The first published standards are expected some time in 2009. These standards will finally allow engineers and scientist to start to gain benefit from the deterministic areal structuring of surfaces. However, the change over from profile standards (currently used on engineering drawings to tolerance surface texture) to

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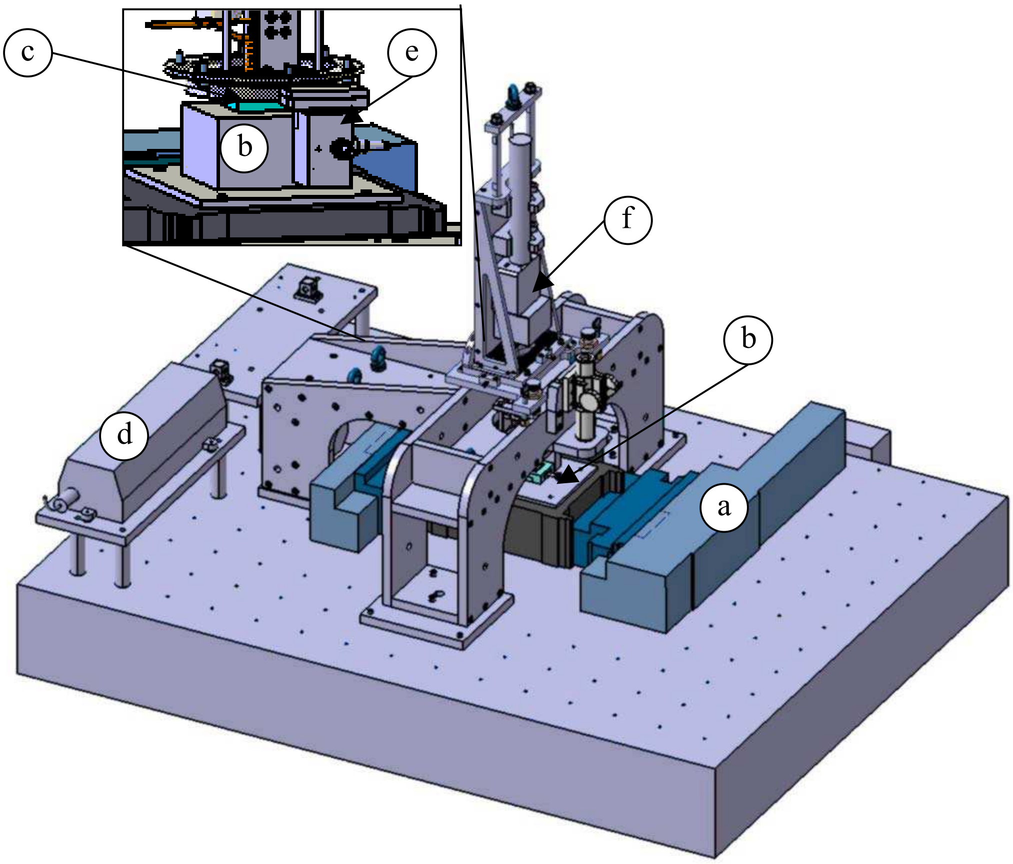

Figure 1 CAD drawing of NPL Areal Instrument: a) co-planar linear air-bearing stage, b) sample holder and Zerodur mirror block, c) reference mirrors, d) laser source, e) linear and angular column-referenced interferometers f) *z*-axis plane mirror differential interferometer (see also Figure 2)

areal standards (of which profile standards will become a subset) will require a great deal of dissemination and education. Whilst this may be a difficult changeover for some industries, the rewards for embracing areal methods for product design and manufacture will be highly significant.

3. A traceable areal measuring instrument

The NPL Areal Instrument (figure 1) was designed to have a working volume of 8 mm × 8 mm × 0.1 mm and a target uncertainty of 10 nm × 10 nm × 1 nm. The instrument consists of an ABL9000 co-planar linear air-bearing stage (figure 1 a) designed for this application by Aerotech on which is mounted a sample holder and Zerodur mirror block (figure 1 b). The design of the stage is such that pitch, roll, yaw and orthogonality errors are less than two seconds of arc. The mirror block is reflectively coated on three sides and has sub-second of arc orthogonality errors and faces flat to less than 60 nm. Two further reference mirrors (figure 1 c) are mounted on the probe body. The position of the mirror block in the *xy*-plane is determined using a commercial laser interferometer system utilising two linear and angular column-referenced interferometers (figure 1 e) (Zygo ZMI2000 series). The surface being measured is mounted within the Zerodur block and the motion of a stylus as it is scanned across the surface being measured is detected by the use of a plane mirror differential interferometer (see figure 1 f and figure 2).

The interferometers for measurement of the motion in the *xy* plane both measure a linear and an angular (yaw) degree of freedom. Therefore, if the mirrors were perfectly flat and orthogonal, one of the angular interferometers is redundant. The light from a frequency-stabilised laser is input to the interferometers using mirrors and the measurement signals are output to the processing electronics *via* fibre optic cables. The output from the pairs of *x* and *y* interferometers (and the *z* interferometer) are synchronised at the sub-microsecond level using bespoke hardware.

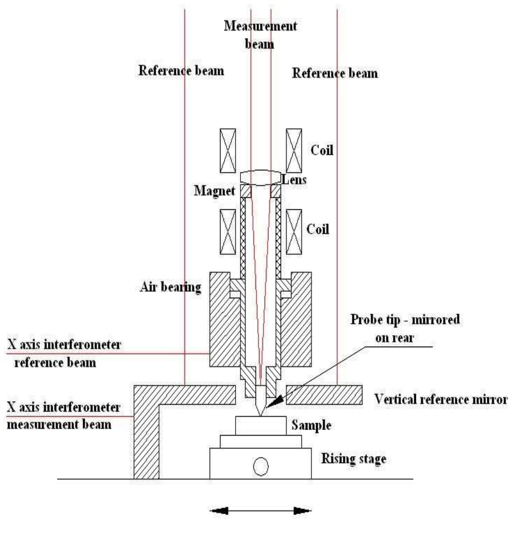

Figure 2 Schematic of *z* interferometer

At the instrument design stage many types of probe design were considered. When performing areal measurements with a tactile probe, the measurement duration becomes an issue and the use of dry bearings is inappropriate due to their relatively slow motion (as on the NPL NanoSurf IV traceable profile measuring instrument [4]). In an industrial application an optical probe is generally much faster than a tactile probe, but for a stylus-based traceable instrument it is much easier to predict the surface-stylus interaction with a conispherical stylus tip than the interaction of a optical beam with the surface. The probing system (Figure 2) utilises an air bearing (developed by Fluid Film Devices) as a linear guide for a stylus with an electromagnetic force control device, akin to a probe design reported elsewhere [5]. The sample is mounted inside a Zerodur mirror block that is described above, so that it comes into contact with the probe (this is achieved with Zerodur spacers and a height adjustment stage). The stylus is attached to the end of a hollow cylindrical air bearing and consists of a Zerodur rod with a polished and aluminised end face with a conventional diamond stylus on the opposite end. The air bearing is hollow to keep the mass of the probe down and allow the passage of the measurement beams of the *z* interferometer. The stylus operates through a hole in the vertical reference mirror and contacts the sample.

The static probing force is controlled by an arrangement of two electromagnets and a toroidal permanent magnet. The electromagnet design is that of a Maxwell pair (akin to a Helmholz coil but with the current passing in opposite directions in the two coils). This ensures a constant static probing force with respect to displacement in the *z* axis [6]. Note that this magnet and coil arrangement requires a current of more than 100 mA and needs to be water-cooled.

The displacement of the probe in response to the surface topography of the sample is measured by a differential plane mirror interferometer [7] where the measurement beams are focused onto the stylus mirror using an aspheric lens. The plane mirror interferometer system is referenced from the vertical reference mirror (see Figure 2). This referencing scheme essentially removes the effect of thermal or mechanical instabilities in the steel metrology frame (although any effects of the spacers and rising stage are not removed). The probe is designed to have a resolution of 0.1 nm, an accuracy of 1 nm, a range of 0.1 mm (with some over travel) and to be capable of responding to structures with wavelengths of 0.001 mm when scanning a surface at 1 mm s^{-1} (*i.e.*, 1 kHz).

At the time of writing only preliminary noise tests for the probe have been carried out. The RMS noise level is less than 3 nm with the probe in contact with a surface and all air-bearings and water cooling running. Comparisons with other traceable instruments [4] and further system performance tests will now be carried out and these results will be presented in a future paper. A full uncertainty analysis is also being developed.

4. Traceable areal transfer artefacts

NPL has collaborated with AWE, Rubert & Co. and Taylor Hobson to produce a set of prototype artefacts to address verification and calibration of various performance aspects of areal surface texture measuring instruments. A primary consideration in the design of the artefacts was the need for compatibility with both contact and non-contact measuring instruments. Compatibility is important to many users, as it is very common to compare data from non-contact areal instruments and stylus profilometers. The artefacts need to transfer the traceable calibration from the stylus based primary instrument to non-contacting instruments in use in R&D laboratories and industry. The ease of manufacture of the artefacts was also a major consideration at the design phase, since the artefacts need to deliver traceable and accurate calibration at reasonable cost. Artefacts have been manufactured using the following methods: silicon processing, optical lithography, and diamond turning combined with replication in electroformed nickel. The artefacts are designed to address calibration of lateral and vertical scales, verification of lateral resolution, dynamic response and probe condition monitoring.

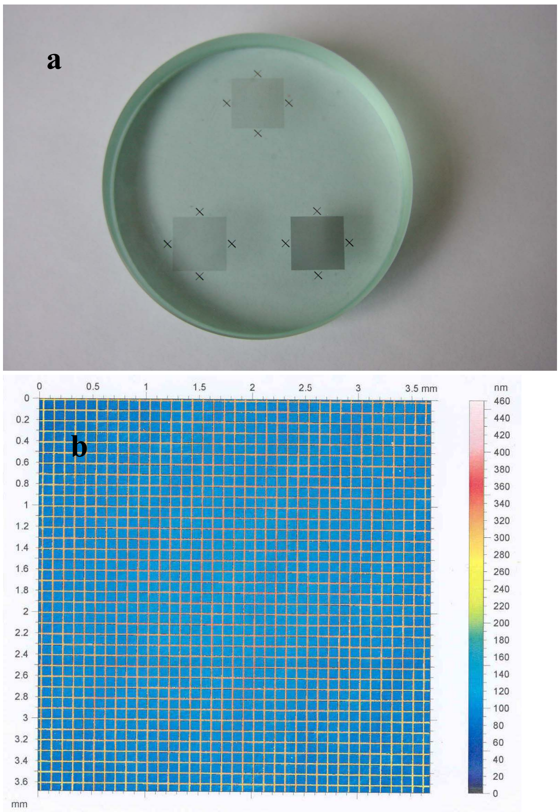

Figure 3 Lateral scale calibration artefact: a) photograph, b) coherence scanning interferometer plot of 100 µm period grid

A set of grid patterns was produced for calibration of lateral scales. The grids are chrome-on-glass patterns with nominal periods of 200 µm, 100 µm and 20 µm with line widths of 20 µm, 10 µm and 5 µm respectively. Each of the three patterns extends over a 12 mm square patch, and all three are on a single, 59 mm diameter, flat glass substrate. Figure 3 a shows a photograph of the artefact and Figure 3 b shows an plot from a coherence scanning interferometer instrument of the 100 µm period grid. The grids were evaluated using two traceable methods of measurement. The average periods of the grids in the two orthogonal directions on four sets of grids were measured by an optical diffraction method [8], and found to be within 0.1% of their nominal values. The uniformity of placement of the lines was measured on one set of grids using a traceable linescale measuring instrument [9]. The cumulative error in line placement over the 10 mm extent of the patterns was measured to

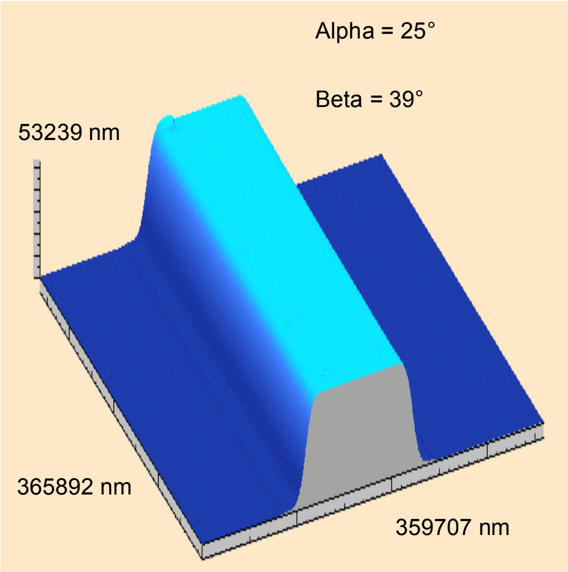

Figure 4 Coherence scanning interferometer plot of a 50 µm step

be less than 0.5 µm. The grids may be used to check linearity of scales and their orthogonality.

It is common practice to calibrate the *z*-axis scale of areal instruments using the method, and standard step height artefact types, described in the stylus profilometry standard ISO 5436-1 (2000) [10]. This practice is satisfactory for calibration, but needs to be supplemented by verification of the uniformity of the response of the probe over the field of view of the instrument. For example, on a coherence scanning interferometer small errors in *z*-axis measurement may be attributed to imperfections in the reference mirror; these may be corrected for by comparison with a calibrated reference flat. A set of artefacts was produced covering the step height range 10 nm to 50 µm, with step widths at 100 µm and 500 µm, permitting the step height measurement described in ISO 5436 to be fitted within the typical field of view of high and low magnification lenses on optical instruments. The larger step heights, 1 µm, 10 µm and 50 µm were diamond turned in copper and then replicated in nickel. Figure 4 shows a coherence scanning interferometer image of a 50 µm step, 100 µm wide. The smaller steps, 1 µm, 100 nm and 10 nm were produced both in glass and in silicon. In addition waffle step height patterns at 30 µm, 100 µm and 200 µm periods were produced in silicon at the same step heights to enable verification of the *z*-axis scale over the field of view. Figure 5 shows an image of a 1 µm waffle pattern.

Diamond turning was used to produce various surface profiles useful for verifying dynamic response of scanning instruments, response to slopes for optical probes and for probe condition monitoring. The diamond turned profiles were all turned in copper and then replicated in nickel to give an affordable artefact with a durable surface. Sine wave profiles have been produced with maximum slopes of 20° and 5°, at 25 µm and 8 µm periods.

There is no agreed, specific definition of lateral resolution for areal instruments, but it is important, both for manufacturers when marketing an instrument, and for users when selecting an instrument fit for purpose. Resolution test structures were fabricated on two silicon samples, approximately 12 mm square, by e-beam lithography. Sample Res A carries nine grating patterns with equal mark/space ratios and periods of 0.6 µm to

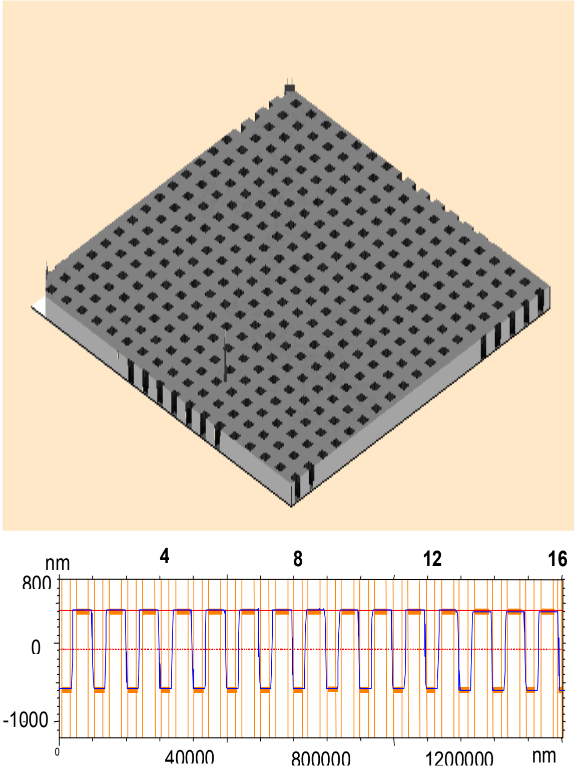

Figure 5 Coherence scanning interferometer plot of a 1 µm waffle pattern

10 µm. Sample Res B carries eight gratings of periods 1 µm to 8 µm and an array of star patterns in the central patch. The periods of the grating patterns have been measured traceably by an optical diffraction method. Figure 6 shows the layout of the two samples with an AFM image of the central grating pattern on sample Res A and a coherence scanning interferometer image of one of the star patterns in the central array on sample Res B. Where the coherence scanning interferometer resolves the pattern on Res B comfortably, the image shows the two levels of the upper and lower surface of the pattern. Near the centre, the pattern may still be distinguished but its true height has not been measured. The measured values agreed with the nominal values to within 0.5 nm in the majority of the patterns.

5. Further work on areal traceability

We have taken the first steps towards a traceable instrument and transfer artefacts for the measurement of areal surface texture. However, there is still a significant amount of research and development required to be able to offer a measurement service to industry. There are many commercially available instruments for measuring areal surface texture, mainly based on stylus or optical methods. ISO 213 is addressing the specification standards for all common types of instruments (at the time of writing of this paper only stylus, coherence scanning interferometry and confocal chromatic instruments are being actively worked on), and research is still required on how to measure the large range of structured surfaces that will become available in the future. Structured surfaces will

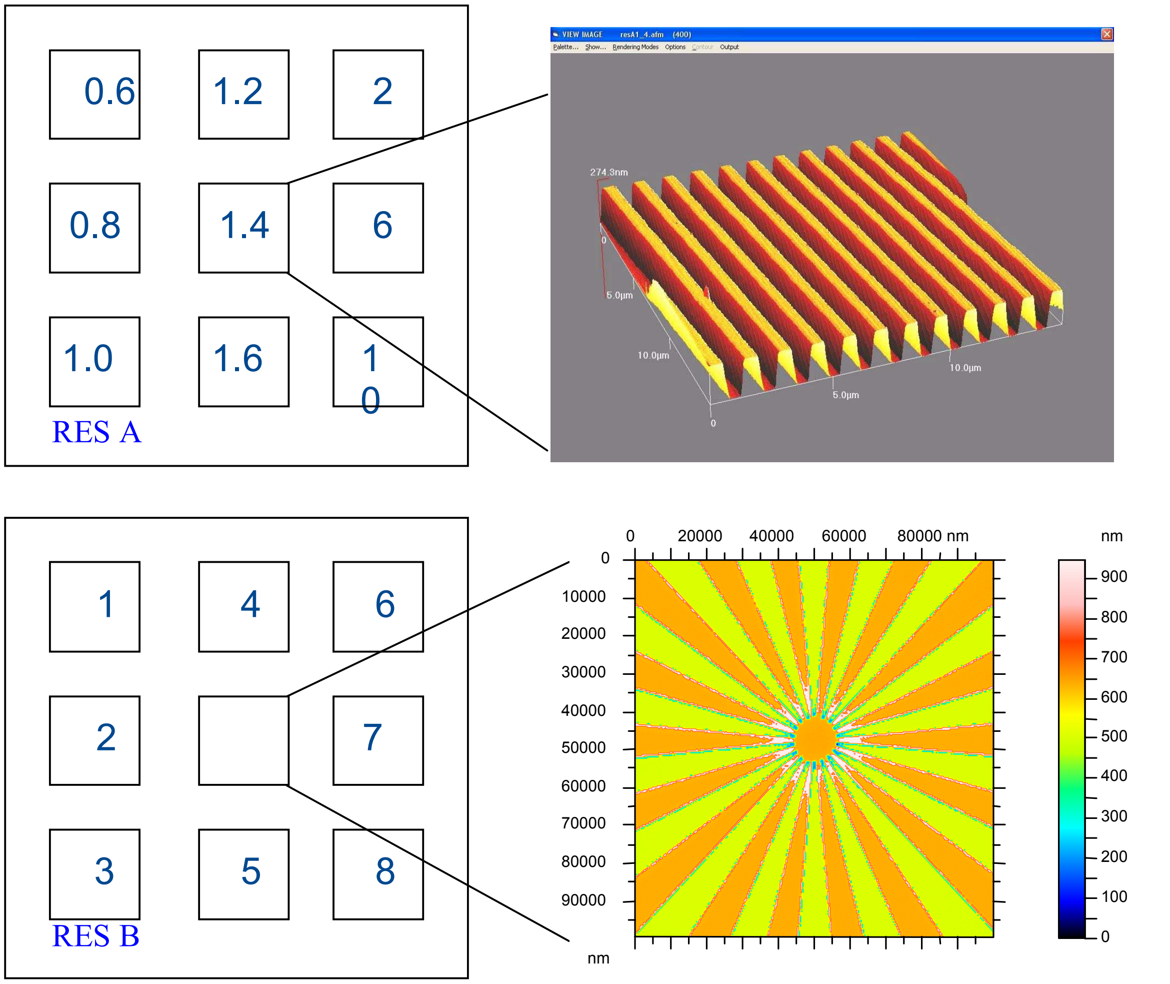

Figure 6 AFM image of the central grating pattern on sample Res A and a coherence scanning interferometer image of one of the star patterns in the central array on sample Res B

present surface bandwidths that may be difficult to measure using some instruments and good practice guidance will be necessary. Coherence scanning interferometers may be very versatile instruments but they can give erroneous results without *a priori* knowledge of the structure of the surface being measured [11]. This is an example where guidance on good practice is required. NPL, the University of Loughborough, the University of Huddersfield, IQE Ltd and Taylor Hobson are producing good practice guides in the use of coherence scanning interferometers (these guides will be published in the first half of 2008).

Once traceable instrumentation and transfer artefacts are in place for areal measurement, software measurement standards will be required to ensure that instrument software for filtering and parameter calculations is correct. New characterisation methods and parameters will also be needed as the number of commercially utilised areal structured surfaces grows.

6. Conclusion

The development of a traceable instrument and transfer artefacts for measuring areal surface texture has been summarised. Future work involves the full characterisation of the instrument and an uncertainty analysis. Once this work is complete the instrument will be fully traceable and used to measure two samples (a waffle plate and a random roughness sample) that have been circulated to and measured by several UK laboratories. Future research will develop software measurement standards for areal filtering and parameters, new characterisation methods for areal structured surfaces and good practice guidance on the use of stylus and optical instruments.

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