SOFTGAUGES FOR SURFACE TEXTURE

By

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Abstract

Surface texture plays an important role in the specification of a precision workpiece. However, the route of traceability for surface texture measurements is not well developed. One of the main technical obstacles is the lack of tools to check traceability of the software of surface measuring instruments and to estimate uncertainty contributed by the software. To this end, the concept of softgauges (i.e. software measurement standards) for surface texture has been introduced into the international standards.

The presented thesis documents the realisation of softgauges for surface texture, which is a part of the National Measurement System in the UK. These standards, in the form of the reference dataset with reference results, have been developed by both simulation and experimental methods. The analysis of software uncertainty has been undertaken. These measurement standards have been used to verify both reference software (developed by the National Measurement Institutes) and commercial packages (developed by instrument manufacturers). In addition, the evaluation of the measurement uncertainty in workshop level has been carried on.

These developed standards provided a novel route to demonstrate metrological traceability of most surface profile parameters. Currently, these standards are distributed via the internet by the National Measurement Laboratory (NPL) in the UK. These standards are also recognised by NIST in the USA and PTB in Germany, and these organisations would also provide a suitable vehicle to distribute of the results of this study.

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List of Related Publications

1. Li T, X Jiang, L Blunt, P Scott, and S Xiao (2007). "*Comparison on F2 softgauges for surface texture"*. In: The Proceedings of 1st European Conference on Tribology (ECOTRIB), Slovenia. pp. 765-774. ISBN 9789619025482
2. Li T, X Jiang, L Blunt, P Scott, and S Xiao (2008). "*The Design and Use of F1 Softgauges for Validating Surface Metrology Software."* Key Engineering Materials, **381-382:** pp 643-646.
3. Li T, R Leach, L Jung, X Jiang, L Blunt (2009). *NPL Report ENG 16 - Comparison of Type F2 Software Measurement Standards for Surface Texture*, London. National Physical Laboratory, UK. ISSN: 1754-2987
4. Li T, L Blunt and X Jiang (2009). "*Uncertainty in surface roughness measurement", In:* Statistical Analysis of Measurement Data for the Evaluation of Measurement Uncertainty (SAMEMU), available at: http://www.sam-emu.ath.eu/
5. Blunt L, T Li, *"Evaluation of Measurement Uncertainty"*, Quality Manufacturing Today, March 2010.
6. Leach R, T Li, X Jiang, L Blunt and C Giusca. *"Comparison of commercial software packages for calculating surface texture parameters"* In: The Proceeding of the 10th EUSPEN International Conference, Delft, Netherlands, 31st May – 4th June, 2010.

Nomenclature

l	Sampling Length
l_p	The sampling length for primary profile
l_r	The sampling length for the roughness profile
l_w	The sampling length for the waviness profile
Ra	Arithmetical mean deviation of the roughness profile
Rc	Mean height of profile elements
Rku	Kurtosis of the roughness profile
Rp	Maximum roughness profile peak height
Rq	Root mean square deviation of the assessed profile
Rsk	Skewness of the assessed profile
RSm	Mean width of the profile elements
Rt	Total height of the roughness profile
Rv	Maximum roughness profile valley depth
Rz	Maximum height of the roughness profile
$Z(x)$	Height of the assessed profile at any position x
Sm_i	Width of a profile element (i th)
λ	Wavelength
λ_c	Wavelength of profile filter which defines the intersection between the roughness and waviness components
λ_f	Wavelength of profile filter which defines the intersection between the waviness and the even longer wave components
λ_s	Wavelength of profile filter which defines the intersection between the roughness and the even shorter wave components

Acronyms and Abbreviations

ASME	American Society Of Mechanical Engineers
BIPM	Bureau International des Poids et Mesures
GPS	Geometrical Product Specifications and Verifications
GUM	Guide to the Expression of Uncertainty in Measurement
ISO	International Organization for Standardization
ISO/TC213	ISO Technical Committee 213 (Dimensional and geometrical product specifications and verification)
NIST	National Institute of Standards and Technology, USA
NMI	National Measurement Institute
NPL	National Physical Laboratory, UK
PDF	The Probability Density Function
PTB	Physikalisch-Technische Bundesanstalt, Germany
SI	International System of Units, (abbreviated SI from the French le Système international d'unités)
VIM2	International Vocabulary of Metrology, 2nd Version (1995)
VIM3	International Vocabulary of Metrology, 3rd Version (2007)

In addition, three type F2 reference software packages and some commercial software packages were used in the uncertainty analysis and the comparison. In this thesis, the square brackets refer to the associated software packages.

[PTB] Ref_soft_PTBIDL and Ref_soft_PTBweb[1]
www.ptb.de/en/org/5/51/517/rptb_web/wizard/greeting.php

[1] PTB provides reference software in the form of a desktop version and web version.

[NIST] Internet Based Surface Metrology Algorithm Testing System
syseng.nist.gov/VSC/jsp/index.jsp

[NPL] nplsmd1.01
www.npl.co.uk/server.php?show=ConWebDoc.160

[CA] Commercial software package A

[CB] Commercial software package B

[CB(V1)] Commercial software package B (Version 1)

[CB(V2)] Commercial software package B (Version 2)

[CC] Commercial software package C

[CD] Commercial software package D

1 Introduction

1.1 Background

Metrology is the science of measurement, which includes all theoretical and practical aspects of measurement (Howarth and Redgrave 2008). There is no doubt that metrology plays an essential role in the economic and industrial development of a country. As the British Victorian engineer Sir Joseph Whitworth (1803~1887) said, "*you can only make as well as you can measure*". Thus, it is often said that the level of industrial development of a country can be judged by the status of its metrology (Silva 2002).

The success of a measurement is generally quantified by the terms of precision and accuracy. *Precision* of a measurement can be described by its comparability between different periods, locations, measurement procedures, instruments and operators. According to the degree of the difference of these conditions, measurement precision is described as repeatability[2] and reproducibility[3]. *Accuracy* of a measurement is the closeness of the agreement between its measured value and its true value (VIM3 2007). The accuracy is ensured by using a method called traceability. *Traceability* is "*the property of a measurement result whereby the result can be related to a reference*

[2] *Repeatability* is the measurement precision under repeatability condition, i.e. the same measurement procedure, same operators, same measuring system used under same operating condition and same location, and repetition on the same or similar objects over a short period time (VIM3, 2007).

[3] *Reproducibility* is the measurement precision under reproducibility condition, i.e. the different location, different operators, different measuring system, and repetition on the same or similar objects (VIM3, 2007).

through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty (VIM3 2007)". Traceability is often obtained by undertaking *calibration*, an operation to establish the relation between the indication of a measurement instrument and the value of a measurement standard (etalon)[4](BIPM 2011).

Traditionally, a *measurement standard* (etalon) is in the form of artefact and physical gauge, called "hardgauge*"* in this thesis, which is intended to define, realise, conserve or reproduce one or more values of an attribute to serve as a reference (VIM2 1995). The design, development and maintenance of measurement standards are the most fundamental works in metrology, generally undertaken by a National Metrology Institute (NMI) within a country, such as the National Physical Laboratory (NPL) in the UK, the National Institute of Standards and Technology (NIST) in the United States, Physikalisch-Technische Bundesanstalt (PTB) in Germany and so on.

It is recognised that software plays an increasingly important role in metrology. Richter (2006), for example, stated that *"a new world of metrology has been opened up by software"*. In this world, metrologists face both opportunities and challenges. On the one hand, software empowers measurement instruments significantly by introducing complex metrological properties. On the other hand, accuracy and precision of the software of instruments are a great issue. The cost due to software fault is significant. In 2002, NIST estimated that the American annual cost of an inadequate infrastructure for software testing is $59.5 billion (Tassey 2002). In the field of metrology, therefore, the idea of a software-based virtual gauging system has been emerged (Smith 2002).

Surface texture is the topography of a surface composed of certain deviations that are typical of the real surface (ASME B46.1 2002)[5]. Surface texture measurements play an increasingly important role in controlling the quality of precision parts. Modern engineers in the field of automotive, aerospace and medical engineering are the examples that have been empowered with the knowledge of surface texture. Surface metrology, i.e. the science of surface measurement, has been developed rapidly in the

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[4] In science and technology, the English word "standard" is used with at least two different meanings: as a specification, technical recommendation, or similar normative document (in French "norme") and as a measurement standard (in French "étalon"). In this thesis, "standard" refers to the second meaning. The term of "standard document" refers to the first meaning.

[5] The definition of "surface texture" will be discussed further in Chapter 2.

last several decades (Lonardo, Trumpold et al. 1996; Lonardo, Lucca et al. 2002). Various types of instruments, new characterisation methods have been put into practice. This prosperity enriches the selection of appropriate metrological solutions. However, the more solutions we have, the more references we need. Since very few references are available, the accuracy of these solutions is a critical issue.

Repeatability of surface measurements has been enhanced. However, surface texture measurements only have an ill-defined traceability route (Leach 2004). In other words, the surface textures measurements are increasingly improved on their precision, but lack enough evidence on their accuracy. It indicates that there are needs to develop new type of measurement standards to ensure the accuracy of surface texture measurements. The rationales for this decision can be summarised as:

1) Hardgauges, existed in the physical world, are costly to manufacture, maintain and difficult to implement. They regularly are stored in specialised laboratories and assessed in difficult and necessarily limited. Although many types of hardgauges have been standardised, only few types, therefore, are often used.

2) There are 63 surface profile texture parameters defined in the ISO (The International Organization for Standardisation) documents. However, only few of them can be checked their traceability by using hardgauges[6].

3) Software engineers need tools to check metrological traceability of the software developed for surface measuring instruments. This requirement is unable addressed soundly by using hardgauges. Hardgauges check the software and the hardware of an instrument as a whole and not just the software in isolation. For software developers, thus, using hardgauges is not convenience and reliable (e.g. the certified values of hardgauges accompany with relatively large measurement uncertainties).

4) Related metrological information, such as measurement conditions and the definition of surface texture parameters, currently spreads in various

[6] According to ISO 5436-1 (2000), the certified value of a type D hardgauge is in the form of *Ra* and *Rz* parameter. This limitation will be discussed in detail in Chapter 2.

graphic/text-based documents. So it could lead different callouts (Scott 1988; Song and Vorburger 1991; Leach and Harris 2002), and results in significant uncertainty due to the lack of information (ISO TC213 2004). Hardgauges do not manage this uncertainty soundly (Rubert 1995).

The concept of software measurement standards (i.e. *softgauges*) for surface texture measurements was introduced into ISO documents (ISO 5436-2 2001). This thesis documents the design and the development of the realisation of this concept in the UK. The developed softgauges, as part of National Measurement System in the UK, are distributed by NPL over the Internet. They have also been recognised by the NMIs around the world, such as NIST in the United States and PTB in Germany.

1.2 Objectives and approaches

The aim of this work is to maintain metrological traceability of the software of surface measuring instruments, which is the basis upon which all output results of the software can be claimed to be accurate. The objectives of this project are classified as follows:

1) *Understanding of softgauges*: It will develop a deep understanding of softgauges, conformed to the latest ISO documents and based on recently evolved philosophy in metrology.

2) *Methodology for software calibration*: It will develop a methodology to calibrate the software by extending the metrology approaches into information science domain.

3) *Software uncertainty*: An expression of the measured results is incomplete, unless it includes a statement of the associated uncertainty. Generalised uncertainty principle proposed in the GPS (i.e. Geometrical Product Specifications and Verifications, a metrological language) will be adapted to evaluate the software uncertainty.

4) *Computing errors*: The computational error seems insignificant with respect to other components (e.g. surface inhomogeneity). However, without a formal validation, this consideration remains intuitive. This project will assess the

computing errors by designing and developing the simulated profiles with the reference results produced with algebraic calculations.

5) *Measurement information*: In order to reduce the uncertainty in communication level, an information model will be developed to organise the measurement information, which needs to be exchanged between different parties.

6) *A set of softgauges*: The softgauges in the form of the reference data and the reference results, as the transfer standards at a national level, will be designed, developed and distributed.

7) *Software calibration procedure, decision rule and user guide*: It will develop a calibration procedure, together with a comparison rule from the software aspect. Case studies will be undertaken to guide the use of the softgauges.

This main concern of this work is to check metrological traceability of the software of surface measuring instruments. Hence we concentrate on the related software quality characteristics such as accuracy, reliability, repeatability, reproducibility and so on. This project does not cover other characteristics, such as usability, efficiency, maintainability and portability [7]. Furthermore, this thesis only documents the development of softgauges for surface profile parameters defined within ISO 4287 (1996), which is the fundamental part of this ongoing project.

1.3 Thesis layout

This thesis is organised as follows. Chapter 2 presents a review of the current state of traceability in the field of surface metrology together with a detailed analysis of the requirements of softgauges. Chapter 3 presents the development of the framework for softgauges. Chapter 4 develops an information model to standardise the measurement information. Chapter 5 is concerned with identification of the software uncertainty of the ISO 4287 parameters. Chapter 6 is devoted to the development of the softgauges. The subjects of Chapter 7 include a proposed software calibration procedure, a decision rule, the verification of reference software, the calibration of commercial packages and two case studies on measurement uncertainty. Chapter 8 is a summary of

[7] They should conform to software quality assure (SQA).

the main conclusions of the work presented in this thesis and the recommendations for the future work.

2 From hardgauges to softgauges

This chapter reviews the current state and the trends in the field of surface metrology. The objectives of this literature review are to develop a better understanding of the issues surrounding traceability of surface texture measurements, to identify the potential research work and to clarify the scope of the work to be undertaken.

2.1 Introduction

The most fundamental reference in metrology is the "*International Vocabulary of Metrology – basic and general concepts and associated terms*"(VIM3 2007). The latest version (3rd) was released in December, 2007 and refers to as the VIM3. The previous version (2nd) refers to as the VIM2 (1995). The VIM3 represents the latest evolution of philosophy and description of measurement (Ehrlich, Dybkaer et al. 2007). Note that many references (published before the release of the VIM3) in this chapter follow the VIM2.

The basic concepts and principles of metrology are to formulate the need to measure (definition), and compare a known value or quantity (a reference) to an unknown (measurand) in order to define the unknown relative to the known (measured values)(Bucher 2004). Their logical relationship is illustrated in Figure 2.1. So metrology covers three main activities: 1) the definition of internationally accepted units of measurement; 2) the realisation of units of measurement; 3) and the establishment of traceability chains (Howarth and Redgrave 2008).

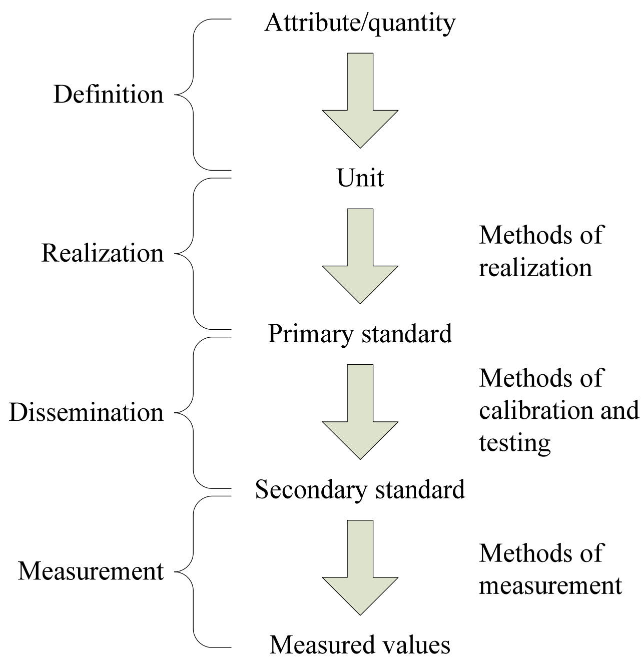
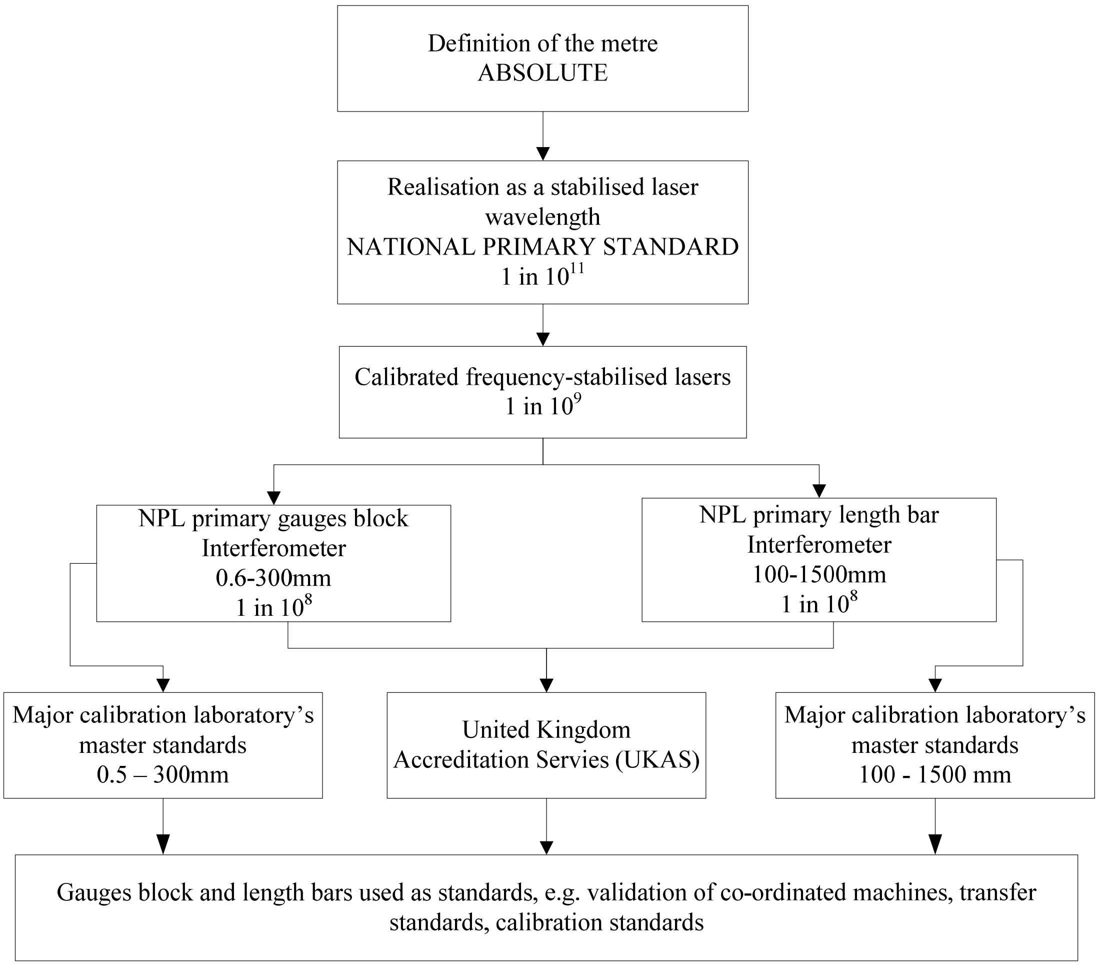


Figure 2.1 Logical relationship among the key concepts in metrology [source: NIST]

These metrology ideas date back to ancient Egypt. The body of the ruling Pharaoh was used as the definition of the first royal cubit. Its realisation was transferred to and carved in black granite (i.e. primary standard). Its copies (i.e. secondary standard/working standard), in granite or wood, were further transferred to the workers at the building sites of the temples and pyramids (Howarth and Redgrave 2008). In modern times, the metre is defined as *"the length of the path travelled by light in a vacuum during a time interval of 1/299 792 458 of a second"*(BIPM 2006). At the primary standard level, it is often realised in terms of the wavelength from an iodine-stabilised helium-neon laser (BIPM 2010). Secondary standards are these calibrated against the primary standard, such as the gauge block interferometer, helium neon laser interferometer, etc. On the sub-levels of the secondary standard, gauge blocks, line standards and standard tapes are used as working standards. The dissemination of the standards makes it possible that all length measurements link with the definition of the metre. Then, the metrological activities establish an unbroken chain of comparisons (all should have stated uncertainty), i.e. a traceability chain. Figure 2.2 shows part of the traceability chain of length measurements in the UK.



(Note: 1 in 10^9 implies an accuracy of 1 nm in 1m)

Figure 2.2 Part of the traceability chain of length measurements in the UK [source: NPL]

Surface metrology is one of the subfields of length measurement in industrial and scientific metrology (Howarth and Redgrave 2008). Precision engineers have carried out quantitative surface texture measurement over a century. However, surface texture measurements only have an ill-defined traceability route (Leach 2004; Leach 2009). To find out the exact reason, the following sections review three main activities in surface metrology. The definition of surface texture is the subject of Section 2.2. The realisations in the form of material measures are discussed in Section 2.3. The current state of the traceability chain, together with the topics of uncertainty and calibration, are covered in Section 2.4. The emergence of softgauges provides a possible solution to address some issues. The concept, related work and the requirements of softgauges are the subjects of Section 2.5.

2.2 Surface description

2.2.1 Definition of surface texture

The real surfaces of a workpiece are a set of features which physically exist and separate the entire workpiece from the surrounding medium (ISO 14660-1 1999). The texture on a surface is one of its key features. As illustrated in Figure 2.1, the definition of the object is the start point in a standardised measurement. So the first question, inevitably, for surface texture measurements is: What is surface texture?

All surfaces have some type of texture, and many of them are easily recognised. However, it is not easy to define the texture. Often the description of surface texture relies on the development of measurement methods, characterisation techniques and manufacturing processes. With the evaluation on these related technologies, the definition of surface texture, inevitability, is evolved. Many are orientated to define surface texture by the wavelength approach which shows a good link to the creation process of a surface. This idea dates back to the beginning of quantitative surface texture measurements in the early twentieth century. Reason, in "*Report on the measurement of surface finish by stylus methods*" which published in 1944, stated that:

> *"1) General curvature of the whole surface, or irregularity of comparatively long wavelength, due perhaps to flexure of the work in the machine, or to lack of straightness in the ways. 2) Surface texture of medium wavelength due to bad condition or bad setting up of the machine … 3) Surface texture of comparatively short wavelength due to the cutting action proper of the machining process …, for instrumental convenience the texture may be roughly sub-divided into two classes: a) texture reasonably within the scope of a stylus of 0.0001inch radius, b) texture too fine for such a stylus."* (Reason, 1944)

This classification decomposes the surface profile topography into three components, namely form error, waviness and roughness according to current terminology. Surface texture is comprised of waviness and roughness. Reason (1944) pointed out that "*this classification is neither very precise, nor inclusive of every kind of texture, but it will serve as a basis for discussion*." This classification, nevertheless, has been widely accepted. It has followed with many similar definitions. For example, Figure 2.3 shows the schematic diagram of surface topography defined in an American standard document (ASME B46.1 2002). In a standard document namely the German DIN 4760 (1982), this method was extended, which separates the roughness into four sub-classes.

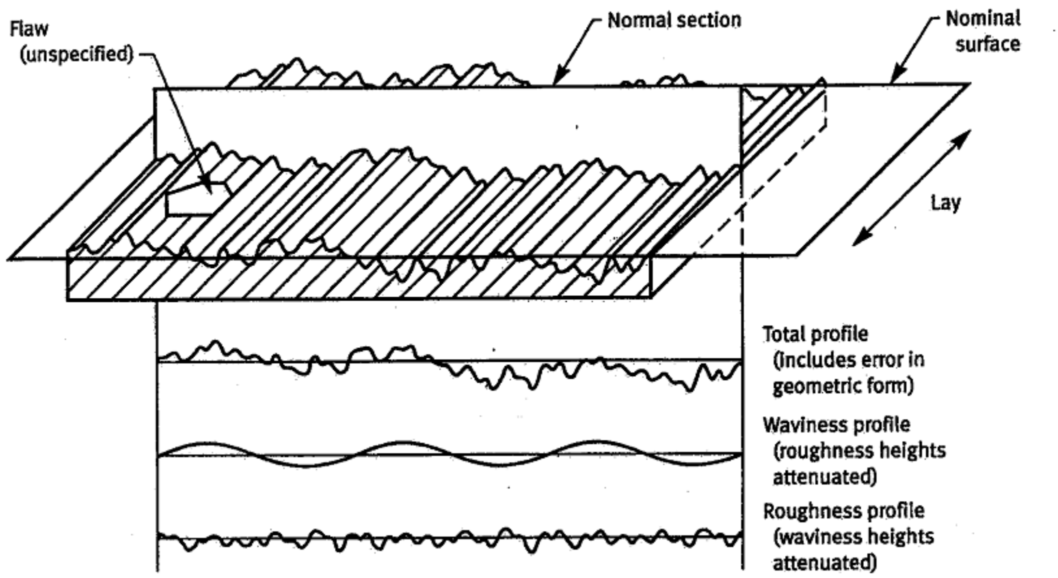


Figure 2.3 Schematic diagram of surface topography (ASME B46.1-2002)

A great problem with the conventional definition is how to define the points to separate these components. Often these points are given arbitrarily. For example, a given wavelength used to define the roughness on an automobile axle would fall into the wavelengths used to defined waviness or form error on a watch spindle (Blunt and Jiang 2001). To address this issue, a VDI[8] guideline (VDI/VDE-2601 1991) used the ratio of the distance between irregularities to their depth to distinguish the form deviation, waviness, roughness and crack. However, the selection of the ratios is arbitrary too.

In areal surface texture characterisation, the boundaries of different components are more ambiguous, so the terms of roughness and waviness were abolished (ISO/DIS 25178-2 2009). The current bandwidth-based definition decomposes the surface topography into many sine waves with different bandwidth. In the last two decades, many new decomposition approaches (e.g. morphologic filters, wavelet filters etc.) has been put into practice. Thus "wavelength" is replaced by a term called "nesting index value" in ISO/DIS 25178-3 (2009).

[8] Verein Deutscher Ingenieure(VDI): The Association of German Engineers.

Scott (1986) summarised that there are two philosophical approaches in surface metrology, namely: 1) *defined in terms of the manufacture process* (it monitors changes in the surface texture and indicates the changes in the manufacturing process such as machine tool vibration or tool wear); 2) *defined in terms of function requirements* (it describes the features of surface that are directly related the functional requirements of a surface). The conventional definition of surface texture is based on the first approach. With the emergence of new methods based on the second approach, the definition of surface texture becomes a problem.

Thus current ISO documents do not provide the definition of surface texture, in spite of the fact that this term was widely used. Recently, Scott (2010) suggested that "*surface texture is the scale limited feature of a surface*". This definition will be introduced into an ISO document, namely ISO 25178-2. The acceptance of this definition is subject to the vote results in the near future.

2.2.2 Surface texture parameters

Engineers face another issue when the surface texture is obtained - how to represent it. This issue arose one century ago, but there has not been satisfactory answered for all purposes until now. It could be represented by the chart directly, but too much data makes difficulty for its communication and comparison. It could be represented by a parameter as a single number. This method goes to another extreme – too little data, which means the number may not probably describe the requirements. Nevertheless, surface texture parameters are still the favourite for surface engineers (Jiang, Scott et al. 2007).

Surface texture does not have any "natural" parameter (for example, the diameter of a cylinder). Therefore, it has always been customary to define each surface parameter in terms of the instrument used to measure it, the algorithms and the setting up of this instrument (Nielsen 2006). Diversity of these components causes another problem – diversity and complexity of surface texture parameters.

Scott (1988) divided the assessment of surface texture in the six stages: 1) choice of metrological solution; 2) data collection; 3) a controlled experiment; 4) data pre-processing; 5) determination of a reference; 6) analysis. Muralikrishnan and Raja (2008) separated the topic of data processing into fitting, filtering parameterization, and uncertainty. In this section, we separate surface texture assessments into four main stages: surface texture classification, data acquisition, pre-processing and characterisation. Figure 2.4 illustrates the operations within these stages (ISO standardised operations are listed in bold).

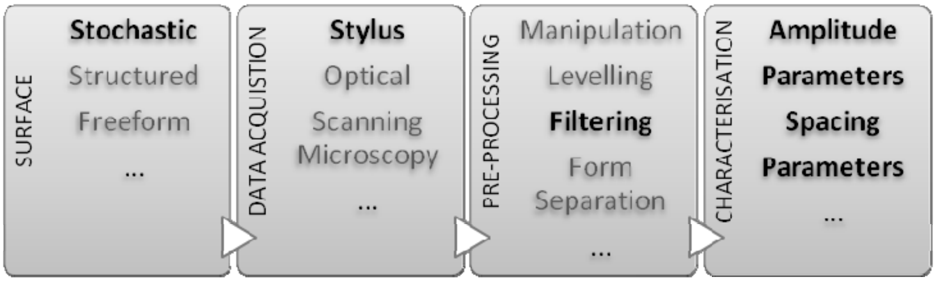


Figure 2.4 Stages of surface texture assessments

Surface classification

There are various types of surfaces, identified by different classification approaches. According to the surface creation processing, Stout and Blunt (2001) classified them into random surfaces, systematic surfaces, unstructured surfaces, structured surfaces and engineered surfaces. Jiang et al (2007) categorised them into three groups, stochastic surfaces, structured surfaces and freeforms by the description approaches. According to the type and the functional requirements of a surface, a possible metrological solution is established, which includes a sampling method, a suitable instrument, analysis methods and parameters.

Data acquisition

In this stage, a set of representative data points are collected from the surface. Many instruments, based on different principles, are available to pick up these data points. Stout et al (1993) listed most of them, such as stylus, optical interference, optical scatting, capacitance, ultrasound, Scanning Probe Microscope(SPM), etc. ASME B46.1 (2002) classifies surface measuring instruments into six types. Each type of instruments has advantages and limitations. According to its measurement principle, an instrument may bring some distortions into the measurement datasets, e.g. effect of stylus radius. Often a considerable disagreement occurs when a surface is assessed by different types of instruments (Whitehouse 1988; Poon and Bhushan 1995; Conroy and Armstrong 2005; Vorburger, Rhee et al. 2007).

Pre-processing

In the stage of pre-processing, a set of mathematical treatments is carried out to refine the useful information out of the raw measured datasets. Pre-processing includes levelling of surface data, form removal, data manipulation (truncation, rotation, inversion, sub-area extraction, etc.) and filtering. Levelling and form removal is often performed by the least squares line/plane or surface fitting with various mathematical methods (Muralikrishnan and Raja 2008).

Filtration concerns the separation of different features by given scales. It extracts key information to provide process feedback and establish the functional correlations. Meanwhile, it is important to limit the unwanted distortions caused by using a filter. Various types of filters have been developed, such as the 2RC, Gaussian, spline, morphological, wavelet, regression filter, etc. Each type of filters has its advantages and limitations (Raja, Muralikrishnan et al. 2002).

Characterisation

A typical profile graph is shown in Figure 2.5. It is difficult to describe all features by one parameter. Many parameters, thus, have been developed. The peak parameters, such as *Rp*, *Rv* and *Rz* shown in Figure 2.5, are the earliest parameters as they can be measured by hand directly from a recording of the profile (Reason 1944). Abbott & Firestone (1933) recommended the use of the material ration curve to represent the surface. Average parameters, such as *Ra* and *Rq,* were introduced when electronic processing became available (Reason 1944). Since the computer being used in surface metrology, an amount of parameters based on different characterisation techniques (e.g. statistical description, spectral analysis, time series analysis, functional characterisation etc.) has been realised. Jiang and Blunt (2001) estimated that more than 100 surface profile parameters had been proposed.

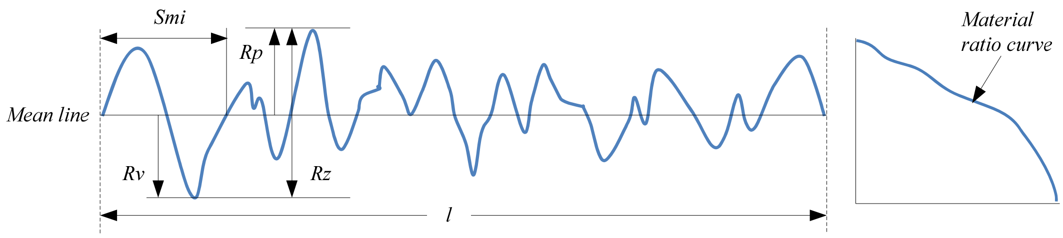


Figure 2.5 A typical profile graph with some descriptors

Most of the characterisation techniques are scale-dependent, which means the results depend on the measurement scale. On the other hand, some topography characteristics are independent of the measurement scale, i.e. using of a fractal dimension (ISO/DIS 25178-2 2009).

The variety of the characterisation methods has brought about a significant explosion in the generation of parameters, aptly defined as the "parameter rash" by Whitehouse (1982). The rash results confusion and expense, thus, it needs ways to minimizing it (Whitehouse 1982). It will be discussed in the next section.

2.2.3 Standardisation

The complexity and variety of surface metrology gives engineers plenty of choice. At the same time, it causes a difficulty in communication between different parties. Thus many national standard documents have been issued (Whitehouse 2002a). The need for global standards has increased dramatically in the trend of globalisation. ISO plays an important role in the development of the common standards around the world. Standard documents for surface texture are developed by ISO TC/213 in the framework of the GPS (*Geometrical product specifications and verification*). It consists of profile characterisation and areal characterisation.

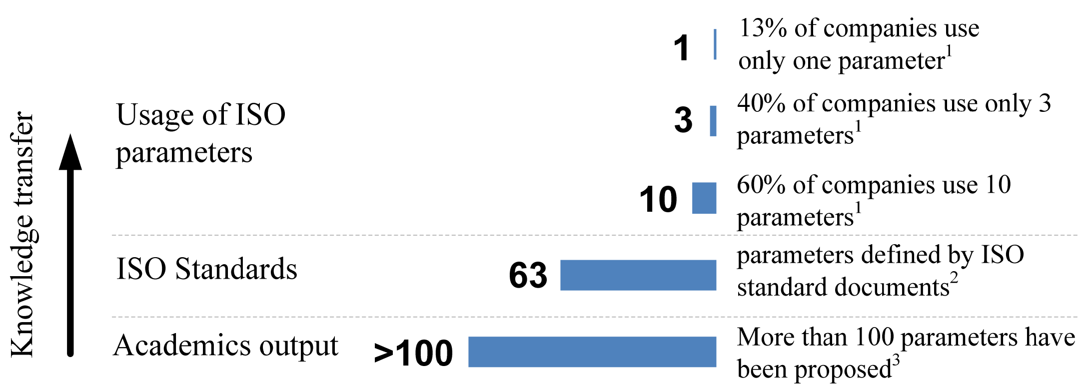
Surface profile characterisation

Table 2.1 lists current surface profile standard documents in the GPS matrix model.

Table 2.1 Position of surface profile standard documents in the GPS matrix model.

Chain link number		*1*	*2*	*3*	*4*	*5*	*6*
Geometrical characteristic of feature		*Codification on a drawing*	*Definition of tolerance*	*Definition for actual feature*	*Comparison with tolerance limits*	*Measurement equipment requirements*	*Calibration requirements*
14	Roughness profile	ISO1302	ISO 4287, 12085, 13565-1, 13565-2, 13565-3	ISO 4288, 12085, 11562, 13565-1	ISO 4288, 12085	ISO 3274	ISO 5436, 12179
15	Waviness profile	ISO1302	ISO 4287, 11562, 12085	ISO 11562, 12085	ISO 12085	ISO 3274	ISO 5436, 12179
16	Primary profile	ISO1302	ISO 4287, 11562, 13565-3	ISO 4288	ISO 4288	ISO 3274	ISO 5436, 12179

Note that only limited academic outputs have been standardised in ISO documents; moreover, limited ISO parameters have been used in industry practices. Figure 2.6 shows an overview of the knowledge transfers in the case of surface profile parameters.



Note: [1] Results from industrial CIRP survey involving 284 companies in 18 countries (De Chiffre 1999)

[2] It does not include parameters in the draft ISO standards.

[3] (Jiang and Blunt 2001)

Figure 2.6 An overview of knowledge transfer in the case of surface profile parameters

The limitation of the knowledge transfer is due to many reasons; some of them are listed below.

1) *Some parameters are not meaningful (or functionally significant).* Some parameters are easy to define, but they are not very useful in industry practice (e.g. W-parameters (Whitehouse 2002b)).

2) *Some parameters are not mathematically stable*. Some parameters are meaningful, but their definitions are unstable (e.g. the *RSm* parameter (Leach and Harris 2002)).

3) *Many parameters show poor repeatability/reproducibility in practise*. It is mainly due to the inconsistencies on the surface (Thomas and Charlton 1981). Disagreements could also arise from the variation of the understanding and implementations of ISO standard documents (Scott 1988).

Areal surface texture parameters and filter toolbox

Many ISO documents for surface metrology are about to be published. Some of the most important are listed as follows.

- *The areal parameters of surface texture within ISO 25178 series*: It includes three standard documents that define more than 40 areal parameters with their default callout.

- *The filter toolbox within ISO 16610 series:* It contains more than 40 documents that attempt to standardise most of the available filters with the user guides.

The areal parameters and filters toolbox are expected to be more meaningful, more mathematical stable, and able to reduce the variation contributed by the surface inconsistent. They are more complex and flexible. Thus, it should pay more attention to the possible disagreements caused by the different understanding and implementations of them. In metrology, this issue can be addressed by using measurement standards. It will be discussed in the following parts of this thesis.

2.2.4 Definitional uncertainty & specification uncertainty

The requirements of surface texture on a component are generally expressed in the drawings by standardised symbols. The most widely used are defined in ISO 1302 (2002). Figure 2.7 illustrates an example and its interpretation.

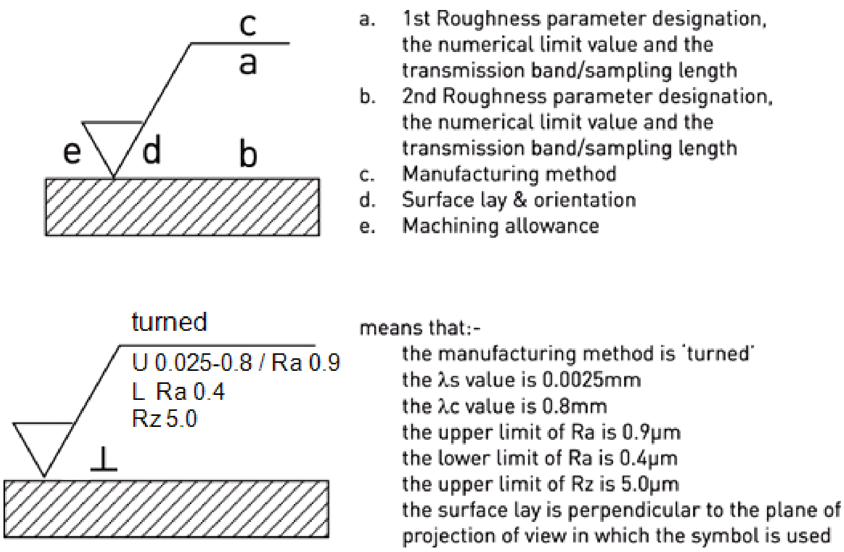
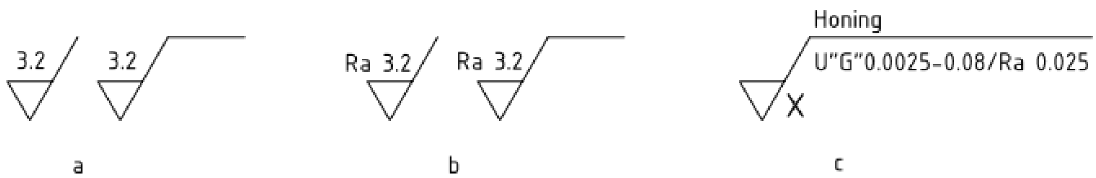


Figure 2.7 An example of the specifications of roughness in drawing (ISO1302:2002)

In the GPS, *specification uncertainty* is used to quantify completion and perfection of the requirements given in technical drawings (ISO/TS 17450-2 2002). The evolution of the drawing symbols of surface texture reduces their specification uncertainty significantly (see Figure 2.8). However, current standard documents still contain some degree of the specification uncertainty. For example, Leach and Harris (2002) investigated the ambiguities in the definition of *RSm* parameter. It shows that an unspecified combination method for parameter *RSm* led to up to 12 % variation of results in given examples.



Key: a) In 1965 version , up to 300% specification uncertainty;

b) In 1991 version, up to 30% specification uncertainty;

c) In ISO 1302: 2002 version, low specification uncertainty.

Figure 2.8 Evolution of drawing symbols (P Bennich and H Nielsen 2005)

It has been recognised that a measurand is defined on a finite amount of information (GUM 1995). Therefore, the concept of *definitional uncertainty* was introduced into metrology which sets a minimum limit to any measurement uncertainty (VIM3 2007). The definitional uncertainty and specification uncertainty aim to address same problem – the lack of knowledge (Nielsen 2009). However, there is no common understanding on definitional uncertainty (Mari 2009) and the relationship between specification uncertainty and definitional uncertainty is unclear (Nielsen 2009).

2.2.5 Information model

There are two types of information for a surface texture measurement:

1) *The measured dataset*: It records the dimensional information which is a digital representation of a measurand in certain condition produced at a certain phase of a measurement.

2) *The characteristic and the measurement conditions*: As discussed above, a measurand is defined on an amount of information. The specified characteristic and measurement conditions state the key information of a measurand.

To measure is to compare. In order to compare the measurements undertaken at a different time or location, it is of importance to store and exchange such information. There are various file formats used to store the measured dataset in a computer. However, the information of the characteristics and the measurement conditions is spread in many graphic/text-based documents, such as user-input, ISO documents, instrument guides, national measurement guides, etc. So an engineer faces another problem: how to organise/manage such information? The more the detailed information is, the less the definitional uncertainty. At the same time, too much information could make it difficult to exchange of information. In the pre-information age[9], all our information was held on paper. Today most of it is held electronically either as digital documents, or as data in databases. The use of computers makes storing and exchanging more detailed information possible, thereby reduces the related uncertainty. This is especially important for surface measurement due to the complexity and variety of surface metrology as discussed above.

In the specification of surface texture, the most often used model is through the technical drawings. This graphic-based method efficiently integrates various geometrical requirements in one technical document. With the developing in Compute-Aid Design (CAD), the traditional paper-based drawings are normally undertaken with

[9] For our purpose, we will assume that the information age started around 1970.

aid of computer and store in digital form. Models have developed to use text-based language to represent the graphic-based symbols. For example, most of the CAD/CAM systems support ISO 10303 -- STandard for the Exchange of Product model data (STEP) to represent and exchange product manufacturing information. Danner et al. (2003) proposed a STEP-Based information model for dimensional inspection was proposed. These models aim to integrate all produce information within its life-cycle. Thus they only provide limit information of the specification of surface texture.

In the verification of surface texture, there are various data file formats available[10]. However, most of them focus on the storage of measured data with little information about the measurement condition[11]. Muralikrishnan and Raja (2002) proposed a common format for exchanging surface texture data across different platform, which is a XML-based container for the information of part, measurement, data file, analysis, process and function. Another file format with lot of detailed measurement information is the SMD file format. SMD is defined as the protocol for software calibration in ISO 5436-2 (2001). The elements of SMD are listed in Table 2.2.

Table 2.2 Elements of the SMD file format (ISO 5436-2 2001)

Section	*Element*
Record 1 – Header	The revision number; File Identifier; Feature Type; Feature Number; Feature Name; Axis Name; Axis Type; Number of Points; Units; Scale factor; Axis Data Type; Incremental Value;
Record 2 – Other information (optional)	Date; time; created by; Instrument Id; Instrument Serial; Last Adjustment; Probing System (It includes Probing System Id; Tip radius value; Units; Tip Angle); Comment; Offset; Speed; Profile Filter (It includes filter type; Ls cutoff value; Lc cuttoff; Lf cutoff value; Motif A, Motif B); Parameter value (It includes Parameter Name; Parameter Value; Units; Uncertainty)
Record 3 – Data	Data value;
Record 4 – Checksum	Checksum value.

There is a logical relationship between specification and verification, and models discussed above mainly focus on one part. The shape and size of such information are

[10] For example, a commercial software package has listed more than 40 supported file formats. (Retrieved 30th January 2011, form http://www.truegage.com/tmformats.php#ts_upgrades)

[11] In this project website, an overview is given for the measurement information storage in several popular file formats.

changed from the designers to the metrologists. It could contribute the uncertainty in communication level. Thus, it is of importance to develop an information model to standardise the message from the specification to verification and vice versa.

There is an ongoing project for developing the protocol of the softgauges for areal surface texture measurements, which includes a proposed data file format and an open resource application to read and write this file format. The data structure follows the structure using in ISO 5436-2.

In addition, an information model needs to limit the amount of detailed information. Measurement standards, discussed in the next section, are useful tools to this end.

2.3 Hardgauges and primary instruments

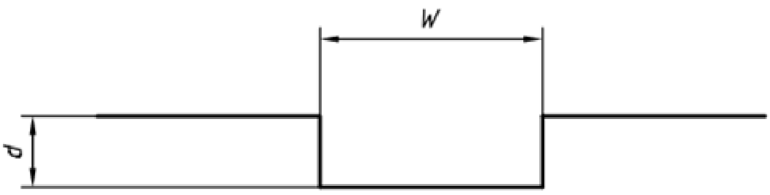
At the national level of a national measurement system, the current realisations of the definitions of surface texture are measurement standards, i.e. hardgauges, and a primary instrument.

2.3.1 Hardgauges

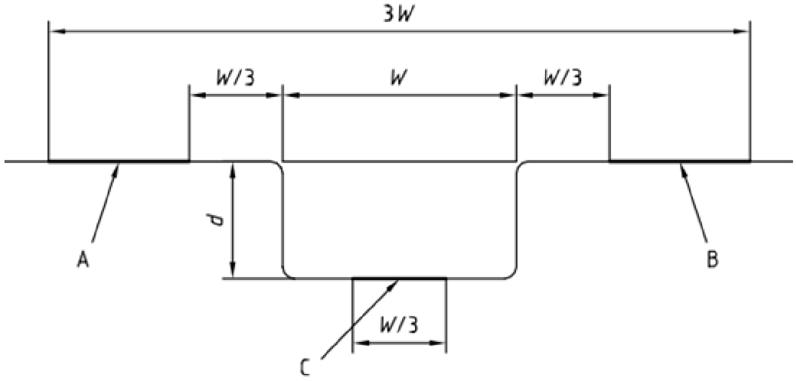
The design and the development of hardgauges to calibrate the surface measuring instruments begun in 1940's, when Tomlinson (1946) at NPL developed one of the earliest hardgauges in the form of acid-etched lines. Thanks to the contributions made by Underwood (1953), Schobinger (1959), Reason (1951), Sharman (1967), Hasing (1965) and Song (1988), many hardgauges have been developed with different shapes on various materials. Most of them are standardised in ISO 5436-1 (2000). This document advocated using these hardgauges to determine the operating characteristics of contact stylus instruments, and lists five different types of hardgauges.

Type A hardgauges

They are used to calibrate the vertical profile component of stylus instruments. They come with two sub-groups, type A1 – a wide groove with a flat bottom (see Figure 2.9), and type A2 – same as A1 but with a rounded valley (see Figure 2.10). Each geometrical feature of these hardgauges should be wide enough to be insensitive to the shape or condition of the stylus tip.



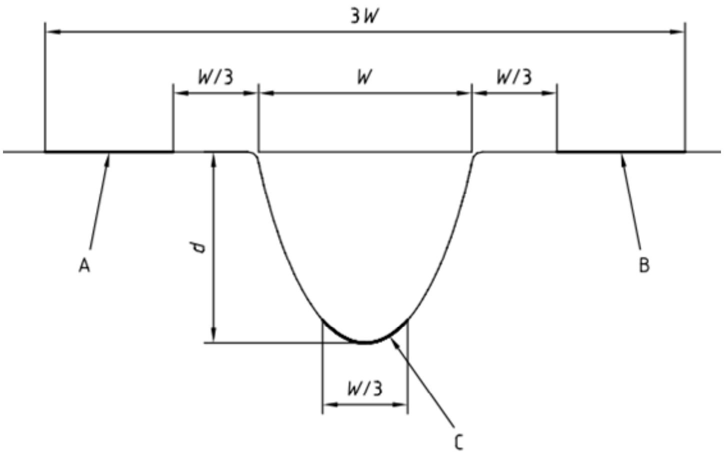
(A) The type A1 hardgauges



(B) Measurement strategy for the assessment of a type A1 hardgauge according to ISO 5436-1

Figure 2.9 Examples of type A1 hardgauges (ISO 5436-1 2000)

(A) The type A2 hardgauges

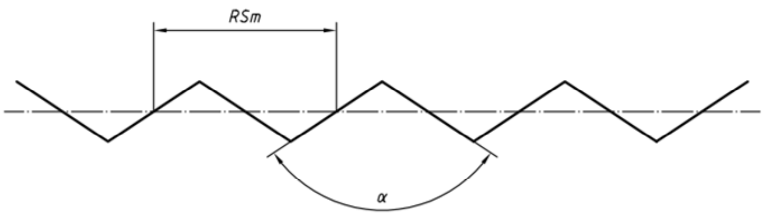


(B) Measurement strategy for the assessment of a type A2 hardgauge according to ISO 5436-1

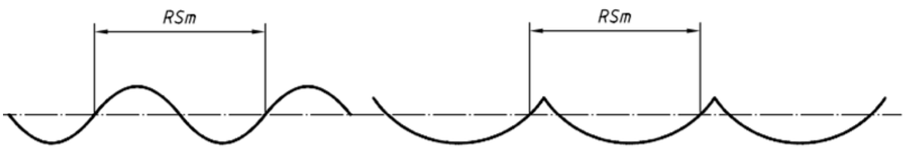
Figure 2.10 Examples of type A2 hardgauges (ISO 5436-1 2000)

Type B hardgauges

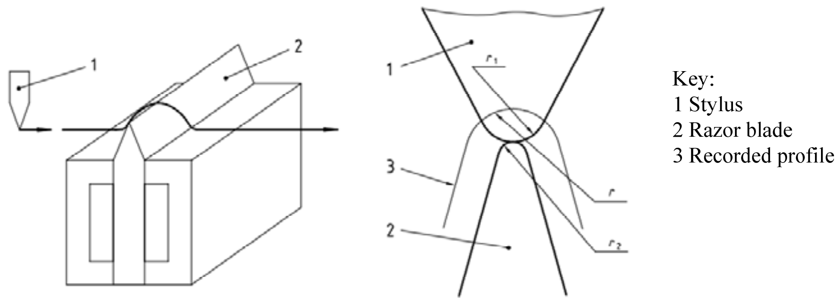
They are used to calibrate the geometry of the stylus tip. They also come with three sub-groups: Type B1 – narrow grooves with rounded bottoms proportioned to be sensitive to the dimensions of the stylus; Type B2 – two grids of equal *Ra*, one sensitive to the tip dimension the other insensitive; Type B3 – a fine protruding edge to assess the stylus condition. Some of example shows in Figure 2.11.



(A) The type B2 hardgauges (sensitive groove pattern)



(B) The type B2 hardgauges (insensitive groove pattern)

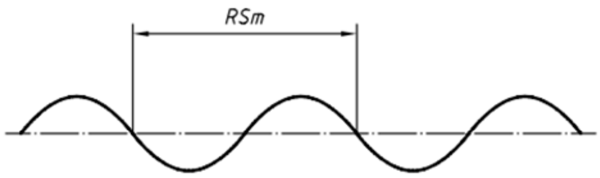


(C) The type B3 hardgauges

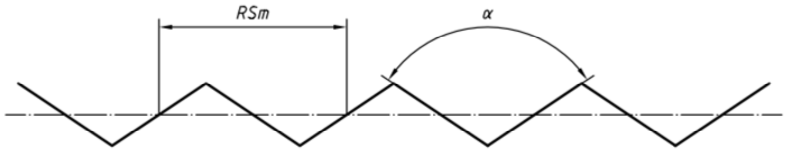
Figure 2.11 Examples of type B hardgauges (ISO 5436-1 2000)

Type C hardgauges

They are used to calibrate both the vertical and horizontal profile components. They consist of a grid of repetitive grooves of similar shape. They come with three sub-groups: Type C1 – groves having a sine wave profile (see Figure 2.12-A); Type C2 – Grooves having an isosceles triangular profile(see Figure 2.12-B); Type C3 - simulated sine wave grooves (see Figure 2.12-C), and Type C4 – grooves having an arcuate profile (see Figure 2.12-D). Type C hardgauges have well documented surface parameters and can be used to calibrate the horizontal magnification.

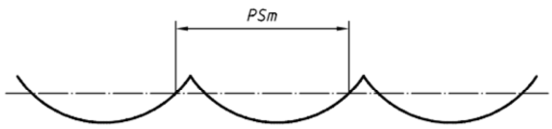


(A) The type C1 hardgauges



(B) The type C2 hardgauges

(C) The type C3 hardgauges

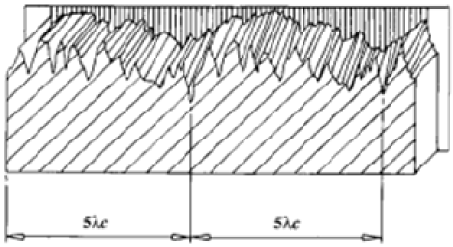


(D) The type C4 hardgauges

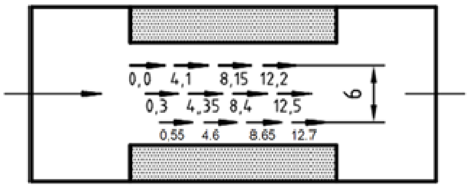
Figure 2.12 Examples of type C hardgauges (ISO 5436-1 2000)

Type D hardgauges

They are used for an overall calibration of instruments. They have an irregular profile in the direction of traverse, but they have the convenience approximately constant cross-section along their lengths (see Figure 2.13-A). Following their measuring plan (see Figure 2.13-B), they can be used to check the overall performance of an instrument while limit effect of the surface inhomogeneity. They also come with two sub-groups: Type D1 – unidirectional irregular profile; and type D2 – circular irregular profile.



(A) The type D1 hardgauges

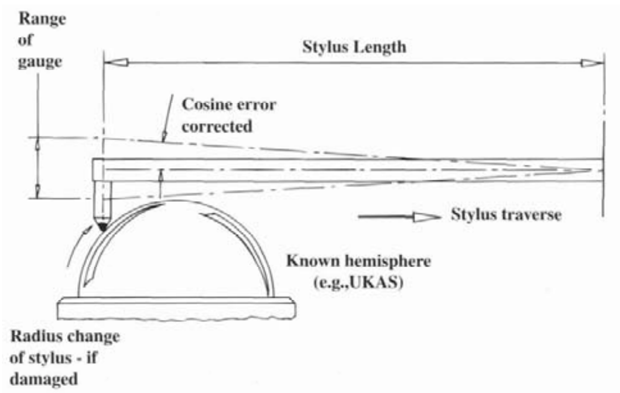


(B) Measuring plan of a type D1 hardgauge

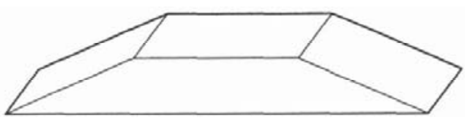
Figure 2.13 A type D1 hardgauge and its measuring plan (ISO 5436-1 2000)

Type E hardgauges

These are used for calibrating the profile coordinate of instruments. They come with two sub-groups, type E1 – precision sphere or hemisphere (see Figure 2.14-A), type E2 – precision prism (see Figure 2.14-B).



(A) The type E1 hardgauges



(B) The type E2 hardgauges

Figure 2.14 Examples of type E hardgauges (ISO 5436-1 2000)

The philosophy of using the type A, B, C, E hardgauges is to identify the influential components and check each of them separately. A hardgauge is normally developed to assess metrological traceability (towards SI units) of one component, while to limit the effect of other components. However, it is still a problem of traceability of the results obtained from the engineered surfaces in the industry practices, due to their geometrical features are unlike the features on these hardgauges. Some suggested using the real engineering surfaces to check the performance of an instrument with the certified values obtained from a primary instrument. The great problem of this method is the inhomogeneity of the surfaces itself. Hasing (1965) and Song (1988) have developed random profile hardgauges (i.e. type D hardgauges) to overcome this drawback.

Hardgauges can be calibrated easily, accurately and unambiguously. They provide the absolute interpretations of the definitions of the surface parameters without going into too much detail (Rubert 1995). Using of hardgauges can identify (and manage) the disagreements between different parties. For example, Song and Vorburger (1991) proposed a measuring procedure based on the calibration procedure of hardgauges at NIST.

There are many typical problems of the calibrations undertaken by using hardgauges. Rubert (1995) listed some of them: 1) less accurate and more uncertain; 2) the disagreement due to non-standardised measurement conditions; 3) wear and damage on the hardgauges after a period of use. More issues will be discussed in Section 2.4.

2.3.2 Primary instruments

A NMI often maintains a primary instrument to provide the certified values of the hardgauges within a country. This well-calibrated instrument establishes the traceability chain toward SI units. Most of NMIs use a commercial instrument; some use their own developed instruments. For example, NPL developed a surface measuring instrument, called NanoSruf IV, with ± 1 *nm* measurement uncertainty (at 95 % confidence) for both vertical and horizontal measurements (Leach 2001).

Self-evidence is provided on the accuracy and reliability of the primary instruments. To avoid a significant disagreement between different countries, NMIs carry out the comparisons among their instruments by using hardgauges. The inter-comparisons are not undertaken very often due to the cost both in time and labour[12]. Two recent inter-

[12] For example, the most recent comparison spent near 4 years (Euromet 600, 2004).

comparisons among NMIs in European have undertaken in 1989 (Hillmann) and in 2004 (Koenders, Andreasen et al.). Significant disagreements have reported, and the later one highlighted the needs to improve both the instruments and the software, have a better understanding of uncertainty and have more precise definitions in standard documents.

2.4 Traceability chain

2.4.1 Measurement uncertainty

2.4.1.1 General concept of error and uncertainty

The hierarchy of measurement standards forms a pyramid. It is obvious that the higher in the pyramid, the more accurate (or less inexactness, in other words) must be of the standard. The m*easurement error*, the difference between the measured value and "true value", was historically used to describe the inexactness. *Errors* are subdivided into random and systematic. As illustrated in Figure 2.15-a, *Systematic errors* are often defined by the difference between the true value and the mean of the measured values. *Random errors*[13], caused by non-controlled random influence quantities, may be characterized by the standard deviation and the type of distribution.

Due to it is impossible to know an exactly true value, the reference value, or certified value provided by the measurement standard, is used to assess the knowable errors (see Figure 2.15-b). Thus, a reliable reference value should be as close as possible to the true value by reducing the effect of unknown errors.

As the "exact value" of an error is unknowable, measurement uncertainty is introduced to quantify the inexactness by estimating the distribution of measurement errors in the form of an interval with a specified level of confidence. The most commonly used procedure for calculating measurement uncertainty is described in *the Guide to the Expression of Uncertainty in Measurement* (GUM 1995). The GUM's method is undertaken with several steps as listed in Table 2.3 and illustrated in Figure 2.15-c.

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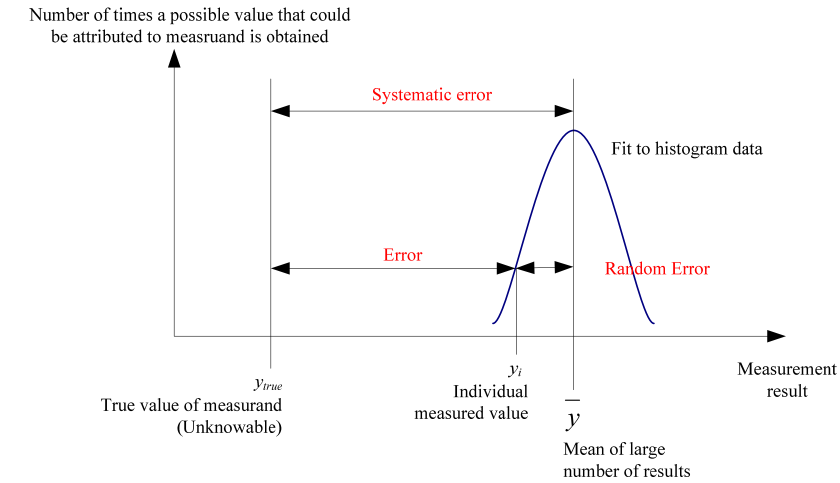
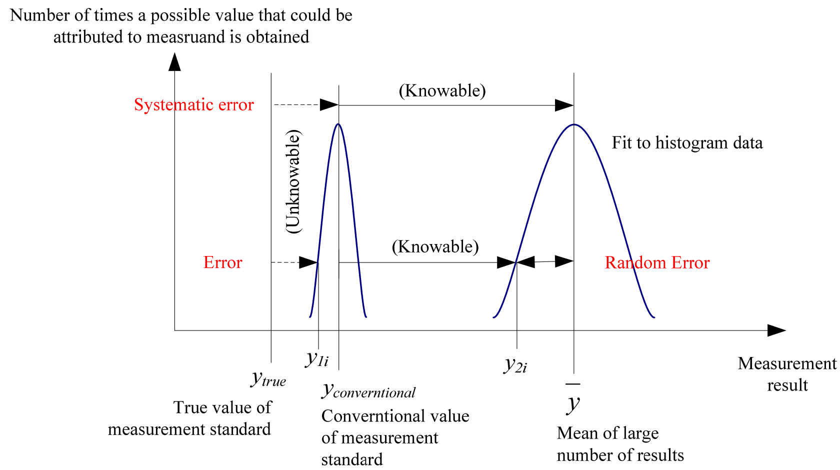
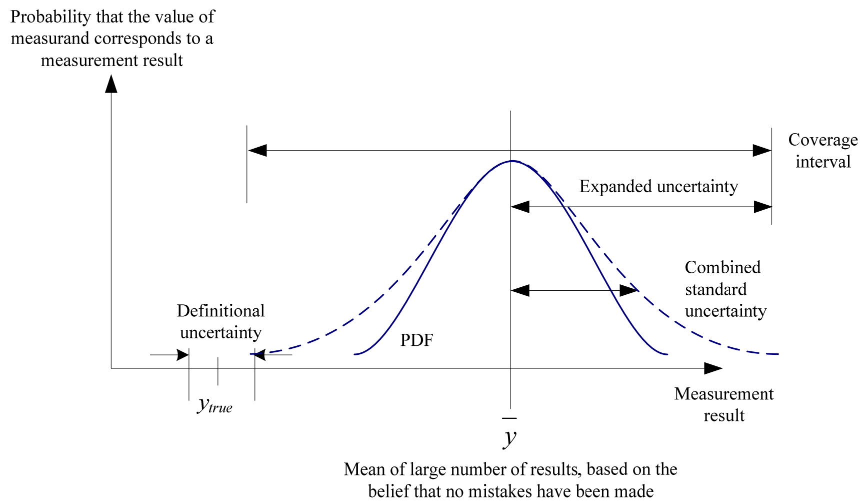
[13] Note that all errors are by nature systematic. When we see errors as non-systematic it is due to insufficient resolution, unknown contributor, etc.(ISO/TS 14253 1999)



(a) Relationship between systematic errors and random errors



(b) Use of measurement standards in the estimation of systematic errors and random errors



(c) The GUM's method

Figure 2.15 Relationship between system errors and random errors [Adapted from (Ehrlich, Dybkaer et al. 2007)]

Table 2.3 The GUM's method (Howarth and Redgrave 2008)

Step	***Procedures***
1	*Identify all important components of measurement uncertainty*: Many sources can contribute to the measurement uncertainty. Apply a model of the actual measurement process to identify those sources. Use measurement quantities in a mathematical model.
2	*Calculate the standard uncertainty of each component of measurement uncertainty*: Expressing each component of measurement uncertainty in terms of the standard uncertainty determined from either a type A or type B evaluation. *Type A components* are estimated by statistical processing of repeated measurements. *Type B components* are estimated by other methods. The most commonly used method it to assume a probability distribution based on experience or other information.
3	*Calculate the combined uncertainty*: In practice, for a sum or a difference of components, the combined uncertainty is calculated as the square root of a sum of the squared standard uncertainty of the components.
4	*Calculate the expanded uncertainty:* Multiply the combined uncertainty with the coverage factor k.
5	*State the measurement result on the form:* $Y = y \pm U$

Note that the term of "uncertainty" has two rather different meanings in a technical sense. The first meaning has its roots in probability and statistics, which is widely used in metrology and normally evaluate by the GUM's method. The second meaning relates to the "lack of knowledge" (i.e. the absence of information in communication and cognise level), which is discussed in the GUM (1995) and is highlighted in the VIM3 (2007). The VIM3 (2007) revised the definition of measurement uncertainty to cover two meanings. However, there is no a guide provided to estimate of definitional uncertainty (the second meaning). Moreover, VIM3 does not define the concept of the measurand definition, the object which definitional uncertainty attempts to quality, which is still an open topic in the field of metrology (Phillips, Estler et al. 2001; Mari 2006; Pavese 2007; Baratto 2008; Mari 2009).

2.4.1.2 Error and uncertainty in surface texture measurements

An uncertainty budget is started from the definition of uncertainty contributors. Many sources of uncertainty in surface metrology can be identified (Blunt and Jiang 2001; Smith 2002); nevertheless, uncertainties vary with the task being performed, the environment, the operator, the chosen measurement methodologies, etc. A typical example of sources of errors shows in Figure 2.16.

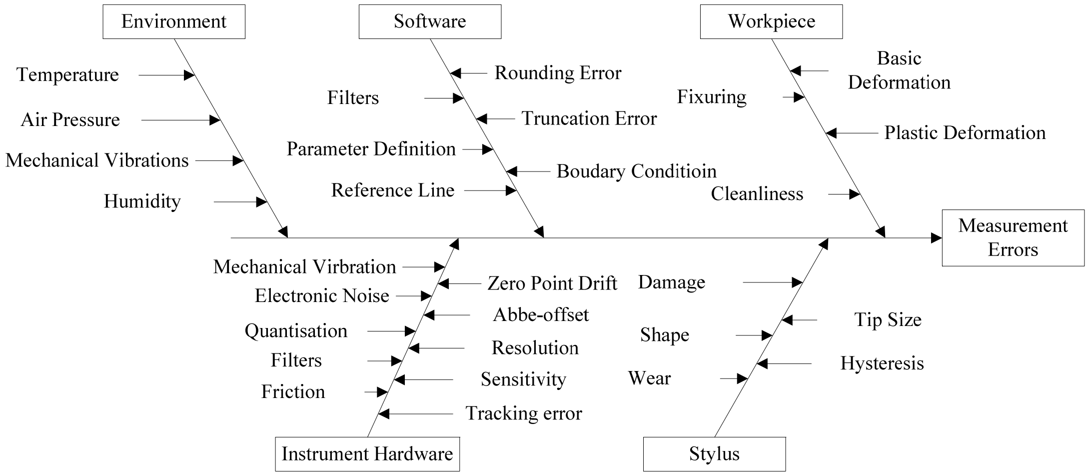


Figure 2.16 Sources of errors in surface texture measurements (Li, Blunt et al. 2009)

To make it clearly, uncertainty contributors are grouped in five categories: hardware, measurand, measurement strategy, software and interpretation of the results by the approach proposed by Wilhelm et al (2001). This categorization gives a straightforward view of the relationship of different components of uncertainty as shown in Figure 2.17.

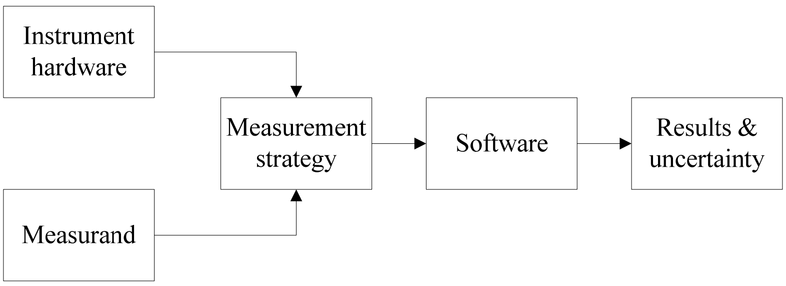


Figure 2.17 Error components that lead to measurement uncertainty

Instrument hardware

It refers to the sources of uncertainty caused by errors inherent to the design of the instruments, its stylus, its dynamics, and the environment in which it is placed. Generally, the effects of temperature, air pressure and humidity are insignificant for surface roughness measurement. Mechanical vibrations can induce outliers in the measured surface and should be avoided.

The use of various measurement methods (e.g. stylus, optical, AFM, etc.) could produce different results on one surface. Many comparisons have undertaken (Church, Vorburger et al. 1985; Whitehouse 1988; Poon and Bhushan 1995). In a recent comparison, Vorburger et al (2007) reported that the discrepancy is up to 75% between optical method and stylus method in some cases. For a stylus instrument, the effects of stylus tip radius, tip worn and stylus flight can be significant (McCool 1984; Song and Vorburger 1996; Pawlus and Smieszek 2005).

Measurand

This uncertainty relates to properties of the measurand and measurement interaction with the workpiece. It is well known that significant variations can occur when small samples are taken from a large population of data. Generally, the measurand is defined within a sampling length to represent the whole surface. Thus, the inconsistent on the surface itself is the biggest contributor of the uncertainty. Thomas and Charlton (1981) investigated the variation of surface parameters on some typical surfaces. It found that the variations are up to 15% on the hardgauges and up to 50% on the typical machined surfaces. Stout and Davis (1986) investigated the variation of the *Ra* parameter when increasing the measuring times. These research works were based on the previous definition of surface parameters. Further study needs be undertaken on the variation of the latest ISO parameters on the typical surfaces.

Measurement strategy

It includes the errors due to the inadequate in sampling, selection of sampling length, evolution length, etc. The default setting up of a stylus instrument is provided in ISO 3274 (1996) and ISO 4288 (1996). This project only takes these standardised measurement conditions into consideration.

Software algorithm

The uncertainty, contributed by the software algorithms, involves two topics: the propagation of the data uncertainty and the "quality" of the software itself. The complexity of the parameter calculations causes the difficulties in the estimate of the propagation of data uncertainty (PU). Haitjema et al. have calculated it (2000; 2000; 2001) based on its experimental results. It has taken into account the following effects:

z axis calibration, x axis calibration, λc cut-off length, λs cut-off length, probe diameter, probe tip angle, probing force, straightness of reference and sampling density. Similar uncertainty models have widely used by NMIs (Koenders, Andreasen et al. 2004). With the drastically increased power of the calculation of computers, the Monte Carlo Simulation (MSC) has been implemented to calculate the uncertainty. Brennan et al (2005) investigated a robust method of PU in the discretely sampling surface profiles. Bui and Vorburger (2007) in the NIST used MSC to calculate the uncertainty by adding random noise to each data point. NIST method assumes the noise has a normal distribution with mean of zero and standard deviation in both x-direction and z-direction, and each point is independent from other points.

The "quality" of software in this context only refers to the accuracy and reliability of the software algorithms. It is a systematic error between the commercial software and the national reference. It reflects the metrological comparability of difference software packages.

Results and uncertainty

The measurement results with associated uncertainty are presented in the form of $Y = y \pm U$ with the coverage factor k. It should pay attention on the possible uncertainty arisen from the presentation of results.

Some issues of uncertainty in surface texture measurements

The GUM's method is summarised in Section 2.4.1.1. However, it is very difficult to implement the GUM's method to evaluate the uncertainty in surface measurements. The reasons are listed as follows.

1) The GUM's method is under the assumption that a measurand can be characterised by an essentially unique value. The definitional uncertainty is considered to be negligible with respect to other components of measurement uncertainty. As discussed in the previous section, the definitional uncertainty of surface texture measurements could be significant.

2) The GUM provides the guidance in the case of a single reading of a calibrated instrument, a situation normally met in industry metrology. However, the measured values of a parameter are produced by a set of mathematical

treatments on thousands measuring points. Uncertainty models as discussed above assumed that the separated effects are uncorrelated, but they are significant correlated indeed. For example, Krystek (2001) investigated the uncertainty contributed by using the Gaussian profile filters, and highlighted the correlated property of the filtered data.

Thus, Leach (2009) states that "*there is not straightforward to calculate a rigorous uncertainty value for an instrument for all surfaces and for all parameters, and only a pragmatic approach can be applied for a given measurement scenario*".

2.4.2 Calibration

The traceability chain is established through the calibrations. Note that the term of "calibration" in many publications is confused with "adjustment of a measuring system". Their definitions in metrology are listed as follows.

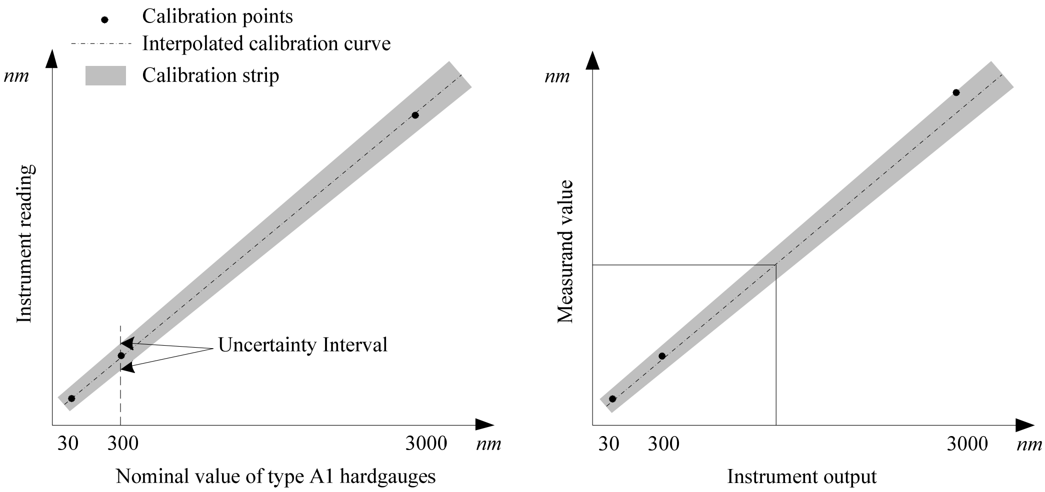
- **Adjustment** is *"set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured.* (VIM3 2007)*"* The adjustment process, therefore, comprises the modification of internal parameters, which characters the relation between the variations given by the probe and its real displacement.

- **Calibration** is *"operation that, under a specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainty and, in a second step, used this information to establish a relation for obtaining a measurement result from an indication* (VIM3 2007).*"*

The first step of calibration consists of the measurements on a certainty number of hardgauges, and the verifications of the measured values with the certified values. Importantly, no modification undertakes on the internal parameters of this instrument. The second step of calibration is to produce a calibration curve by a suitable interpolation. For example, one wants to calibrate the vertical displacement of the stylus of a surface instrument. She/he could use three type A1 hardgauges, certified by NPL, with nominal height at 30 nm, 300 nm and 3000 nm, and each of them comes with associated uncertainty. As illustrated in Figure 2.18, the calibration process includes two steps.

- This instrument measures three hardgauges; the corresponding readings are recorded; and the measurement uncertainties are evaluated;

- A calibration curve is constructed by using these reading and a suitable interpolation algorithm, e.g. Least-Squared fitting of a straight line. A calibration strip is created in a similar way by using uncertainty interval (see Figure 2.18-a). This function is then inverted, so that each reading of this instrument can be associated with a measurand value (see Figure 2.18-b).



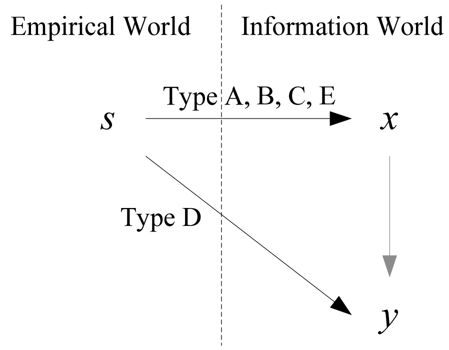
(a) a curve generated by using of three A1 hardgauges

(b) the use of a calibrated instrument

Figure 2.18 Diagram of calibration process

2.4.3 Some issues of traceability of surface texture measurements

There are some issues surrounding the traceability chain of surface texture measurements, which currently established by using hardgauges only. To make it clearly, Figure 2.19 shows a typical surface measurement progress, together with the position of hardgauges. The measurements link the empirical world and the information world (which is of the abstract concepts and knowledge). It includes two phases, data collection and data processing. Correspondingly, traceability of surface measurement can be split into two parts, traceability of the instruments (in the empirical world), and traceability of the implementations of the algorithms (in the information world). Figure 2.19 illustrates the position of the hardgauges in two worlds.



Key: *s*: a surface;
x: a set of measured data points
y: measurement results expressing in the form of a surface parameter
s→*x*: Data collection
x→*y*: Data processing
s→*y*: Whole measurement

Figure 2.19 Position of hardgauges

There are two routes to demonstrate traceability of measurement results in the form of the surface parameters, that of route 1 though *s*→*x*→*y*, and that of route 2 through *s*→*y* directly. Type A, B, C and E hardgauges are used to check traceability of instruments in aspects of the tip condition, vertical and horizontal components, etc. It maintains a route of traceability of each measuring point obtained a surface (i.e. *s*→*x*) toward SI unit. Obviously, this route is incomplete without the check traceability of data processing phase (i.e. *x*→*y*).

Type D hardgauges are able to check traceability of the whole measuring process (s→y), but there are some issues on this route. Firstly, there are 63 ISO parameters, but a type D hardgauge normally only provide certified values of parameter *Ra* & *Rz*.

Secondly, the certified values are obtained from a primary instrument in a country. Much evidence shows traceability of the data collection in this instrument, but limited evidence shows its software traceability. In this situation, other tools should be applied to assure at least comparability of the measurement results. Unfortunately, it has found that significant disagreement (up to 35%) in the phase of data processing(Koenders, Andreasen et al. 2004).

Finally, it is a problem to produce a reliable calibration curve by using type D hardgauges. It is well known than same *Ra* value can be obtained from significant various surfaces (Whitehouse 2002b). So the existing of the calibration curve of *Ra* parameter is an issue (Scott 2011). Type D hardgauges only provides few reference points, and the eyeballed fitting curves are often used (Song and Vorburger 1991). Figure 2.20 shows the calibration points (provided by some typical used type D hardgauges) and range of *Ra* value on typical surface produce by different processes. It can be found that the type D hardgauges only provide few calibration points, and the points do not fall into the range of Ra values on many typical engineered surfaces.

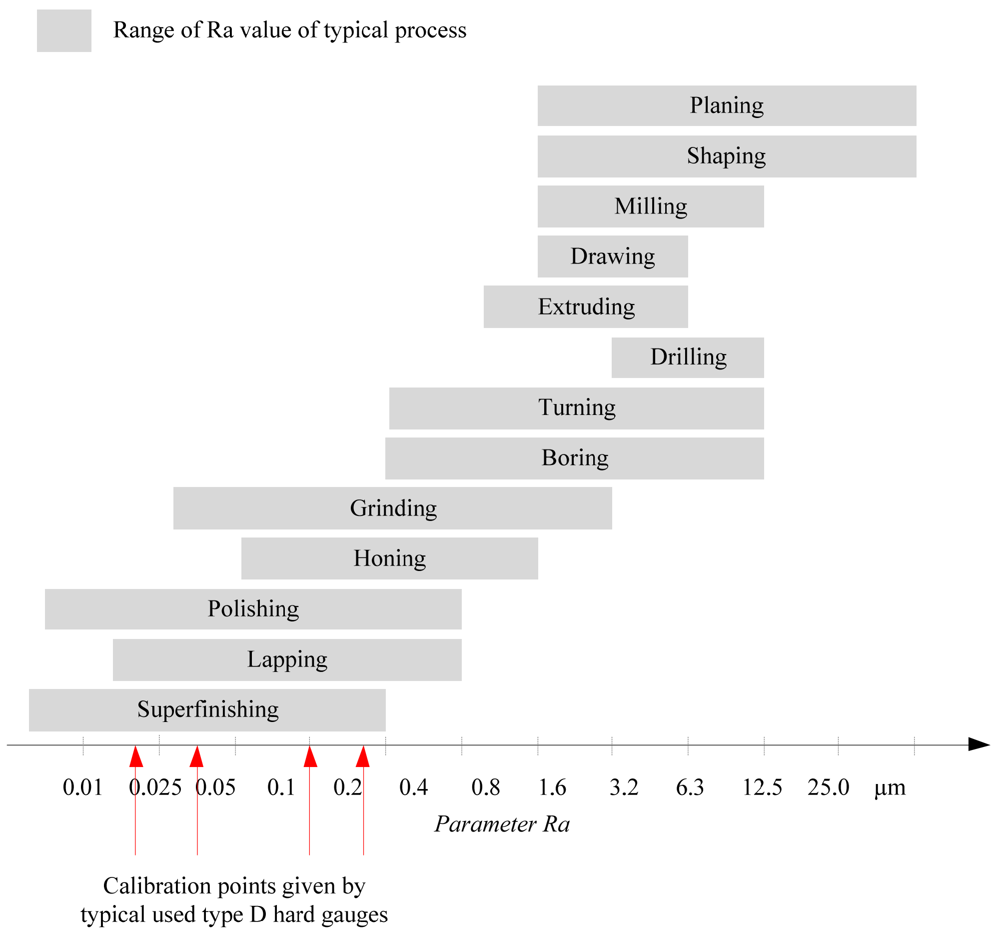


Figure 2.20 Calibration points and range of Ra value (source: Rubert & Co Ltd and Taylor Hobson Ltd)

Therefore, type D hardgauges, the standards close to the engineering surfaces, only deliver limited evidence on traceability of an instrument in the form of parameter Ra and Rz. It is unable to claim the metrological traceability of most of the surface measurement results through current route (via $s \rightarrow x$ or $s \rightarrow y$). Fortunately, type F measurement standards (i.e. softgauges) provide another route (via $s \rightarrow x$ and $x \rightarrow y$) which is expected to address this issue.

2.5 Softgauges

2.5.1 Concept of softgauges

The most important ISO standard document, for this thesis, is the ISO 5436-2 (2001), *"Geometrical Produce Specifications (GPS) – Surface Texture: Profile method; Measurement standard – Part 2: Software measurement standards"*. Software measurement standards are defined as "*reference data or reference software intended to reproduce the value of a measurand with known uncertainty in order to verify the software (i.e. filter algorithms, parameter calculations, etc.) used to calculate the measurand in a measuring instrument."*(ISO 5436-2 2001). They come with two sub-groups.

Type F1 *software measurement standards* are reference data files, which are a digital representation of a profile with reference results attached. They are used to test software by inputting them into the software under test, and comparing the results with the certified reference results provided with the type F1 software measurement standard (ISO 5436-2 2001).

Type F2 *software measurement standards* are reference software. The reference software consists of traceable computer software against which software of a measuring instrument can be compared. Type F2 software measurement standards are used to test software by inputting a common data set into both the software under test and the reference software and comparing the results from the software under test with the certified results from the reference software (ISO 5436-2 2001).

2.5.2 Requirements

Before the design and development of the softgauges for surface texture, it is necessary to understand the requirements from the standard documents, the end-users and the development of surface metrology.

Requirements from standard documents

Many originations have issued the requirements on metrological software [14]. For instance, ISO/IEC 17025 (2005) specifies the software requirements [15] within the general requirements for the competence of testing and calibration laboratories. "*A guide to the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in the product verification*", states software contribution for the measurement uncertainties (ISO/TS 14253-2 1999). Its clause 7.6 lists the main possible contributors, such as rounding/quantification, filtering, algorithms, correction of an algorithm, certification of an algorithm, implementation of an algorithm, interpolation, extrapolation, number of signification digits in the computation, outlier handing, sampling, etc. In the field of surface measurement, ISO 5436-2 (2001) highlights the requirements for verifying the software by introducing the concept of *software measurement standard*. Thus, the software measurement standards are essential parts in a national measurement system.

Note that the requirements and the validate objectives are often vague, such as "the software shall be of high quality", or "the software shall be of function correctly"(Greif 2006).

Requirements from end-users

To understand the end-users' requirements, an industrial consultation exercise has undertaken at the start of this project. The results are summarised as follows.

- A total number of 30 responses was received, and they represented a good converge across a number of industrial sectors. The majority of the respondents were from the automotive sector (8), followed by metrology instrument manufacturers (5) and educational institutes (5).

- Precision finishing of metal was highlighted as the main manufacturing process for the majority of the respondents, with grinding and lapping/polishing of steels appearing to be the most critical (see Figure 2.21). It is clear from the

[14] Many standards are developed or under developing. Tasic and Grottker (2006) undertake a survey of the guiding documents for software in metrology, with an emphasis on requirements defined.

[15] Such clauses are, e.g.: 5.4.7.2a, 5.5.2, 5.5.4, 5.5.10, 5.5.11 and 5.5.12 (ISO/IEC 17025:2005)

consultation that industries producing such surfaces have a fair knowledge of their metrology needs and tools.

- For surface profile measurement, contacting stylus instruments remains the key tool with all but one of the respondents using them. The use of standards was strongly supported, particularly ISO 4287 (53%). However, a significant proportion of instruments' users employs no standards at all and has no knowledge of the standards (40%). Most seemed aware of problems with the software.

- The great majority of respondents (80%) use the Gaussian filter extensively. However, a significant number (20%) still uses the 2RC filter – this may be due to a lack of knowledge of standards development or, more probably, the fact that they possess older instrumentation.

- A wide variety of surface texture parameters was reported as being used. Parameter *Ra*, *Rsk*, *Rv*, *Rp*, *Rz*, *Rt* and *RSm* seem to be the most widely used (see Figure 2.22). However, there were exceptions and, for example, the automotive respondents reported the use of the *Rmr* and *Rk* parameters.

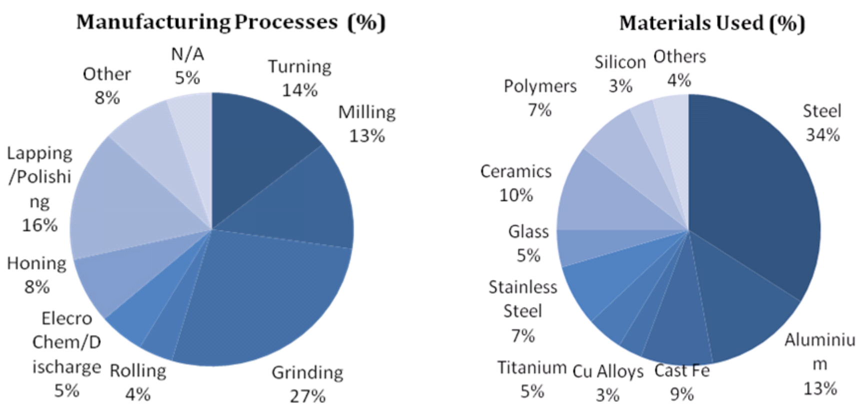


Figure 2.21 Manufacturing processes and materials used by respondents

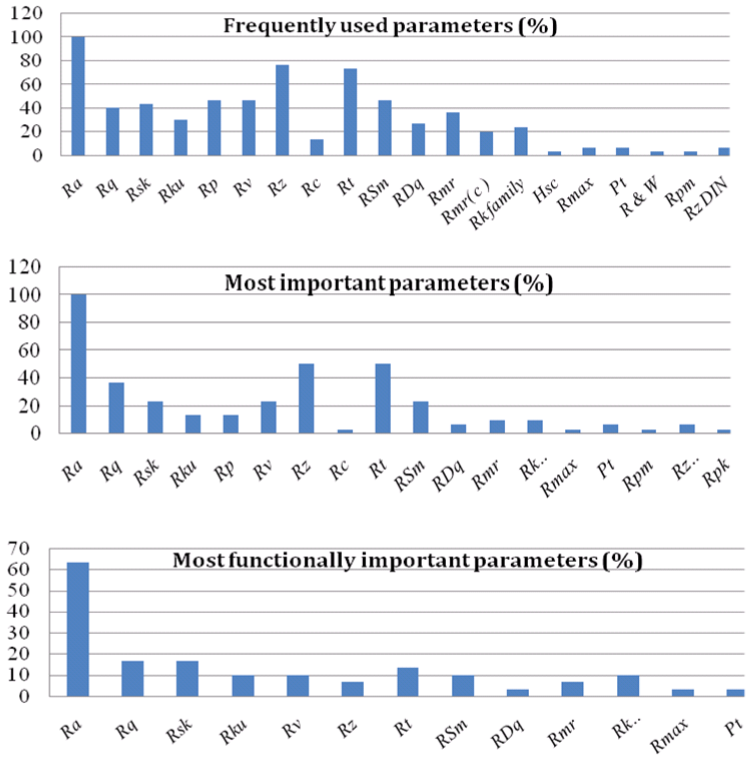


Figure 2.22 Frequency and importance of R-parameters

The impact of the results of the consultation exercise on the development of software measurement standards within the current project is summarised as follows.

- The parameters to be considered are (a subset of) these covered in ISO 4287(1996), comprising: *Ra, Rq, Rsk, Rku, Rp, Rv, Rz, Rc, Rt,* and *RSm*.
- Consideration will be given to guide the use of the software measurement standards.

Requirements from the future development of surface metrology

The need for softgauges is also driven by the future development of surface metrology. Some of them are listed below.

- *The development of specification language and verification method for surface texture:* The GPS language is going to be of richer and more complex. Softgauges are the essential metrological tools to make sure the reliability of the realisations of those standard documents.

- *The development of the databases and the expert systems for surface texture*: Those systems aim to help the designer to predict the performance of the design components and enhance the management of information for surface. Softgauges are key tools to check traceability of information in these systems.

2.5.3 Related work

The use of digital methods in surface metrology was introduced in the late 1960s. The first commercial available digital surface instrument was released by Taylor-Hobson Ltd in 1972. In 1970s and 1980s, the software effect on the digital instruments was considered to be negligible with respect to other components of measurement uncertainty. For instance, an ASME standard document on measurement uncertainty states that "*computations on raw data are done to produce output (data) in engineering units; Typical errors in this process stem from curve fits and computations resolution. These errors are often negligible*" (ASME 1985).

In the late of 1980s, however, much evidence was discovered that software could be a significant source of errors in the use of the coordinate measuring machine (Porta and Waldele 1986). Since the beginning of 1990s, there is considerable ongoing research work on the validation and verification of metrological software, and growing interest by NMIs in testing the performance of the software. Some of them provide services to test software (Hopp 1993).

For surface measurement, Scott (1988) introduced a conceptual instrument, namely "the reference surface measuring instrument", to address the disagreements arisen from the various interpretations of standard documents. The "reference algorithm" is one of its essential components. Song and Vorburger (1991) at NIST also stated that checking parameters algorithms are a necessary step (and first step) in a calibration procedure.

A software verification method developed (Stout, Sullivan et al. 1993) in an EC funded project which aims to develop the draft 3D surface characterisation standards. It uses a simulated specimen (3D) with known characteristics to carry out software verification.

Since the middle of 1990s, ISO has issued a series of standards for surface texture. And the concept of software measurement standard is introduced (ISO 5436-2 2001).

To analysis the software variability in the surface profile measurement, NIST has undertaken a round robin testing together with a further investigation (Bui, Vorburger et al. 2003; Bui, Renegar et al. 2004). These investigations pointed out that software is a primary contributor of the variation on the surface measurement results. In Europe, 17 national metrology institutes (NMIs) undertook an inter-comparison on their surface measuring instruments (Koenders, Andreasen et al. 2004). For the first time, three reference data files were used for comparing the software of their instruments, and significant difference were found. In Asia, Chen et al (2005) reported inaccuracy of filter function in a commercial surface metrology software.

Many NMIs have developed their own software packages. Some of them have been used as part of its national measurement system (Koenders, Andreasen et al. 2004). In addition, some open-resource and web-based software implementations have been developed (Bui, Gopalan et al. 2001; Sacerdotti, Porrino et al. 2002; Bui, Muralikrishnan et al. 2003; Bui, Muralikrishnan et al. 2005). Moreover, NMIs in European, American, and Asia have undertaken some parallel projects to develop the reference software, i.e. type F2 softgauge (Jung, Spranger et al. 2004; Nie, Liu et al. 2006; Bui and Vorburger 2007; Li, Liu et al. 2007; Nemoto, Yanagi et al. 2008).

These works underlines the requirements of the verification and validation of surface metrological software. However, there is a lack of a common understanding of the softgauges, from its concept to its implementations. Some of the questions listed as follows.

- *Is it a measurement standard, which can be used to maintain the metrological traceability?* The type F standards, i.e. softgauges, are named as "measurement standards" in ISO 5436-2 (ISO 5436-2 2001). Obviously, they do have different "nature". They exist wholly in the information world, while the traditional measurement standards exist in the physical world. Some of NMIs, such as PTB and NIST, do not recognise that the type F standards are "real" measurement standards.

- *Do the metrological concepts, such as traceability and uncertainty, suitable for software?* According to ISO 5436-2, two key properties of the type F standard, as same as hardgauges, are uncertainty[16] and traceability[17]. Uncertainty and traceability are the most fundamental concepts in metrology. However, these metrological concepts do not be well understood by software developers. Thus, currently, some of the reference software only provide the reference results without stated uncertainty and demonstrate their traceability.

– *How to model and evaluate the software uncertainty?* Software uncertainty, as discussed in Section 2.4, has different meaning from traditional understanding of the measurement uncertainty.

– *How can we prove the accuracy of the softgauges?* It is of importance due to the certified values should as close as possible to the "real" value.

– *How to establish the metrological traceability chain with the aid of the softgauges?*

– *How to use the softgauges to calibrate product software?*

This thesis will attempt to address these questions that begin from next chapter.

2.6 Summary

This chapter has reviewed some of the key topics in surface metrology. It leads to the following summary:

1) The definition of the surface texture is complex and flexible. The ambiguous definitions have already led disagreements between different parties. A method

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[16] In clause 3.1 (ISO 5436-2 2001), it states, "*software measurement standard is reference data or reference software intended to reproduce the value of a measurand with known* ***uncertainty*** *in order to verify the software used to calculate the measurand in a measuring instrument*." And in clause 6 (ISO 5436-2 2001), it states "*..the calibrated value with its estimated* ***uncertainty****, U (see GUM) for each relevant metrological characteristic (for both F1 and F2 types)* ;" and "*For reference software it may not be possible to give a closed form equation for the* ***uncertainty*** *of some values of metrological characteristics. In these cases all relevant information should be given to allow the user to calculate the* ***uncertainty*** *for themselves*."

[17] In clause 4.3 (ISO 5436-2 2001), it states, "*reference software consists of* ***traceable*** *computer software...*" & "*Reference software values shall be* ***traceable***." And in clause 6, it states, "*the actual* ***specification operator*** *(see ISO/TS 17450-2) for each relevant metrological characteristic (for both F1 and F2 types)*."

is required to assess the degree of such ambiguity. This is especially important due to the coming standard documents are more complexity and flexibility.

2) Current information model for the information of specification and verification of surface texture is not well structured, has a difficulty to exchange via the Internet.

3) The hardgauges provide the absolute interpretations of the definition of surface parameters without going to much detail. The methodology in the design and development of hardgauges is to identify the influential conditions, assess each of them, interpreted them into the reference results with associated uncertainty. Lessons, summarised in Table 2.4, have been learnt from the design and use of hardgauges.

4) The current traceability chain of surface measurements is ill-defined by using the hardgauges only. Most of the surface measurement results are unable to demonstrate traceability. The use of hardgauges is also costly.

5) The evaluation of uncertainty for the surface measurements is relative immature. We need to pay attention to definitional uncertainty and specification uncertainty.

6) There are requirements for softgauges from standard documents, end-users and the future development of surface metrology.

Table 2.4 Lessons to learn from the design and use of hardgauges

no.	*lessons to learn*	*examples*
1	It needs to check all influential conditions and traceability of each component.	Type A, B, C, E
2	A realisation, as the absolutely interpretations of the definition, can identify and reduce specification uncertainty.	Type D
3	The realisations should be closed to real engineering surface.	Type D

In the following chapters, a set of softgauges will be designed and developed to address above metrological issues.

3 A framework for softgauges

The previous chapter has highlighted some issues surrounding metrological traceability of surface texture measurements. To address them, the chapter presents a framework for softgauges for surface texture, which is developed based on the latest philosophy and description of measurement according to the VIM3 (2007) and the GPS. The role of softgauges in the traceability chain is the subject of Section 3.1. The GPS concepts in the field of surface metrology are discussed in Section 3.2. A terminology in the context of software calibration is the subject of Section 3.3. A framework for softgauges is covered in Section 3.4.

3.1 Role of softgauges in the traceability chain

Some questions on softgauges were listed in Chapter 2. Two of them should be addressed at the beginning of this project.

1) Are they real measurement standards - which can be used to maintain the metrological traceability?

2) Are the metrological concepts, traceability and uncertainty, suitable for the software of instruments?

To address the questions, Table 3.1 compares some related concepts in the VIM2 and the VIM3.

Table 3.1 A comparison of the definitions of some key concepts in metrology

Terms	*Definitions in the VIM2 (1993)*	*Definitions in the VIM3 (2007)*
Definitional uncertainty	-	component of measurement uncertainty resulting from the finite amount of detail in the definition of a measurand
Measurand	particular quantity subject to measurement	quantity intended to be measured
Measurement	set of operations having the object of determining a value of a quantity	process of experimentally obtaining one or more quantity values that can be reasonably be attributed to a quantity
Measurement result	value attributed to a measurand, obtained by measurement	set of quantity values being attributed to a measurand together with any other available relevant information
Measurement standard	a measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce one or more values of an attribute to serve as a reference	realisation of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference
Measurement uncertainty	parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand	non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used
Traceability	property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties	the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty

The noticeable evolutions are underlined in Table 3.1, and discussed as follows.

- The metrological traceability chain is established by using “reference” (e.g. reference data, reference material, reference procedure), and a measurement standard is a “realisation”. A software measurand standard, a realisation in the form of reference data and reference procedure (ISO 5436-2 2001), should be capable as a measurement standard to establish the traceability chain.

- Definitional uncertainty is related to the description of a measurand. Much information is detailed within the software of instruments. Software, therefore, is a contributor to measurement uncertainty.

- In addition, the VIM3 revised the definition of *calibration*, *measurand* and *measurement*. These changes underline the importance of related information of measurand and metrological algorithms. Note that a measurand is defined by specification ("intended to be measured" according to the VIM3), not verification ("subject to measurement" according to the VIM2).

According to the VIM3, a software measurement standard, therefore, should be qualified as a measurement standard; and uncertainty and traceability of software needs be taken into consideration. The VIM3 is a milestone which marks a new world of metrology opened up by information science. It is believed that softgauges will play an increasingly important role in this world.

3.2 Surface texture in the GPS language

Software effect on measurement uncertainty is highlighted in ISO 14253-2 (1999), *"Guide to the estimation of uncertainty in the GPS measurement, in calibration of measuring equipment and in product verification"*. However, ISO 14253 (1999) does not provide an approach of the evaluation of software uncertainty. Even there is no a common understanding on software uncertainty.

Fortunately, the GPS provides a generalised uncertainty principle to assess the "quality" of communication between designers, industrial engineers and metrologists via the technical drawings. Software uncertainty is an uncertainty in communication level as well. Thus, this GPS principle will be adapted to define and estimate software uncertainty. This section presents the GPS uncertainty principles, and develops a better understanding in the context of surface metrology.

3.2.1 Geometrical features in three worlds

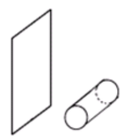
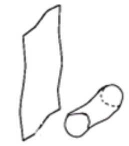
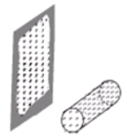
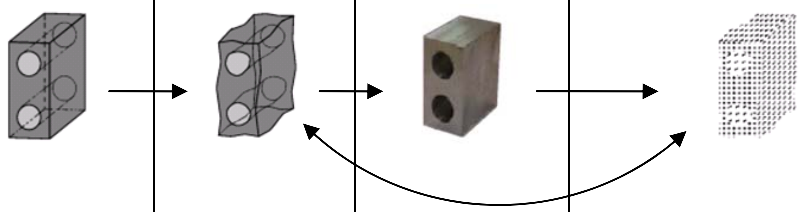
The GPS is an internationally accepted common language for expressing the geometrical requirements on the engineered components between designers, production engineers and metrologists. It covers all requirements (such as size, location, orientation, form, surface texture, etc.) indicated on a technical drawing to the geometry of industrial workpiece, all related verification principles, measuring instruments and their calibration (ISO/TR 14638 1995). In GPS philosophy, a geometrical feature is a point, a line or a surface, which exists differently in three "worlds" (see Table 3.2).

1) *The world of specification*, in which the designers have in mind several representations of the future workpiece: 1) A perfect workpiece, called the *nominal model*, is defined by perfect form, shape and dimensions to fulfil the functional requirements. 2) A non-ideal surface model, called *skin model*, is used to simulate the variations of the surfaces at a conceptual level (because some variations are expected on the real surface of the workpiece) and deliver the designers' requirements.

2) *The world of workpiece*, i.e. the physical world, in which a *real workpiece* is manufactured, as the result of a set of manufacture processing.

3) *The world of inspection*, in which a representation of the given workpiece is produced by sampling this workpiece via measuring instruments. Metrologists need to undertake a comparison between measurand (designers' requirements in a skin model) and the measured results (obtained from a real workpiece). It is impossible (and also unnecessary in many case) to obtain the variations over whole surface of the workpiece. Only finite points, therefore, are collected on the workpiece to represent the features of the real surface. A *verification model* is built based on limited measured information.

Table 3.2 Examples of geometrical features in three worlds

Features	*Nominal feature*	*Non-ideal feature*	*Real feature*	*Extracted feature*	*Associated feature*
Sample					
					
	Nominal model	Skin model	Real workpiece	Verification model	
Process	Design		Manufacture	Verification	
People	Designers		Product Engineers	Metrologists	

3.2.2 Operators and duality principle

GPS uses *operators* to define the feature requirements in three worlds, such as the specification operator, the verification operator, etc. Each of operators comprises an ordered set of *operations* (Figure 3.1). And each of the operations has its own set of selectable parameters. To express the connection between specification and verification, GPS introduces the duality principle:

"A *specification is defined independently of any measurement procedure or equipment. The measurement and equipment are fully controlled by the specification. All the results are defined for specification only – and metrology shall apply to the rules – deviations/difference will be part of the uncertainty of measurement* (ISO/TS 17450-2 2002)."

As illustrated in Figure 3.1, the design intent is expressed in specification characteristics within the specification operator. According to the requirements, the metrologists create the evaluation of characteristics within the actual verification operator. These operators can be compared with each other for conformity.

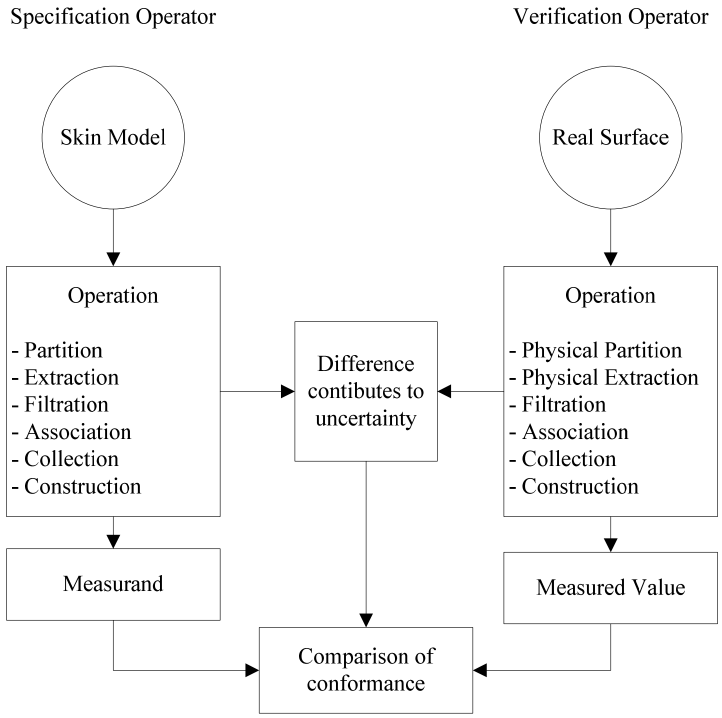


Figure 3.1 Duality principle (ISO/TS 17450-2 2002)

The GPS reflects a significant change of the definition of the measurand: from the "*particular quantity* *subject to measurement*" in the VIM2 (1995) to "*quantity* *intended to be measured*" in the VIM3 (2007). As shown in Figure 3.1, the measurand is specified by the specification operator, while the measured value is obtained from the verification operator. Note that both have associated uncertainties.

Moreover, the GPS introduces many terms to describe the operators according to their states, such as complete specification operator, incomplete specification operator, default specification operator, special specification operator, actual specification operator, etc (ISO/TS 17450-2 2002). Figure 3.2 shows an example to illustrate these GPS concepts in the context of surface metrology. The intent of designer is expressed via "-2,5/Ra 1,6" in the technical drawing. The *default specification operator* is a set of the default operations in a default order, which consists of a series of callouts of the default setting up of the instruments according to ISO documents (e.g. the value of the evaluation length, λc, λs, Max. sampling spacing, etc.).

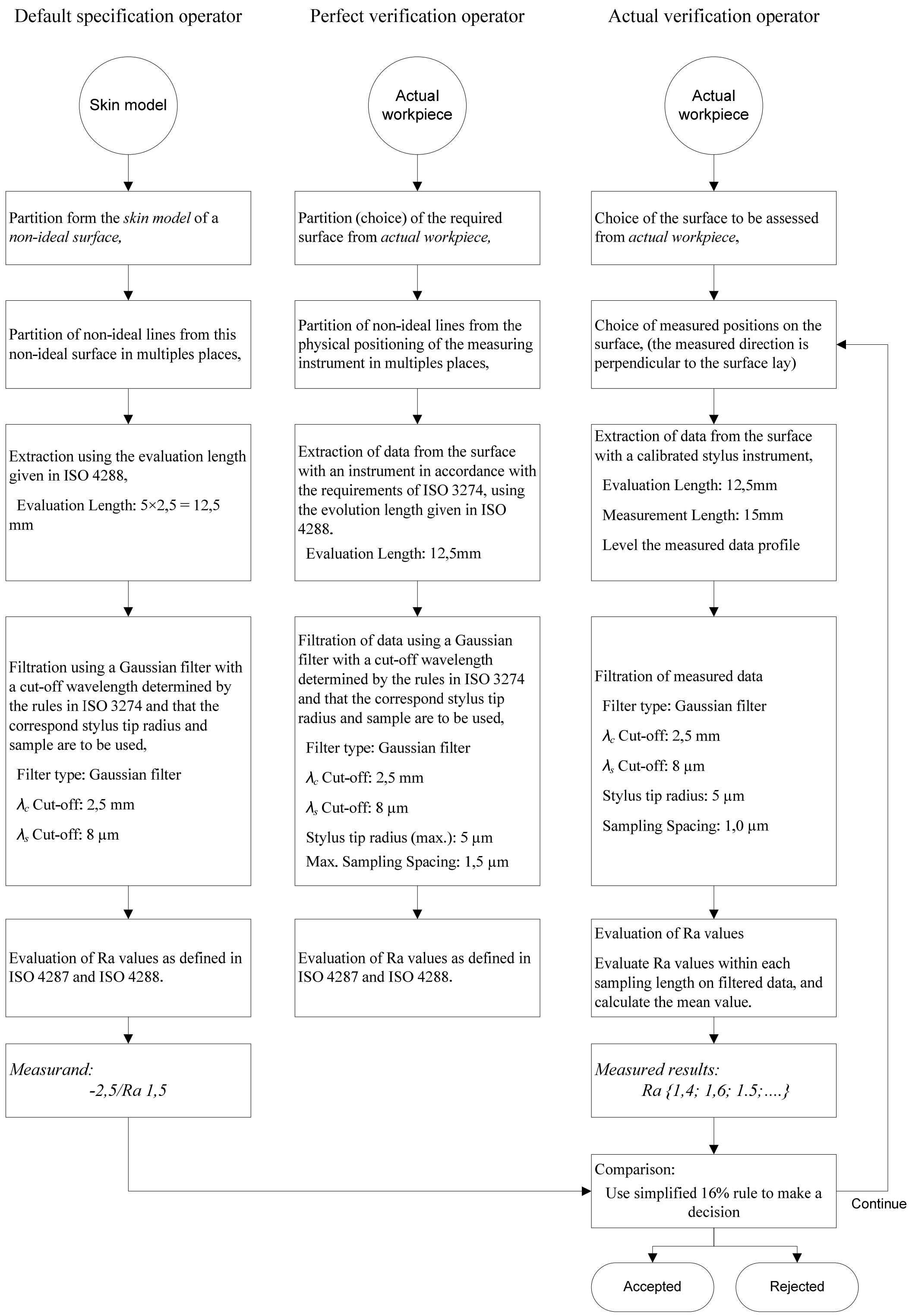


Figure 3.2 Operators and operations of -2,5/Ra 1,5

Firstly, a metrologist needs to develop *a perfect verification operator,* which is based on a full set of operations. Operations of the specification operator (in the world of specification) are mapped into operations of the perfect verification operator (in the world of inspection). The major difference between them is the objectives (skin model and workpiece separately) and the creators (designer and metrologist individually).

Secondly, the perfect verification operator is realised by an *actual verification operator*, which is an ordered set of actual verification operations (such as the measuring instruments, software, measurement condition, etc.) selected by a metrologist. Attention should be paid on the deviations between each actual operation and perfect operation. An extra process can be introduced to minimise such deviation if necessary (e.g. the levelling process to reduce the tilt effect arisen from an imperfect placing of the workpiece on an instrument, see Figure 3.2).

Finally, the measured results compare with the measurand for conformity by the simplified "16%-rule" (ISO 4288 1996). A workpiece is accepted or rejected by the metrologist according to its requirements. The requirements are specified by the designer, transferred via the technical drawings, and interpreted and realised by the metrologist.

This example illustrates how to transfer the information of a measurand from a designer to a metrologist within the GPS framework. For product engineers, the GPS framework is of importance in the information era, when the information technology plays a significant role in the life cycle of a production.

The GPS also provides a key vehicle for transferring the standardised information between instrument manufacturers. To enhance reproducibility of the measurement results, instrument manufacturers need to develop the perfect verification operations based on the available ISO documents, and realising them on the actual verification operations.

It is impossible (and also not necessary) to transfer all information of a measurand without any loss/distortion. However, it is important to estimate the effect of the loss/distortion, which is discussed in the next section.

3.2.3 Generalised uncertainty principle

In GPS, *uncertainty* is used as "an economic tool" to quantify: 1) how well the specification expresses the functional requirements; 2) what ambiguities exist in the specification itself; 3) the uncertainty of measurement (ISO TC213 2004). According to ISO/TS I7450-2 (2002), the uncertainty is divided into: correlation uncertainty, specification uncertainty and measurement uncertainty[18]. Their relationship is shown in Figure 3.3.

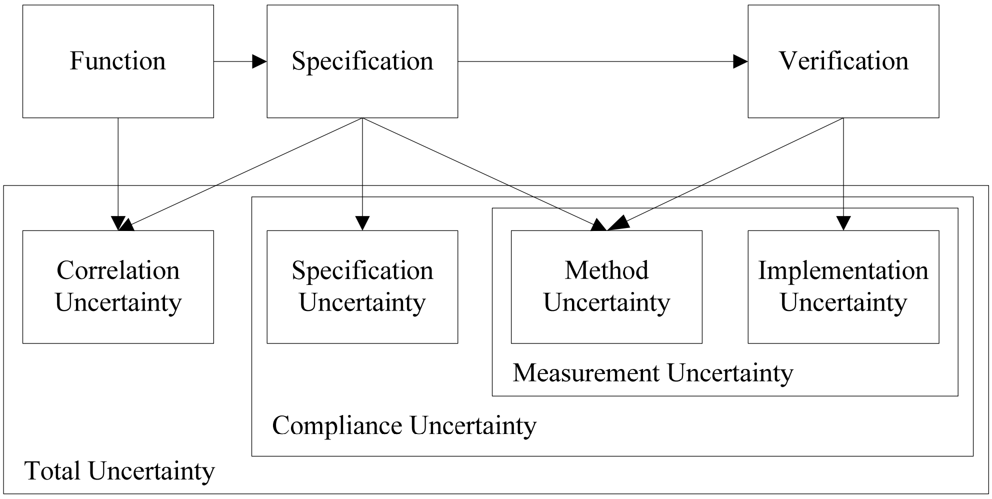


Figure 3.3 Relationship of various uncertainties in GPS (Wang, Ma et al. 2004)

According to ISO/TS I7450-2 (2002), c*orrelation uncertainty* describes how well a controlled geometric feature (e.g. -2,5/Ra 1,5) matches the intended functionality (e.g. 2000 h without leaking, see Figure 3.4).

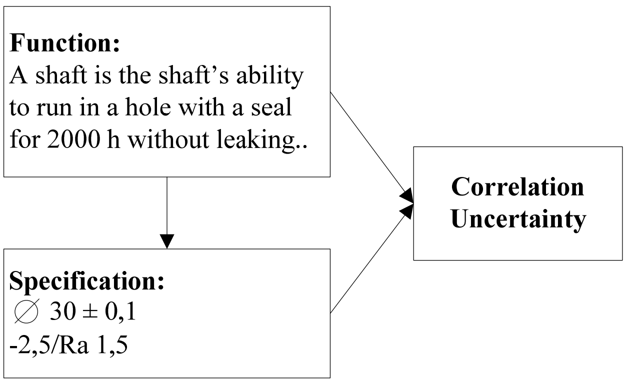


Figure 3.4 An example of correlation uncertainty

Specification uncertainty quantifies the ambiguity in the requirements set out by the specification (Nielsen 2003). Ambiguity is often arisen from an incomplete/improper use of a specification language, or an imperfection of the language itself. For example,

[18] Note that measurement uncertainty in ISO 17450-2 (2002) follows the VIM2 (1995).

the specification uncertainty of "*RSm* 60" is significant due to the ambiguity of its definition (Leach and Harris 2002).

Measurement uncertainty is a statistical parameter associated with the result of a measurement, and it characterises the dispersion of the values that could be attributed to what is being measured (VIM2 1995). Measurement uncertainty contains two components, method uncertainty and implementation uncertainty.

Method uncertainty quantifies the difference between an actual specification operator and a verification operator, disregarding the metrological characteristic deviations of the actual verification operator (ISO/TS 17450-2 2002). For example, if the specification for a surface indicates "-2.5/Ra 1,5", and an optical instrument is used to verify this specification, then method uncertainty is derived from the difference in values obtained by a perfect optical instrument and the values obtained by a perfect stylus one.

Implementation uncertainty arises from the actual verification operator and perfect verification operator. For example, a skid is used in the extraction of surface profiles in a measurement, while the specification is provided without using it. Then the distortion, caused by using of a skid, is a contributor for implementation uncertainty (see Figure 3.5).

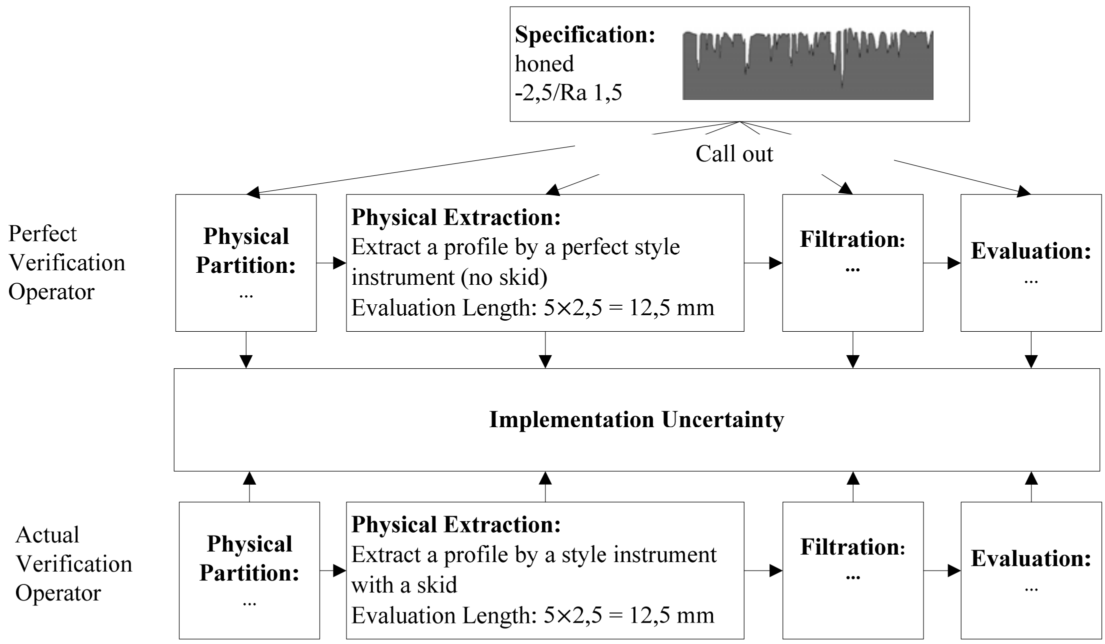


Figure 3.5 An example of implementation uncertainty contributed by the use of a skid

The GPS generalised uncertainty principle provides an approach to evaluate the "quality" of information of a measurand in the life cycle of a production. We adopt this approach to evaluation the software uncertainty by comparing the verification operators produced by different software. It is discussed in the next section.

3.3 Development of terminology

There is a wide variety of different terminology used by metrologists and software developers. Many effects have been undertaken to develop a consistent terminology for software measurement (Jacquet and Abran 1997; Abran and Sellami 2002; Garcia, Bertoa et al. 2006). However, we expect there will be long-term ambiguity and confusion resulting from the terminology differences in the verification and validation of metrological software. Therefore, before presenting the activities involved in the software calibrations, it is necessary to provide the definitions of related concepts in order to avoid ambiguity. The design and the development of softgauges are strictly adhered to the VIM3 and the GPS (the related documents are listed in the ISO/TC 213's website[19]). This terminology has attempted to remain as close as possible to these that appear to be the most widely accepted, including the both software engineers and metrologists.

3.3.1 Metrological traceability of software

The *(metrological) traceability of software* refers to the property of a measurement result obtained from a metrological software package whereby the output result can be related to a reference through a documented unbroken chain of calibration, each contributing to the measurement uncertainty (Adapted from the VIM3 2007).

Note that for a software engineer, the term "traceability" normally means "requirements traceability", which refers to the ability to describe and follow the life of a requirement, in both forwards and backwards direction (i.e. from its origins, through its development and specification, to its subsequent deployment and use, and through all periods of on-going refinement and iteration in any of these phases) (Gotel and

[19] http://www.iso.org/iso/iso_technical_committee?commid=54924.

Finkelstein 2002)[20]. In this thesis, traceability refers to the metrological traceability, which is the major concern of metrologists.

3.3.2 Software calibration, verification and validation

The terms of verification and validation are widely used in both metrologists and software engineers. Adhered to their definitions in the VIM3[21], we interpret them as:

> *Software Verification* is the provision of objective evidence that the output of a particular phase in the software development meets the requirements specified in this phase;
>
> *Software Validation* is the provision of objective evidence where the specified requirements are adequate for an intended use.

Software verification provides evidence that a conceptual model is realised correctly by a computer code. It does not address the question of whether this model has any relationship to the empirical world. On the other hand, software validation addresses the question of the fidelity of a metrological software package on the applications in the empirical world. Verification is the first step of the validation process.

Another widely used term is calibration. *Software Calibration* refers to the operation to establish a relationship between the output results of test software with a reference, which is clearly related to a national measurement system (adapted from the VIM3 2007). In another word, software calibration is the verification of test software by the national or international software measurement standards, i.e. softgauges. The process of software calibration does not involve any activities for adjusting code or internal parameter setting of the software. For example, the use of ball standards to "calibrate" acruate movement is not a software calibration (according to the VIM3, it is an adjustment).

---

[20] This is a much cited definition according to the Wikipedia.com (Retrieved 2011-1-30 from http://en.wikipedia.org/wiki/Requirements_Traceability#cite_note-5)

[21] In VIM3, it states "*validation* is verification, where the specified requirements are adequate for an intended use," and "*verification* is provision of objective evidence that a given item fulfils specified requirements."

3.3.3 Model and code

Detailed software process models are still the subject of research, but it is now clear that a number of general models or paradigms of software development can be identified. We simply separate software development into two phases, modelling and coding. The corresponding outputs are models and codes. The terms of *model* and *code* are defined based on the ASME definitions (ASME V&V Guide 10 2006).

- In general, a model is anything used in any way to represent anything else. In this context, *model* refers as the conceptual, mathematical representation of a measurand.

- A code refers to the computer implementation of an algorithm developed to facilitate the metrological solution. The development of a code includes two phases, that of the mapping of a mathematical model into a discrete model, and that of the translation of a discrete model into a software code.

This terminology distinguishes the responsibilities of metrologists and software engineers. Metrologists take charge of modelling; and the responsibility for coding lies with software engineers. This is of importance in a quantity management system.

3.3.4 Software uncertainty/error

According to the GPS (ISO TC213 2004), the concept of uncertainty is extended to assess the quality of communication between designer, product engineer and metrologists[22]. A similar communication exists in the phases of the design and development of metrological software packages that deliver results in the form of ISO parameters.

Software uncertainty refers to the measurement uncertainty contributed by metrological software. As illustrated in Figure 3.6, we segregate the sources of errors and uncertainties related to software into data uncertainty, model uncertainty and code uncertainty.

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[22] Previously, it only used to evaluate the quality of communication between different metrologists.

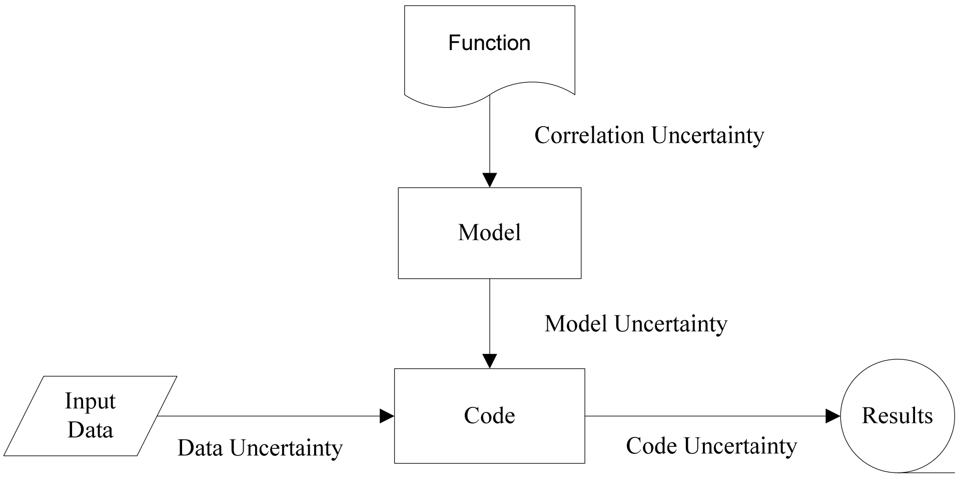


Figure 3.6 Error and uncertainty in metrological software

Correlation uncertainty

The correlation uncertainty is defined within ISO/TS 17450-2 (2002) as the difference between a functional requirement and an actual geometric specification. Correlation uncertainty varies from application to application and should be evaluated by experiments. Thus, the calibration of software does not take correlation uncertainty into consideration.

Model uncertainty

Following traditional presentation of vocabularies, the ISO documents describe terms individually in textual information and with a single level of classification. Thus, an interpretation is required to build a complete mathematical model from the ISO documents. Due to the misunderstanding of these documents, different parties may create various models. *Model uncertainty* quantifies the variation of arisen from the modelling process.

Code uncertainty

Code uncertainty quantifies the variation arisen from coding process. It can be separated into two parts: method uncertainty and implementation uncertainty. Method uncertainty quantifies the divergence of discrete models developed from a perfect and complete mathematical (continuous) model. Implementation uncertainty quantifies the variations of results contributed by the limitation of computer hardware, such as the rounding error, truncation error, etc.

Data uncertainty

There are errors within the input data (the measurement data) due to noise, variation of the measuring environment, *etc.* These errors are referred as data uncertainty in this thesis. Investigating and quantifying such data uncertainty is the subject of uncertainty evaluation based on a statistical model.

Error

It is recognised that it is impossible to gain a unique “true value” of measurand on which is the term of error based. Thus, the VIM3 (2007) defines measurement error as the difference between a measured value with a reference value. Therefore, *software error*, in this context, refers to the difference between the results obtained from a test software package and reference value provided by a softgauge.

Note that the model uncertainty has same nature as specification uncertainty, while code uncertainty has same nature as method uncertainty and implementation uncertainty.

3.4 The proposed framework

3.4.1 Objectives of software calibration

The aim of software calibration is to check metrological traceability of the software of surface measuring instruments. GPS defines the measured results of a geometrical property as output of an ordered set of operations. Therefore, the objectives of software calibration of surface texture measurements are 1) the order of operations and 2) each operation realised by using the software.

3.4.2 Methodology

The fundamental strategy of software calibration is to identify, quantify, and reduce uncertainty arisen from the software of surface measuring instruments by the aid of the softgauges. Figure 3.7 shows the routes toward absolute standards of surface texture measurements by using the type A-F standards. Two components of a surface measuring system are required to calibrate, the hardware (which collects data), and the software (which analysis data). The software is comprised of two sub components, model and code. Correspondingly, software uncertainty is separated into model uncertainty and code uncertainty.

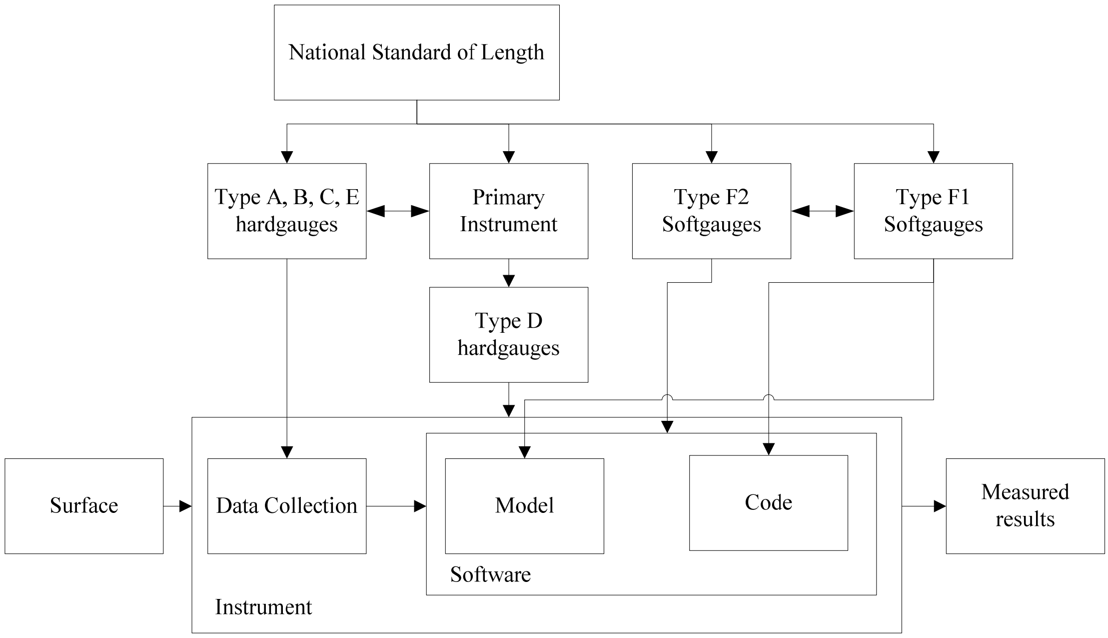


Figure 3.7 Routes toward absolute standards of surface texture measurements

From a definition to a realisation, the size of related information is increased significantly. For example, the definition of the metre is given in one sentence with less than 20 English words (BIPM 2006). The recommended measurement conditions for its realisations contain hundreds of pages (BIPM 2010). For a realisation, the size of information is increasing to infinite, so only significant information is stated (VIM3 2007). This example shows one major approach to control the model uncertainty: detailing and distributing the interpretations of an abstract concept. Another approach, as discussed in Chapter 2, is provided an absolutely interpretation by using measurement standards.

To implement two approaches, therefore, the proposed framework for software calibration consists of three key components: NPL's interpretation, type F1 softgauges and type F2 softgauges. NPL's interpretation documents the detailed interpretations of the ISO conceptions, while type F1 and F2 softgauges provides the absolutely interpretations. In addition, this framework includes two tools, that of an information model to connect different components, that of uncertainty to evaluate the reliability of each component. Their relationship is shown in Figure 3.8.

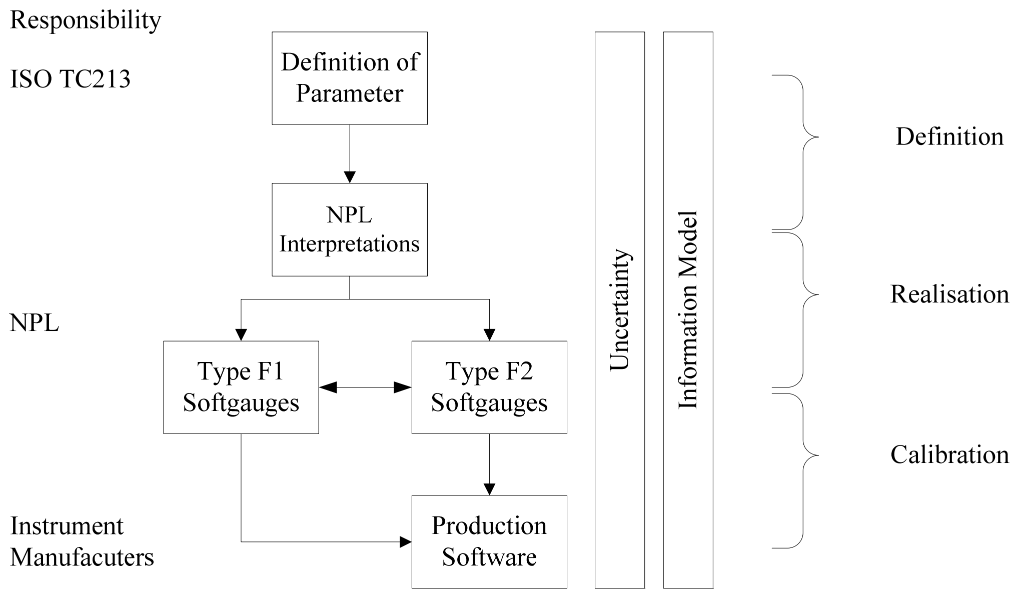


Figure 3.8 Framework for the softgauges for surface texture in the UK

3.4.3 Key components

3.4.3.1 NPL's interpretation

The design of softgauges requires the definition of the measurement results. It is vitally important that the measurement results are mathematically well defined and unambiguous; otherwise specification uncertainty will be automatically built into the definition. The parameter definition and measurement condition are standardised in the ISO documents. NPL's interpretation provides detailed documents of the interpretations of ISO documents in the national level. NPL's interpretation will be developed to adhere to ISO documents with the following considerations.

Model of the interpretation

The measurement results (profile parameters in this case) contained in ISO 4287 (1997) are all defined on Gaussian band limited continuous profile data rather than discrete profile data that can be handled directly by a digital computer. It is possible, with a suitable sampling and reconstruction theory, to map a Gaussian band limited continuous profile to discrete profile data, and conversely, without loss of information. It believes this aspect is too advanced for potential users and would add greatly to the cost of the project. Consequently, it is proposed to start with discrete profile data and definitions of each profile parameter expressed in terms of such discrete data. For each profile parameter considered in the project a mathematically well-defined and unambiguous definition in terms of discrete data will be provided. The definition will take the form of a formula or an algorithm. The definitions will constitute the starting point for the design of the software measurement standards. The work to develop definitions in terms of discrete data rather than continuous profile data is critical to the project.

Ambiguity existed in current ISO standards

As discussed in Chapter 2, some of the ISO definitions are ambiguous, and they often cause disagreement between different parties. A full specification operator and a full verification operator, based on the current ISO document, will be developed by the following stagey.

- Current ISO standard document described terms individually in a single level of classification. To reduce the possible ambiguity, NPL's interpretation will provide clearly the relationship of key terms in a structured data model.

- The incomplete information from ISO standard document could lead many different interpretations. Some of them should be complete by end-users if they are highly depended on a particular application. Other will be completed by softgauges.

- There are some imperfect definitions provided in ISO standard document. NPL's interpretation will develop/introduce a more stable and reliable definition to replace them if possible.

Dissemination

The NPL's interpretation will be distributed via two ways: in the form of a textual document, and in the form of its realisations, i.e. type F1 softgauges and type F2 softgauges.

3.4.3.2 Type F2 softgauges

It is a primary software or master software, as a realisation of the ISO concepts at the national level, which provides as a reference for production software. Type F2 softgauges are used to test software by inputting a common data set into both the software under test and the reference software and comparing the results from the software under test with the certified results from the reference software (see Figure 3.9). The NPL's type F2 softgauge will be developed with the following considerations.

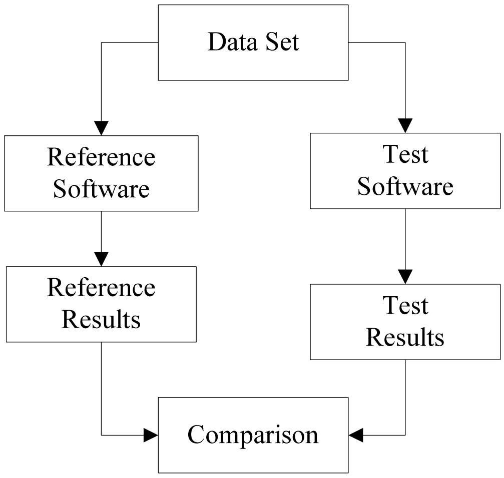


Figure 3.9 Procedure for the testing software using the reference software

Accuracy and reliability

The most important considerations in the design and implementation of type F2 softgauge are its accuracy and reliability. This contrasts with the considerations for production software, for which the requirements on numerical correctness are generally more modest, but the issues of efficiency (computing time and memory) as well as usability are of concern.

To maintain its quality, the development of type F2 softgauge is adhered to SSfM[23] Best Practice Guide "*Validation of Software in Measurement Systems*" (BPG1) [16]. The BPG1 provides recommended techniques to ensure the software is fit-for-purpose and to meet the requirements of ISO 9000.

Model cannot be demonstrated for all possible conditions and applications. Indeed, one cannot prove that complex computer codes have no errors; they can only be disproved (Oberkampf and Trucano 2002). In this project, selected type F1 softgauges will be used to probe the errors in this type F2 softgauge. Some mathematically defined profiles with the nominal value will be used to check the accuracy of type F2 softgauge. And some modified profile pair will be used to check its stability.

[23] Software Support for Metrology, a project undertaken by NPL since 1997.

Traceability

It is important to note again that type F2 softgauge should be traceable. Traceability of software means that its output result is related to a reference. For production software, this reference can be type F1 and F2 softgauges. For a type F2 softgauge, this reference can be the ISO standard document directly or type F1 softgauges.

Dissemination

The principal mechanism for dissemination of this type F2 softgauge is via the internet. So the end-users can assess this type F2 softgauge easily, and establish a link from their measurements to national standard.

3.4.3.3 Type F1 softgauges

Type F1 softgauges are akin to a primary standard in measurement, such as a kilogram mass to which secondary standards are compared for calibration purposes. The type F1 softgauge, in the form of the reference data sets with reference results, provides the basic testing specimens for both type F2 softgauges and production software packages. Same as the hardgauges, type F1 softgauges provide the absolute realisations for ISO standard definitions without going into too much detail. It can be calibrated easily, accurately and unambiguously. The NPL's type F1 softgauges have developed with the following considerations.

Scope of reference dataset

A measurand is defined as the result of a pre-ordered set of operations on a skin model (see Figure 3.1). Therefore, it is important to verify the order and each of operation. The type F2 softgauge can only verify the software (model + code) as a whole. The type F1 software can verify the order and each of operation by special design. For example, a sine wave can be used to verify a filtration operation. In addition, the reference dataset should also include the typical engineering surface to address the industrial requirements.

Reference result

The nominal value of some type F1 softgauges (most of the simulated profiles) can be obtained analytically in the specification chain. Type F1 softgauges can be used to verify type F2 softgauges. In the other way around, the verified type F2 softgauges can be used to product the reference results for the type F1 softgauges (most of measure profiles).

Dissemination

The principal mechanism for dissemination of type F1 softgauges is also via the internet.

3.4.4 Key tools

3.4.4.1 A information model for exchanging information

In general, a message is an object of communication. It is a vessel which provides information. In this context, the term of message refers to the object which is used to exchange information between different parities. A message provides the detailed information of surface texture. The shape and size of the message are changed from the designer to metrologists, and it could contribute the specification uncertainty. An information model will be developed to standardise the messages in order to reduce/manage the uncertainty in communication and cognise level. This model will be used by softgauges to deliver its default callout based on NPL's interpretation. It will be developed with the following considerations.

Data structure

According to the GPS, a function of a workpiece is related to a set of features; each feature is defined by a set of characteristics; each characteristic is defined by an operator; an operator is consisted of an ordered set of operations; each operation comes with its own set of selectable parameters (Nielsen 2006). So a tree structure will be used to contain these elements, and the order of some elements should be specified.

Extendibility and exchangeability

The size of information is increased when develop a full verification operator from a specification operator. In other ways around, the size is reduced when produce a measurement report based on a full verification operator. The mapping work (i.e. specifying the requirement, producing measurement reports etc.) often undertaken by different engineers at various locations (see section 3.2). Thus, the data model should be extendable and exchangeable. In the age of the internet, it should be able to exchange via the World Wide Web. So the data file based on this model should be independent on software and operation systems.

Computer and human understandable

The conventional file formats for surface texture measurement are normally unable to read by an engineer directly without other help documents to interpret its terms. And the traditional measuring reports are no friendly for a computer – the key measuring information cannot be automatically recognised by a computer. For example, a string of “0.8 mm” needs to be separate to “0.8” (number format) and “mm” (text format). It is understood by a computer only the format is clearly stated. Thus, the developed data model will be able to self-interpreted, and friendly to both human and computer.

Traceability

Currently, to complete an operator needs to call out many documents that may come from various resources. In other words, it may trace to different references. NPL’s interpretation (maintaining a complete default callout) will be stored in a permanently existed website, and all files developed in this model will provide the link this website. So it will only trace to one resource to reduce the uncertainty.

Balance of information

It needs to pay attention to the balance of information to avoid two extremes: 1) too little information could lead significant specification uncertainty; 2) too much information could make difficult on its realisation (e.g. a specified process may not be available), transfer and so on.

3.4.4.2 Associated uncertainty

According to the terminology developed in Section 3.3, the software uncertainty consists of model uncertainty and code uncertainty. In addition, the input data contains data uncertainty arisen from the data collection process.

Data uncertainty

Type F2 softgauges, as well as most of the production software, does not provide the (measurement) uncertainties associated with the calculated reference values for surface texture parameters. This is due to data uncertainty is the traditional meaning of measurement uncertainty, which is contributed by measuring instruments, environment, measurand, etc. The influences of these contributors vary from application to application. It also depends on the user's instrument performance, measurement condition and surface under measured.

Due to the same reason, the type F1 softgauges do not provide the associated measurement uncertainty. It assumes throughout that the variations associated with the measurement conditions and operating errors are minimal in their effect on the software calculation.

Model uncertainty and code uncertainty

Model uncertainty is used to evaluate the ambiguity of ISO standard documents. It reduced by NPL's interpretation and realisations, i.e. softgauges. Code uncertainty is used to evaluate the variation of implementation from a perfect specification. The combined effect of two uncertainties on the measured value can be assessed as systematic errors between test software and national reference, i.e. softgauges (see Figure 3.10).

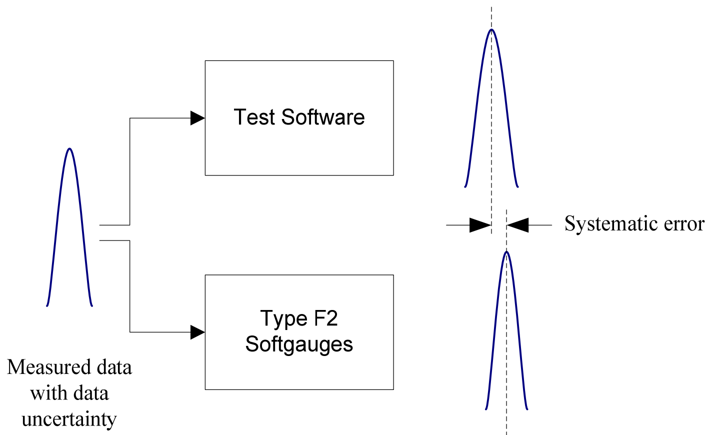


Figure 3.10 Assessment of model uncertainty and code uncertainty

3.4.5 Others

3.4.5.1 Management issues

Metrology is largely organised based on division of labour and cooperation. In the field of surface metrology, organisations include ISO/TC 213, NMIs, instrument manufacturers and end-users.

To maintain software traceability, it requires clarifying the responsibility of these organisations. It proposes the following structure in applying ISO standards.

- ISO/TC 213: Developing and maintaining the conceptual model and mathematical model. The output is the GPS languages in the form of International standard documents.

- National Metrology Institutes: Developing and maintaining the realisations of concepts defined in ISO standard documents. The realisations are in the form of guide documents (e.g. NPL's interpretation), type F1 softgauges and type F2 softgauges.

- Instrument manufacturers: Developing the commercial software packages which should meet all requirements from metrology to software quality assurance (SQA), such as traceability, user-friendly, speed and so on. These implementations should be traceable to the national standards via the aid of softgauges.

3.4.5.2 Calibration procedure

Software Calibration is the operation to establish a relationship between the output results of production software, and a reference which is clearly related to a national measurement system. Software calibration verifies the test software by using of softgauges. As shown in Figure 3.7, three routes can be used to demonstrate the traceability of surface texture measurements, they are:

1) *Route via the type D hardgauges*: Type D hardgauges calibrate three components as a whole.

2) *Route via the type A, B, C, E and type F2 standards*: Hardgauges calibrate the data collection and type F2 standards calibrate the software as a whole.

3) *Route via the type A, B, C, E and type F1 standards*. Hardgauges calibrate the data collection and type F1 standards calibrate the software model and code separately or as whole.

The use of hardgauges (type A-E) and the first route have already been reviewed in chapter 2. The softgauges will be developed to replace most of the function of the type D hardgauges. For the end-user, it recommends through second route, which can quickly link any of standardised measurements with national standards. For the instrument manufacturer, it recommends that all three routes should be checked in order to produce reliable and traceable software.

A calibration curve is of importance, and its reliability depends on reference points and the interpolation algorithm (see Chapter 2). In the stage of data processing, more calibration points can be provided with type F1 softgauges, unlimited calibration points can be provided by using a type F2 softgauge. Therefore, the calibration curve is more reliable than the curve produce by using type D hardgauges only. In addition, calibration curves of all ISO parameters can be established by using of softgauges.

A key question concerns the comparison of the results delivered by the type F2 standards and commercial packages. The comparison should be objective and address the requirements of the application. The result of the comparison is the means by which a decision is made about the fitness-for-purpose of the F2 software standards and commercial packages. The "weakness chain" principle, a chain is as strong as its weakness part, will be use to manage the components of uncertainty. Therefore, fitness for the purpose means software uncertainty are quantitatively small compared to the effects arising from the data, the latter being described by data uncertainty.

3.5 Conclusions

This chapter has developed a terminology and a framework for softgauges. The developed terminology adheres to the GPS and the VIM3, which reflect the latest philosophy in metrology. The framework has clearly interpreted the role of softgauges in the metrological traceability chain of surface texture measurements. The methodology of software calibration has been developed, and the structure of softgauges has been outlined. The function and relationship of the key components have been outlined. The remaining part of this thesis will present the development of these components.

4 An information model of surface metrology

The objective of this chapter is to develop an information model to standardise the message, which is the vessel for containing specification and verification information for surface texture, between measurement institutes and industry. Its output is a XML-based markup language, called Surface Texture Markup Language (STML), used to describe the message, together with a validation tool for this message. This model is used by softgauges for storing and exchanging specification and verification information for reducing the specification uncertainty.

4.1 Methodology

4.1.1 The information modelling process

An *information model* is a representation of concepts, relationships, constraint, rules, and operations to specify a data semantics for a chosen domain of discourse (Lee 1999). An information model described here centres on providing the sharable, stable, and organised structure of information requirements in the field of surface metrology. This model provides a container to the description of the measurand and measured value of surface texture measurement.

There are various practices to develop an information model. The underlying methodologies for the recent modelling practices are based on three approaches:

1. *The entity-relationship approach*: An entity-relationship model is an abstract and conceptual representation of structure data, which depicts data in terms of

the entities and relationships described in the data. Its building blocks are entities, relationships, and attributes.

2. *The functional modelling approach*: It is a structured representation of the functions, behaviours, activities or processes within a modelled system. It uses objects and functions over objects as the basis, and it often uses data-flow diagrams.

3. *The objected-oriented approach*: The fundamental construct of this approach is the object, which incorporates both data structures and functions. Its building blocks are object classes, attributes, operations, and associations.

These approaches view the data with different emphasises. The entity-relationship approach lacks the preciseness in supporting the detailed level. The functional modelling approach is often used in the development of a certain software application. The objected-oriented approach considers both the data and the function, which has the advantage to describe the measurand and measured of surface texture measurements. Wang (2008) pointed out the disadvantages of these approaches to present GPS information in a database, and introduced the category approach in the design and development of knowledge-based GPS systems. Currently, it is still under development in the academic domain. This project, therefore, will use an objected-oriented approach to model the message due to it more widely used in industry.

Many information modelling languages, in graphical form or texture form, have been developed. They provide various ways to formally represent an information model. This project has used XML schemas to express the constraints on the structures and contents of the message.

An information modelling process has been developed by NIST (Lee, 1999), which includes three phases: 1) to develop the definitions of the scope of the model's applicability; 2) to collect information requirements; and 3) to develop the model. This modelling process has implemented in this project.

4.1.2 XML and XML Schema

Extensible Markup Language (XML) is a set of rules for encoding documents in a computer-readable form. It is defined in the XML 1.0 specification (Bray, Paoli et al. 2000) recommended by the W3C[24]. This open standard produced standardises the format of an XML document and specifies the behaviour of XML processing software. A XML document is made up a tree of elements with a short specification. To develop an XML processing software implementation, thus, is relative easy. And many free implementations exist. These implementations can be employed in the creation of STML processing software, making it simple to read and write STML documents.

A XML Schema is a description of a type of XML document. It is expressed in terms of constraints on the structure and content of that type of XML documents. The reasons to choose XML Schema over others (e.g. DTD[25]) are as follows:

- *Syntax*: A XML Schema itself uses XML syntax.
- *Datatypes*: 1) it supports a rich set of built-in datatypes; 2) It allows users to define their own datatypes; 3) It allows datatypes inheritance, which is suitable for object-oriented modelling.
- *Constraints*: It provides some data constraints, which make it easy to validate the data.
- *Namespace*: It supports namespace hooks. So various schema files can be put into different namespaces.

4.2 The development of SMTL

4.2.1 Scope of SMTL

In this context, a message is the vessel for containing specification and verification information of surface texture, which provides the description of the object intended to

[24] The World Wide Web Consortium (W3C) is the main international standards organization for the World Wide Web (abbreviated WWW or W3).

[25] i.e. Document Type Definition

produce and verify. The messages are built based on the following ISO standard documents:

- *Fundamental ISO standard document in metrology*: the VIM3 (2007) and the GUM (2008).

- *GPS Language developed by ISO TC/213*: Key standard documents are ISO/TS 17450-1(2005), ISO/TS 17450-2 (2002), ISO 14253-1 (1998), ISO/TS 14253-3 (2002).

- *ISO standard documents for surface texture measurement*: At current stage, this project focuses on the ISO 4287 (1996) parameters. The related standard documents are ISO 3274(1996), ISO 4288(1996), ISO 11562(1996).

This project focuses on the consistentce of the message from the metrology point of view. It does not cover how the description is mapped to an actual software implementation. Some parallel projects (Wang 2008; Xu 2009) have developed the data model for storing the messages in a database, and an expert system to produce them.

4.2.2 Collecting the information requirements

To collect the information requirements, this project used two methods: 1) literature survey and standards survey; 2) industrial data reviews.

4.2.3 Developing the information model

4.2.3.1 Indication and its sub-elements

Currently, an often used mechanism to express the requirements of surface texture is through the drawing indication in the technical documents. The indication defined in ISO 1302 (2002) is widely accepted. SMTL uses it as the key reference to produce and interpret a message. As the example shown in Figure 2.7, an indication of the surface texture requirements specifies the following information: manufacturing method, filtering bandwidth, tolerance, parameter and the surface lay.

The keyword <Indication> is the XML element or tag representing the drawing indication of surface texture with its hierarchical composition of lower levels of information (see Figure 4.1). The sub-elements of the <Indication> are the <MaterialRemoval>, <ManufacturingMethod>, <SurfaceLayAndOrientation>, <MachiningAllowance> and <SurfaceTextureRequirement> tags. The first four elements are of importance to develop its manufacturing operator. A certain pattern is produced by a certain process. So it is also useful in the prediction of the future performance of this component. Their descriptions and some valid contents of these tags are listed in Table 4.1. Although the abbreviations are accepted, it is recommended avoiding them. For example, using "Any process allowed" is more easily understood than "APA".

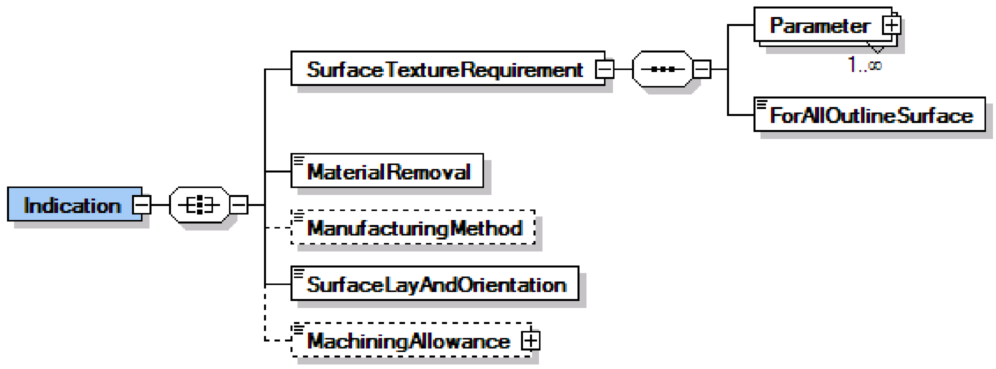


Figure 4.1 Diagram of schema for surface texture indications

Table 4.1 Description and contents of tags for specifying manufacturing requirements

Tags	*Valid Options/Examples*	*Description*
<MaterialRemoval>	'Any process allowed'; 'Material removal required'; 'No material removed' Or 'APA'; 'MRR'; 'NMR'.	Specifying the requirements of material removal.
<ManufacturingMethod>	'turned'; 'ground'; 'plated'; 'milled'; 'Fe/Cr50'	Specifying the manufacturing process such as or coating requirements.
<SurfaceLayAndOrientation>	'='; 'X'; 'M'; 'C'; 'R'; 'T'; 'P'; or used the text such as: 'Parallel'; 'Perpendicular'; 'Crossed'; 'Multi-directional'; 'Circular'; 'Radial'.	Indicating the required surface lay and the orientation,
<MachiningAllowance>	3	Specifying the requirements for machining allowance in millimetre.

The <SurfaceTextureRequirement> tag encapsulates all related information of the surface texture requirements. Its sub-elements consist of a <ForAllOutlineSurface> element and one/several <Parameter> elements. The <ForAllOutlineSurface> tag specifies whether the surface texture requirements are for all surfaces represented by the outline of a workpiece. The surface texture requirements on an engineered surface are expressed by one or several parameters. Each parameter is a quantity intended to be measured (i.e. each parameter defined a measurand). An indication, therefore, defines one or several measurand(s). For example, the drawing indication, given in Figure 2.7, specifies three measurands.

According to ISO 1302 (2002), each of the <Parameter> elements should specify the following information: specification limit type, filter type, transmission band, parameter name, evaluation length, specification limit interpretation and parameter value. They are defined as new datatype, namely "ParameterType", marked up with corresponding tags as shown in Figure 4.2.

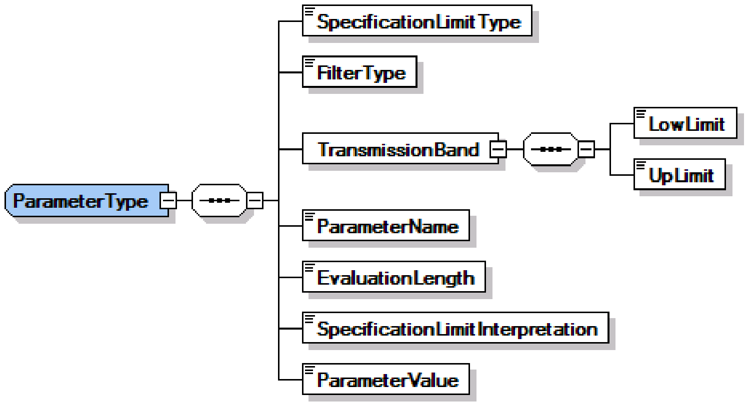


Figure 4.2 Diagram of a surface texture parameter according to its drawing indication

So, a graphic-based drawing indicating is mapped into a text-based XML document. Then, for example, an XML document for the drawing indication given in Figure 2.7 can be generated as IndicaitonSample.xml in Appendix 1.

The indication specifies both the manufacturing requirements and the surface texture requirements on an engineering surface. They are the basis on where the manufacturing operator and the specification operators are produced. We do not discuss the manufacturing operator here due to it beyond the scope of this thesis. The next section will use the indicated information to form the specification operator.

4.2.3.2 Measurand and its sub-elements

As discussed in Chapter 3, the measurand is defined as the result of the specification operator, which is an ordered set of operations. So, the keyword <Measurand> is the XML element representing the measurand. Its sub-elements are the <Partition>, <Extraction>, <Filtration> and <Evaluation> tags. The contents of the indication are mapped into this structure with some rename labels[26] as shown is Figure 4.3.

[26] This is due to different terms used by different ISO standard documents.

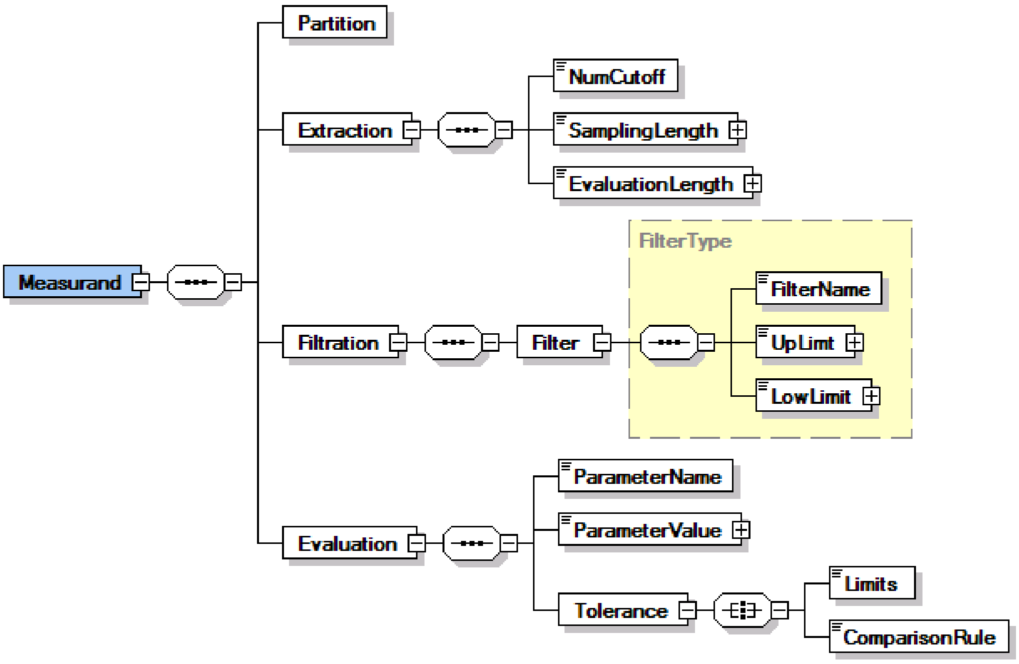


Figure 4.3 Diagram of a measurand according to the drawing indication

Obviously, this specification operator is incomplete and a further callout is required. ISO 1302 (2002) listed 17 related ISO standard documents. They have been used to develop the sub-elements of each operation.

The <Partition> tag specifies the operation used to identify bounded feature(s). In the case of surface profile texture parameters, it includes two sub-operations: 1) partition of a non-ideal surface from the skin model, and 2) partition of non-ideal lines from the non-ideal surface. The key reference of this operation is ISO 4288 (1996), which provides the rule for selecting the areas to be inspected for homogenous surface and inhomogeneous surface. For a default callout, the content of <Partition> tag could be:

- For a homogenous surface, the partition is undertaken over the whole surface. The direction of this operation is perpendicular to the surface lay.

- For an inhomogeneous surface and requirements specified by the upper limit of the parameter, those separate areas of the surface shall be used, which appear to have the maximum parameter value.

- For an inhomogeneous surface and requirements specified by the lower limit of the parameter, those separate areas of the surface shall be used, which appear to have the maximum parameter value.

– For a type D hardgauge, the partition follows the pre-set measurement plan.

The <Extraction> tag specifies the operation for extracting the feature. Only one nominal stylus instrument is specified in ISO document, namely ISO 3274 (1996). So the default values given in ISO 3274 (1996) are called out if they are not specified. The sub-elements of the <Extraction> tag include maximum sampling spacing, maximum tip radius, measuring force, and max measuring speed. Their corresponding tags are shown in Figure 4.4.

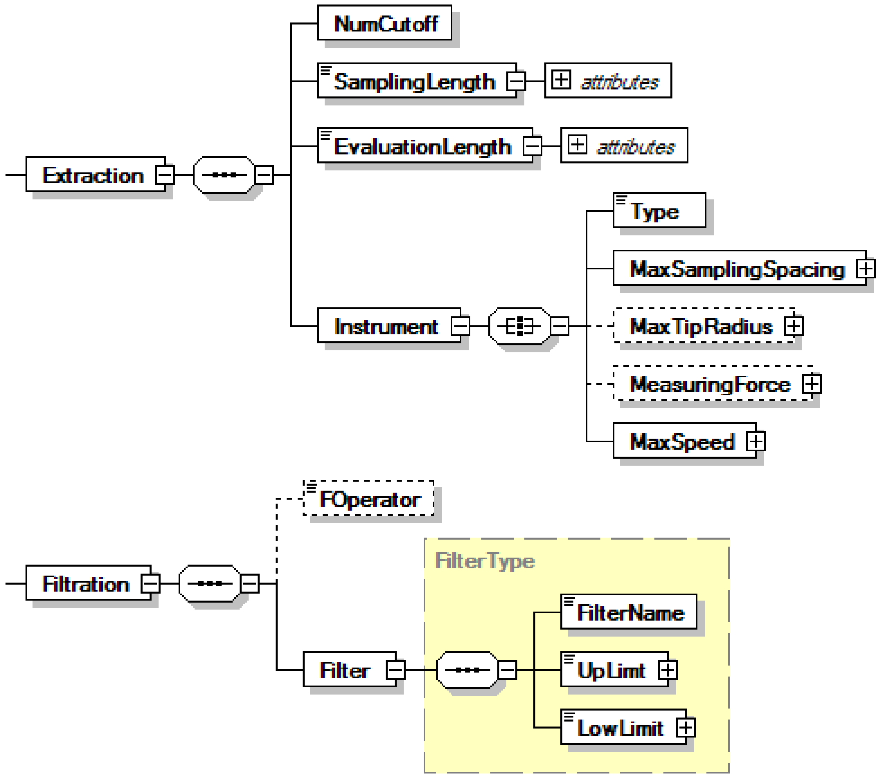


Figure 4.4 Extension of the extraction operation of a specification operator

The tag of <FOperator> specifies the F-Operator, which is the process to remove the nominal form in the measuring data. In technical drawings, F-Operator does not need to be indicated due to form (error) is not a component of surface texture. However, F-Operator is often undertaken in surface measurement practice. So F-Operator should be stated if necessary. F-Operator utilise same or similar techniques in the filtration operation (F-Operator is named as the form filter in some publications). Moreover, the output of extraction operation is surface texture and form. Thus, the F-operator is grouped into the extraction operation.

To balance the information, some of the information does not detail in this model, due to the following considerations:

- Extraction operation does not need to specify the measuring environment because a measurand model is free from environment effects according to the VIM3.

- Filtration operation and evaluation operation does not need to detail the algorithms. Compared with the variation in extraction operation, their variations are relatively insignificant. (However, this variation needs to be assessed by the calibration with the aid of softgauges.)

Then, the specification operator is formed in STML based on the current GPS language. A XML document for the measurand "L Ra 0.4" given in Figure 2.7 can be generated as MeasurandLRa0.4.xml (see Appendix 1).

4.2.3.3 Measured value and its sub-elements

Developing the perfect verification operator

A perfect verification operator is built based on a perfect instrument within a perfect environment (ISO/TS 17450-2 2002). A metrologist often faces two situations: 1) a measurand with specification; 2) a measurand without a specification. In the first situation, a perfect verification operator will be formed by mapping the element from the complete specification operator (see Figure 4.5). In the second situation, she/he will develop a metrology solution based on her/his knowledge of surface metrology and results obtained from measurement. A perfect verification operator can be produced based on the metrology solution.

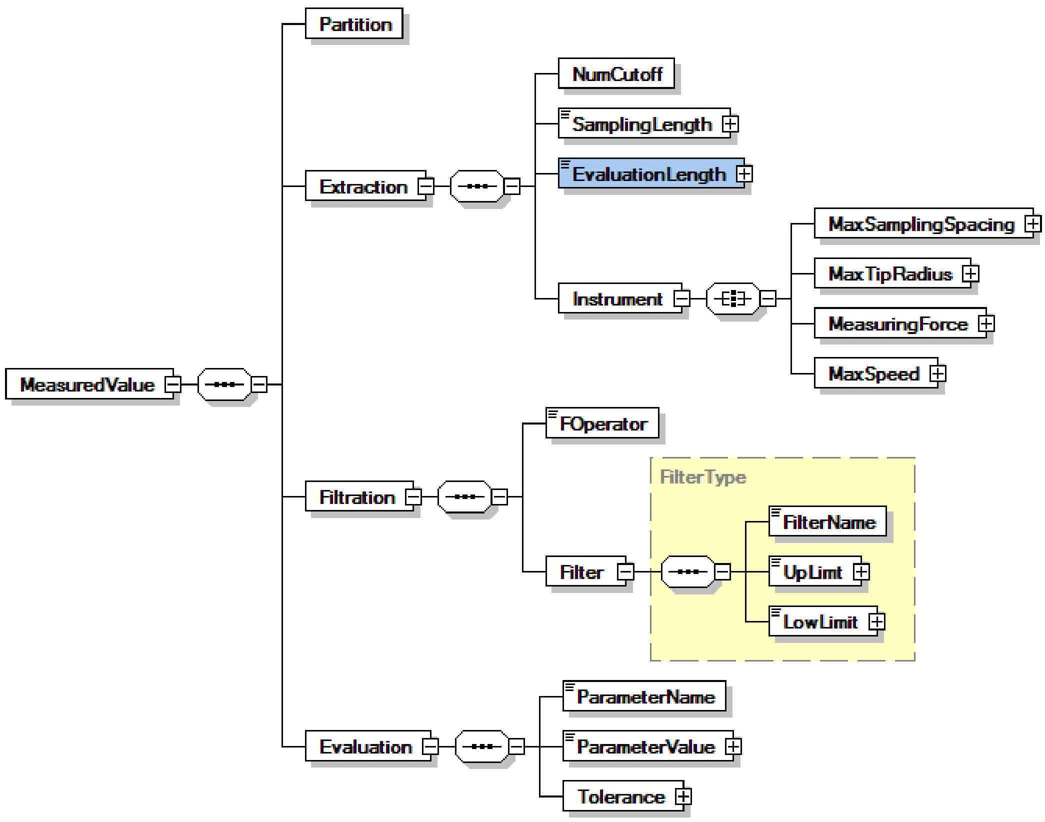


Figure 4.5 Diagram of a perfect verification operator

According to the duality principle (ISO/TS 17450-2 2002), a specification operator and its corresponding verification operators consist of duplicated operations in the same order. The differences of two operators are input and output of them. The input of the specification operator is the skin model, while that of the perfect verification operator is an actual workpiece. Their outputs are "measurand" and "measured values" separately. As the result of a perfect operator, the "measured value" described here should be the "true value" of the measurement. The true value is unknown, so "reference value" and "nominal value" could be used as the true value (VIM3 2007).

– According to the VIM3 (2007), the "reference value" is used as the "true value" of a measurement. This situation is often met when a metrologist calibrates an instrument by measurement standards. He/she interprets the measurement conditions according to the requirements of the standards.

– In a certain application, the reference value may not be available. The "nominal value" can be used as the "reference value". This situation often occurs when an engineer assesses a workpiece. He/she interprets the measurement conditions according to a technical drawing or a previous measurement report.

Developing actual verification operator

Based on the perfect verification operator, an actual verification operator is developed. The actual verification operator describes the measurement condition within in a certain laboratory or workshop. The sub-elements of <Partition> may include the <Replica> to specify the using of replica of the assessed surface. There are more sub-elements of the <Extraction> tag as showed in Figure 4.6.

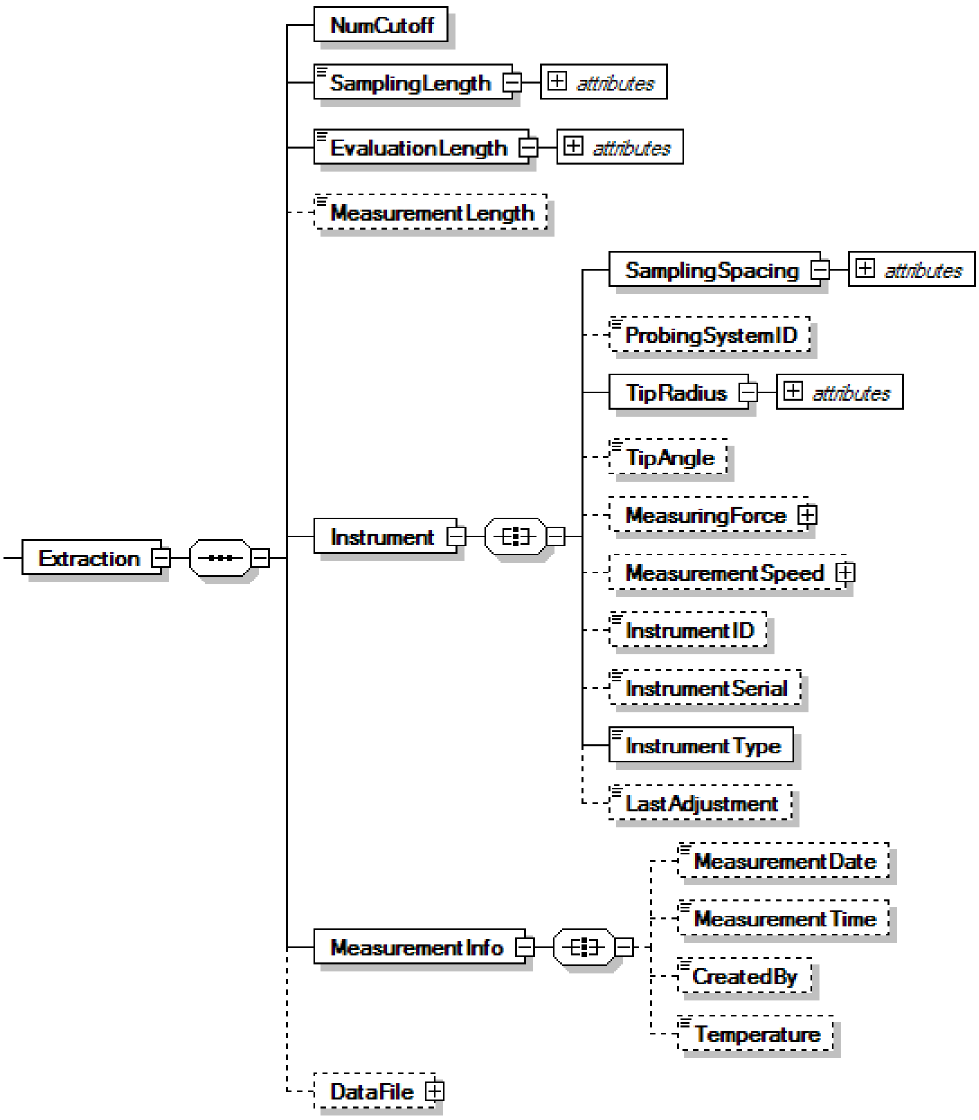


Figure 4.6 Diagram of the extraction operation of an actual verification operator

Note that the <SamplingSpacing>, <TipRadius> and <MeasurementSpeed> tags record actual value of the measurements, while their corresponding tags in the perfect verification operator only specify their maximum values.

An implementation of a default filter (ISO 11562 1996) has an end effect (ISO/TS 16610-28 2010). So the <EndEffect> and <MeasurementLength> tags are introduced to record the handling method, and the corresponding changing on the actual measurement length.

In addition, more tags can be developed to address various application requirements. For example: more detailed information for the actual instrument such as tip angle, skid, instrument id and so on; data file information such as location of file, file name, axis information, etc. (Note that the measuring data point information does not recommend storing in this file).

Then, an actual verification operator is formed in STML. An example is given in MeasuredValueRa0.5.xml (see Appendix 1), which produce according to the message from MeasurandLRa0.4.xml.

4.2.4 Validation of message

The validation of a message should take consideration on the following parts:

- *Constriction and rule*: Many constrictions and rules have been stated in ISO standard documents. It sets the relationship between some contents, for example, the ratio of the filter λs and the filter λc. It can be validated by an expert system.

- *Syntax*: The message should follow the SMTL's syntax. It can be validated by the XML Schemas developed as follows.

XML Schema is another standard that allows the definition of a full specification for a XML document. The messages in SMTL states the location of the Schema (in the form of a URL address of this project web site), which is used to validate this file. This web site is also provided detailed interpretation of each tag to avoid the ambiguity and to make the document traceable.

4.3 A case study: Euromet Project 600

Euromet Project 600 - comparison of surface roughness standards, is the most recently inter-comparison between 17 NMIs in Europe. The travelling of standards and measurements took two years (May 2001 to May 2003), and a 578 page final report was released via BIPM website in May 2004. Parts of this report (from www.bipm.org/utils/common/pdf/final_reports/L/S11/EUROMET.L-S11.pdf) will be use as a case study of SMTL. This comparison used one type A2 hardgauge, one type C3 hardgauges, three type D1 hardgauges, one type D2 hardgauges and three type F1 softgauges. The type D1 hardgauge 663g are used in this case study.

4.3.1 Defined measurand

The measurand is defined in the Appendix A3 of the report (Koenders, Andreasen et al. 2004). Eight parameters are required to be measure for the hardgauge 633g. Thus, it is defined eight measurands, and one of them (parameter Ra), expressed in STML form, is listed below.

Measurand - 633gRa.xml

```
<Measurand xmlns="http://www.surfacetext.info/Schemas/SpecificationOperator"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.surfacetext.info/Schemas/SpecificationOperator
L:\Projects\STML\FullSpecificationOperator.xsd">
	<Partition>According to the measuring plan of Type D defined in ISO
12179</Partition>
	<Extraction>
		<NumCutoff>5</NumCutoff>
		<SamplingLength Unit="mm">0.8</SamplingLength>
		<EvaluationLength Unit="mm">4</EvaluationLength>
		<Instrument>
			<Type>Stylus</Type>
			<MaxTipRadius Unit="um">2</MaxTipRadius>
			<MaxSpeed Unit="mm/s">0.5</MaxSpeed>
			<MeasuringForce Unit="mN">1</MeasuringForce>
			<MaxSamplingSpacing Unit="um">0.5</MaxSamplingSpacing>
		</Instrument>
	</Extraction>
	<Filtration>
		<Filter>
			<FilterName>Gauss</FilterName>
			<UpLimt Unit="mm">0.8</UpLimt>
			<LowLimit Unit="um">2.5</LowLimit>
		</Filter>
	</Filtration>
	<Evaluation>
		<ParameterName>Ra</ParameterName>
		<ParameterValue Unit="um">1.5</ParameterValue>
```

```
		</Evaluation>
</Measurand>
```

4.3.2 Measured values

The measured values is reported in Appendix B1 of the report (Koenders, Andreasen et al. 2004). Two of them, expressed in SMTL, are listed as follows.

Measured Value - PTB633gRa.xml

```
<?xml version="1.0" encoding="UTF-8"?>
<MeasuredValue xmlns="http://www.surfacetext.info/Schemas/SpecificationOperator"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.surfacetext.info/Schemas/SpecificationOperator
L:\Projects\STML\AcutualVerificationOperator.xsd">
	<Partition>According to the measuring plan of Type D defined in ISO
12179</Partition>
	<Extraction>
		<NumCutoff>5</NumCutoff>
		<SamplingLength Unit="mm">0.8</SamplingLength>
		<EvaluationLength Unit="mm">4</EvaluationLength>
		<Instrument>
			<SamplingSpacing Unit="um">0.2</SamplingSpacing>
			<TipRadius Unit="um">2</TipRadius>
			<MeasuringForce Unit="mN">1</MeasuringForce>
			<MeasurementSpeed Unit="mm/s">0.1</MeasurementSpeed>
			<InstrumentID>Taylor Hobson Nanostep1</InstrumentID>
			<InstrumentType>Stylus</InstrumentType>
		</Instrument>
		<MeasurementInfo/>
	</Extraction>
	<Filtration>
		<Filter>
			<FilterName>Gauss</FilterName>
			<UpLimt>0.8</UpLimt>
			<LowLimit>2.5</LowLimit>
			<EndEffect/>
			<SoftwareID>PTB</SoftwareID>
		</Filter>
	</Filtration>
	<Evaluation>
		<ParameterName>Ra</ParameterName>
		<ParameterValue Unit="um">1.520</ParameterValue>
		<Uncertainty>
			<Value Unit="nm">46</Value>
			<CoverageFactor>2</CoverageFactor>
			<DegreesofFreedom/>
		</Uncertainty>
	</Evaluation>

</MeasuredValue>
```

Measured Value - SMU633gRa.xml

```
<?xml version="1.0" encoding="UTF-8"?>
```

```
<MeasuredValue xmlns="http://www.surfacetext.info/Schemas/SpecificationOperator"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.surfacetext.info/Schemas/SpecificationOperator
L:\Projects\STML\AcutualVerificationOperator.xsd">
	<Partition>According to the measuring plan of Type D defined in ISO
12179</Partition>
	<Extraction>
		<NumCutoff>5</NumCutoff>
		<SamplingLength Unit="mm">0.8</SamplingLength>
		<EvaluationLength Unit="mm">4</EvaluationLength>
		<Instrument>
			<SamplingSpacing/>
			<TipRadius Unit="um">2</TipRadius>
			<InstrumentType>Stylus</InstrumentType>
			<InstrumentID>Talysurf 6</InstrumentID>
			<MeasuringForce Unit="mN">1</MeasuringForce>
			<MeasurementSpeed Unit="mm/s">1</MeasurementSpeed>
		</Instrument>
		<MeasurementInfo/>
	</Extraction>
	<Filtration>
		<Filter>
			<FilterName>Gauss</FilterName>
			<UpLimt Unit="mm">0.8</UpLimt>
			<LowLimit Unit="um">2.5</LowLimit>
			<EndEffect/>
			<SoftwareID>TalyProfile 3.0.8</SoftwareID>
		</Filter>
	</Filtration>
	<Evaluation>
		<ParameterName>Ra</ParameterName>
		<ParameterValue Unit="nm">1525</ParameterValue>
		<Uncertainty>
			<Value Unit="nm">24</Value>
			<CoverageFactor>2</CoverageFactor>
			<DegreesofFreedom/>
		</Uncertainty>
	</Evaluation>
</MeasuredValue>
```

4.3.3 Discussions

Thus, a traditional report is transformed into SMTL. The unstructured data, therefore, map into structure data which are arranged by operators and operations according to GPS. Each XML file specifies its XML Schema file name (e.g. FullSpecificationOperator.xsd) and location (e.g. "http://www.surfacetext.info/Schemas/SpecificationOperator") which used to validate it. The Schema file is stored in this project website, which also provides the detailed definition for each tag. It makes this document traceable and reduces the possible misunderstanding.

In addition, many XML related techniques make the use of SMTL easily. Many available XML editors[27] can be used to create the SMTL file. Using XSLT (Extensible Stylesheet Language Transformations)[28], SMTL can be easily mapped into another XML data file or a report (in PDF or Word format and so on).

4.4 Conclusions

This chapter has presented the development of a XML-based information model for specification and verification of surface texture. Traditional paper-based documents with unstructured data are integrated into one structured data format for surface metrology. The structure of this model is adhered to the latest GPS. Examples have given. This model will be used by softgauges to state the measurement information.

[27] For example, a list of XML editors is given in http://en.wikipedia.org/wiki/List_of_XML_editors.

[28] XSLT is a declarative, XML-based language used for the transformation of XML documents.

5 Uncertainty analysis

The objective of this chapter is to identify model uncertainty and code uncertainty of the software of the surface measuring instruments. These uncertainties are the major concern in the design and development of softgauges, because they often cause disagreements between different parties.

5.1 Methodology

Many references are available in the modelling of a surface measuring system. The softgauges only verify the ISO standardised model built based on the ISO documents. The modelling processing is subject to the error and uncertainty. Main sources of model uncertainty are listed below.

1) *Incomplete definitions in the ISO standard documents:* For the ISO documents, it is impossible and unnecessary to detail every measurement procedure and condition because standards need to achieve a balance between over-specification and lack of focus. However, incompleteness of the definition can lead to ambiguity. The ambiguity establishes a one-to-many relationship between one ISO document and its implementations (i.e. one incomplete ISO definition has many interpretations). In this situation, each of interpretations is valid, but accuracy of each is different. The interpretation given by a NMI (as national interpretation) is the reference of others to assess the accuracy. Often this interpretation does not clearly stated in a published document, but presents

within its realisation in the form of measurement standard or a primary instrument (see Chapter 2).

2) *Imperfect definitions in the ISO standard documents:* We may never claim perfection in standards because the process of standards' development is in a continuous improvement mode[29]. Instrument manufacturers may adhere to the definitions or make an improvement, and an improvement may become ISO standard in the future (e.g. the Gaussian filter has replaced the 2RC filter in current ISO documents). Using a non-standardised definition should be clearly specified, otherwise, it can be recognised as a mistake when it causes a disagreement.

3) *Mistakes:* There are human errors due to the misunderstandings of the ISO standards. A mistake should be corrected when found.

Table 5.1 lists the procedure to handle these sources of model uncertainty in the development and maintenance of the softgauges.

Table 5.1 The procedure to handle model uncertainty

Sources of uncertainty	*Handling method*
Incomplete definitions in the ISO standard documents	1. Completing them based on the best understanding of ISO document; 2. Documenting their interpretations if necessary; 3. Realising them in softgauges; 4. Distributing their interpretations by the documents and the softgauges.
Imperfect definitions in the ISO standard documents:	If there are appropriate replacements, 1. Improving them with better interpretations; 2. Documenting their interpretations; 3. Realising them in softgauges; 4. Distribute their interpretations by the document and the softgauges. Otherwise, following them.
Mistakes	Correcting the known mistakes by updating the documents and the softgauges.

Two methods are used to identify the source of model uncertainty and code uncertainty.

[29] However, we could say that the standards are based on the best knowledge for surface texture at the time of writing.

1) **Top-down method**: This approach identifies these uncertainties by analysing the definitions given in ISO standard documents and the related interpretations. ISO 4287 (1997) and its related documents, namely ISO 4288 (1996), ISO 1302 (2002) and ISO 11562 (1996), are key documents of this project. In addition, the interpretations of these ISO documents are investigated by reviewing the publications of NMIs (Leach 2001; ASME B46.1 2002; Koenders, Andreasen et al. 2004) and major instrument suppliers (Zego Corp. 2002; Taylor Hobson Ltd. 2003).

2) **Reversing method:** This approach identifies these uncertainties by investigating the unexpected variation of the output results obtained from test software. In this project, we have investigated three type F2 softgauges developed by NPL, NIST and PTB, and four commercial software packages developed in the UK, France, Germany and the USA. Commercial packages are named as CA, CB, CC and CD for commercial protection. In this thesis, the square brackets refer to the associated software packages (see Table 5.2).

Table 5.2 Type F2 softgauges and commercial packages

	Institute	Software packages
[PTB]	PTB, Germany	Ref_soft_PTBIDL and Ref_soft_PTBweb[30] www.ptb.de/en/org/5/51/517/rptb_web/wizard/greeting.php
[NIST]	NIST, USA	Internet Based Surface Metrology Algorithm Testing System syseng.nist.gov/VSC/jsp/index.jsp
[NPL]	NPL, UK	nplsmd1.01 www.npl.co.uk/server.php?show=ConWebDoc.160
[CA]	Company A	Commercial software package A
[CB]	Company B	Commercial software package B
[CC]	Company C	Commercial software package C
[CD]	Company D	Commercial software package D

Section 5.2 highlights the significant model and code uncertainty of ISO 4287 parameters. The full detailed analysis is available on this project website[31] and this

[30] PTB provides reference software in the form of a desktop version and web version.

author's publication (Li, Leach et al. 2009). The effects of these uncertainties are estimated (see Section 5.3) and are also assessed (see Chapter 7).

5.2 Identifying the uncertainty of the ISO 4287 parameters

There are literally hundreds of numerical roughness parameters and a few filters available to characterise aspects of the surface roughness. In this project, we only focus upon ISO 4287(1997) parameters and Gaussian filter (ISO 11562 1996). According to the consultation in Chapter 2, it covers most of industry requirements.

The most common philosophy in surface metrology is to separate roughness, waviness, and form by the bandwidth of that information. An example of a possible flowchart of mathematical treatment for surface assessment, defined in the ISO document, is illustrated in Figure 5.1.

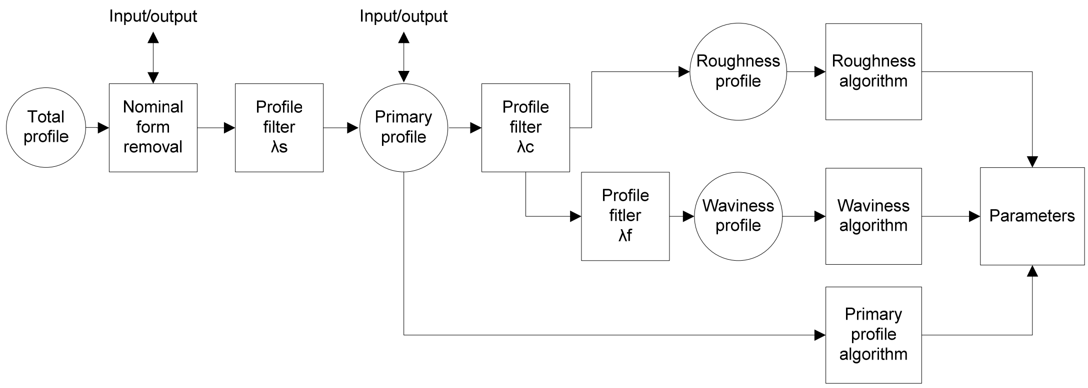


Figure 5.1 A flowchart for surface assessments according to ISO 3274 (1996) and 4287 (1997)

5.2.1 NPL's interpretation

This project has developed the absolute interpretations of ISO standard documents. This work was carried out by a partnership led by the University of Huddersfield in collaboration with Taylor Hobson Ltd and the National Physical Laboratory (NPL). It is distributed via this project website maintained by NPL and University of Huddersfield. It refers to as NPL's interpretation in this thesis. Its basic framework is

[31] www.npl.co.uk/server.php?show=ConWebDoc.160

illustrated in Figure 5.2. To the author's knowledge, this interpretation presents our best understanding of the ISO standard documents. Some of the key features of this interpretation are: 1) applying the cubic spline interpolation method on the discrete profiles to reconstruct the continuous profiles; and 2) implementing a mathematical stable approach to assess the spacing parameters, i.e. *RSm/PSm/WSm parameter*.

ISO 4287-1997 (ISO 4288-1996)

SOFTGAUGE POINTS

ASSUME: λs Filtered
Equally spaced
No Form

↓

FILTRATION Gaussian Filter (ISO 11562)		
R	**W**	**P**
λc High pass	λc Low pass	No Filter

↓

	FIELD PARAMETERS		**FEATURE PARAMETERS**	
	Amplitude	Other	Peak/Valley	Spacing
	Ra, *Rq*, *Rsk*,*Rku*, *Rp*, *Rv*, *Rz*	*Rt*	*Rc*	*RSm*
Feature Type[1]	Points	Points	Local Peak/Valley	Crossovers
Segmentation[2]	Cut-off	Evaluation	Based on feature	Based on feature
Combination[3]	None	None	Remove insignificant features	Remove insignificant features
Attributes	Cut-off	Evaluation	Significant features	Significant features
Statistics	Mean/Max	Value	Mean/Max	Mean/Max

Notes
1. Feature type is the basic element from which subsequent calculations are determined.
2. Segmentation is used to determine the initial portions of the profile.
3.Combination removes "insignificant" segments to leave significant segments. This removes artificially small segments due to noise, etc. making the measurand stable.

Figure 5.2 Basic framework for NPL's interpretation of surface profile texture

5.2.2 Start point

According to ISO 5436-2 (2001), the start point of softgauges is the primary profile which means no form and λs filtered. However, there are disagreements on this start point, and they are discussed as follows.

5.2.2.1 Form removal

Description

Form removal is an operation to separate the form error from a surface profile. Raw profile data may possess some kind of form (e.g. residual tilt). Normally, least squares best-fit line (LSQ) is implemented to remove this tilt prior to filtering during data processing. More complex form error may be removed by using polynomial fitting or nominal form minimum zone fitting. There are many other types of association methods as well (Muralikrishnan and Raja 2008).

Model uncertainty

The selection of form removal methods relies on the type of the nominal/existed form. As the form is varied from case to case, ISO 3274 (1996) does not state a default method to remove the forms. However, the LSQ is an indispensable operation in some software packages (e.g. PTB's type F2 Softgauges) because it is widely used in industrial practice.

NPL's interpretation defines the LSQ as an optional operation because: 1) LSQ line is not physically realistic in some case, e.g. a sine wave (Whitehouse 2002b); and 2) total least square method is more accurate than the linear least square method, especially in the case when the slope is significant (Murthy, Reddy et al. 1982).

5.2.2.2 λs filtering

Description

The λs profile filter is the filter that defines where the intersection occurs between the roughness and shorter wavelength (noise) components (ISO 4287 1997).

Model uncertainty

According to ISO 5436-2 (2001), Gaussian λs filtering is an optional operation in NPL's interpretation. However, a ratio between λs and λc is provided in ISO 3274 (1996). Some software packages (e.g. [CC]) interpret the λs filtering as an essential part of the λc filtering.

Code uncertainty

The uncertainty contributors for the λs filtering operation are the length definition (see Section 5.2.4.1), end effects (see Section 5.2.3), etc.

5.2.2.3 Other operations

Description

There are some non-standardised operations in production software.

Code uncertainty

In a commercial software package, namely [CC], the last point of the data set is deleted when inputting a data file.

In [CB], an extra point is added when opening a data file. This operation includes the several steps: 1) adding an extra point in the middle of the inputted profile, 2) changing the height value of the last point to be equal to the penultimate point, and 3) adjusting the value of the spacing to make the sampling length consistent.

The behaviour of these software packages suggests that they implement a conversion between a point-based length definition and an interval-based length definition (see Section 5.2.4.1).

5.2.3 Filtration

Filtering is the procedure to separate certain spatial frequency components of the surface profiles. A filter is an electronic, mechanical, optical or mathematical transformation of a profile to attenuate wavelength components of the surface outside the range of interest of the user. The Gaussian filter is currently the only standardised surface texture filter (ISO 11562 1996).

5.2.3.1 The Gaussian filter

Description

ISO 11562 (1996) defines the long wave (low pass) Gaussian filter as a continuous weighted convolution for an open profile, with the weights taking the classic Gaussian bell shape and a cut-off wavelength value of 50%. The short wave (high pass) Gaussian filter is defined as the difference between the surface profile and the long wave profile component resulting from the long wave Gaussian filter with the same 50% cut-off wavelength.

Code uncertainty

ISO 11562 (1996) does not give any information on implementation (algorithms, implementation problems, etc.) of the Gaussian filter. There are no tolerance values given within this standard document. Instead of tolerances, a graphical representation of the deviations of the realised Gaussian filter from the defined Gaussian filter shall be given as a percentage value over the wavelength range 0.01 to 100 cut-offs.

The weighting function of this filter (see Figure 5.3) has the shape of a Gaussian density function and is given by the equation

$$s(x) = \frac{1}{\alpha\lambda_c} \exp\left[-\pi(\frac{x}{\alpha\lambda_c})^2 \right] \quad \textbf{(5.1)}$$

where $\alpha = \sqrt{\frac{\ln 2}{\pi}} = 0,4697$, x is the position from the origin of the weighting function and λc is the long-wavelength cutoff.

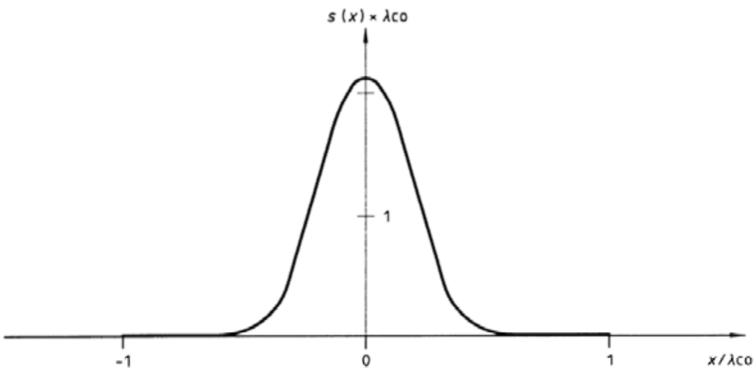


Figure 5.3 Weighing function of the profile filter according to ISO 11562 (1996)

There are many approaches to implement a discrete approximation of the long wave Gaussian filter, and two of them (which are principally typical) are listed as follows.

1) One approach is via a discrete weighted convolution in the spatial domain;

2) Another approach is via a transformation to the Fourier domain, applying a transmission weighting to the individual wavelengths and transforming back to the spatial domain.

In theory, the outputs of both approaches are same. NPL's interpretations use the first approach since it is less complicated to implement with differing numbers of points in the profile.

End effect

When implement the Gaussian filter, there is a distortion on the filtered profile at its beginning (run-up) and end (run-down). Methods are available to reduce the end effect (ISO/TS 16610-28 2010). However, no default one is provided in ISO documents.

NPL's interpretation recommends that one cut-off at each end of the profile are removed, while some of the production software (e.g. [CC]) only removes half cut-off.

5.2.4 Basic elements

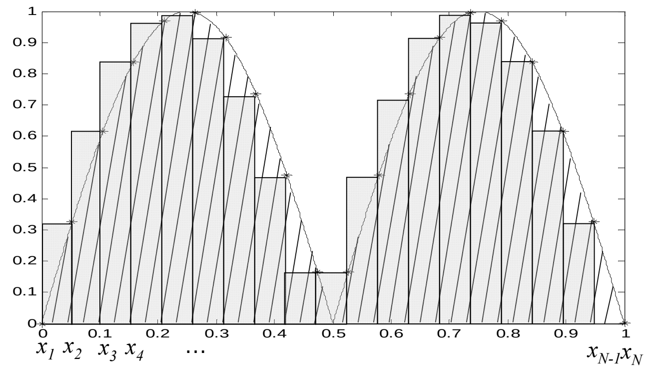
5.2.4.1 Points

A set of measuring points, which contains the dimensional information with associated errors, is the basic element that all digital processing based on.

Code uncertainty

Discretization error

Brennan et al (2005) found that it can lead to unacceptable errors when changing a continuous definition directly to a discrete form (replacing integrals to summations, etc.). Figure 5.4 shows the discretization error by comparing the values of *P* parameters obtained from continuous form and discrete form separately. To reduce this error, NPL's interpretation utilises a cubic spline interpolation method to reconstruct the continuous profiles.



Parameter	*Result (Discrete Model)*	*Nominal Value (Continuous Model)*	*Relative Difference*
Pa	0.60341	0.63662	5.22%
Pq	0.6892	0.7071	2.53%
Psk	3.8152e-017	0	-
Pku	1.5789	1.5	5.26%

Figure 5.4 An example of the discretization errors

Length definition

The meaning of a measuring point is not well understood. Some states that it represents the height information of the measured point, which some argue that it represents the height information of the measured interval. Therefore, different length algorithms are implemented to calculate the length in X-axis direction (see Table 5.3). The length algorithm affects the definition of sampling length, evaluation length, parameters, *λc*, *λs*, form removing operation and so on (an example given in Table A2.1). NPL's interpretation uses the point-based definition due to it is more mathematically reliable.

Table 5.3 Length algorithms

	Point-based definition	*Interval-based definition*
Where *n* is the number of points between its ends, and *i* is the sampling interval.	The length *l* calculated as $l=(n-1)\times i$,	The length *l* calculated as $l=n\times i$,

Interpolated points

Some key points, used to define the features and calculate the parameter values, are often not directly available. These points are produced by an interpolation method. NPL's interpretation uses a cubic spline interpolation. The variation due to different interpolation algorithms should be considered.

5.2.4.2 Peak/valley

Description

Profile peak (valley) is the outwardly (inwardly) directed portion of the assessed profile connecting two adjacent points of the profile with the X-axis (ISO 4287 1997).

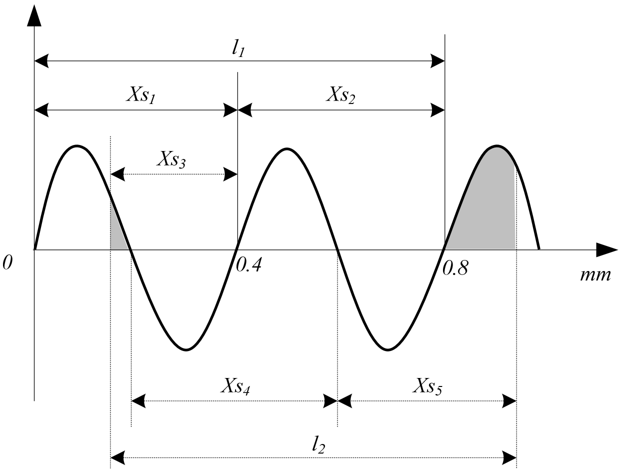
Model uncertainty

Incomplete feature

The *incomplete portion* is the feature at the beginning or end of a sample length (e.g. the gray areas in Figure 5.5), and a handling method is provided in ISO 4287 (1997).

> *"The positive or negative portion of the assessed profile at the beginning or end of the sampling length should always be considered as a profile peak or as a profile valley. When determining a number of profile elements over several successive sampling lengths, the peaks and valleys of the assessed profile at the beginning or end of each sampling length are taken into account once only at the beginning of each sampling length."* (*ISO 4287:1997 Clause 3.2.7)*

The imperfection of this definition is significant. This ambiguity could cause significant distortion on feature parameters. In the example given in Figure 5.5, *RSm* values is varied from 0.325mm to 0.4 mm while the true value is the 0.4mm. NPL, PTB and NIST do not follow this definition and propose the revised methods separately.



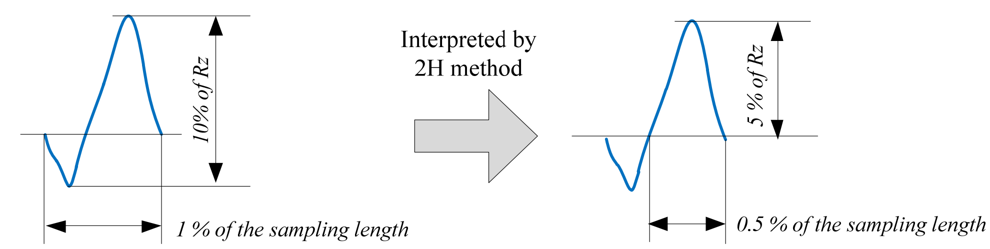
Sampling Length	*Measuring Direction*	*RSm (mm)*
l_1	⇨	0.4
l_1	⇦	0.4
l_2	⇦	0.375
l_2	⇨	0.325

Figure 5.5 Ambiguity of definition of the incomplete portion

NPL's interpretation is: 1) discarding the incomplete features at each end of evaluation length; 2) calculating feature parameter (e.g. *RSm)* over evaluation length.

Identifications of the insignificant features

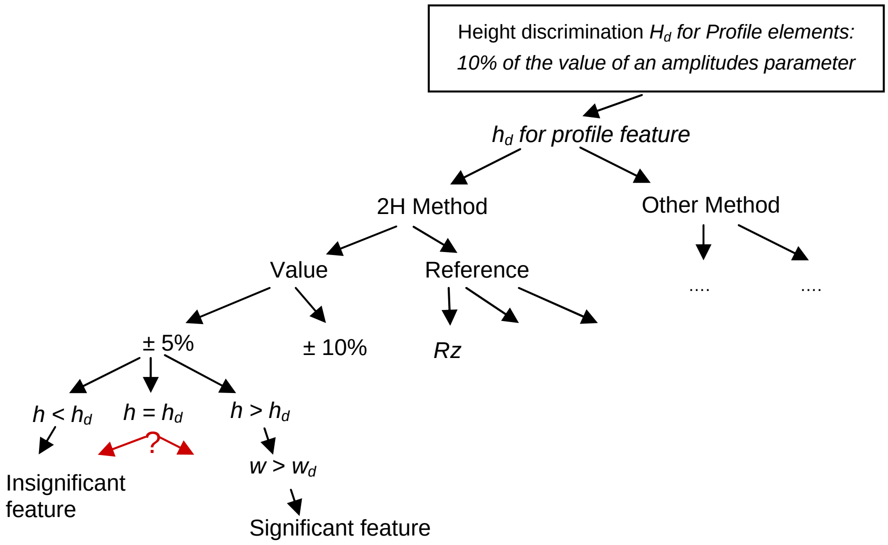
Discrimination for the profile elements is used to identify the insignificant features. The definition of profile elements is ambiguous (see Section 5.3.4.2), so most software implementations identify the insignificant peaks/valleys (i.e. profile features) directly. 2H method is often used to interpret the discrimination of a profile element to the discrimination of a profile feature. An example is given in Figure 5.6. In NPL's interpretation, the default discrimination for a profile feature is 5% of parameter Rz and 0.5% of sampling length. Many software packages also use 2H method. In some packages, the default discrimination for a profile feature is 10% of parameter Rz and 1% of sampling length. Figure 5.7 illustrates the ambiguity of this ISO definition by listing some possible interpretations.



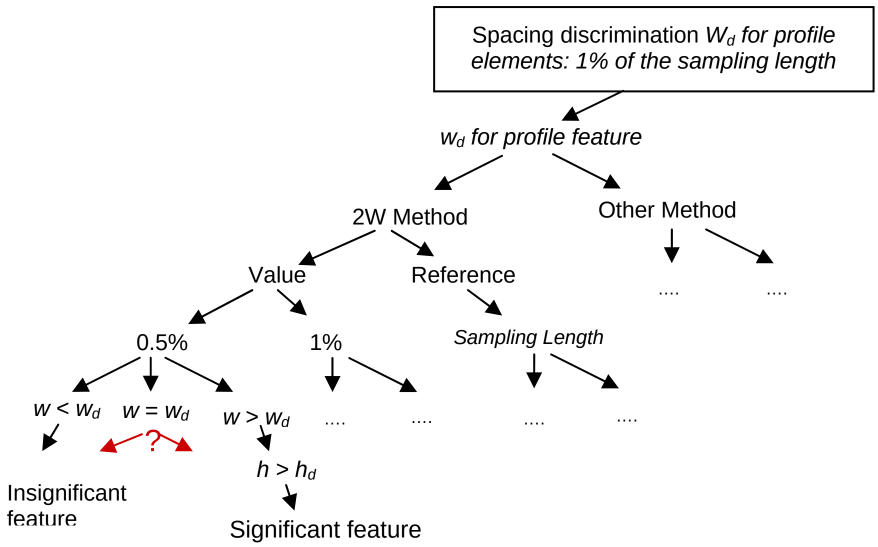
(a) Discrimination for a profile element in ISO 4287 (1996)

(b) Discrimination for a profile feature in NPL's interpretation

Figure 5.6 NPL's implementation of the 2H method



(a) Height Discrimination



(b) Spacing Discrimination

Figure 5.7 Ambiguity of the discrimination for a profile element

5.2.4.3 Profile element

Description

A profile element is defined as a peak with its followed valley (ISO 4287:1997 - figure 3), or a valley with its followed peak (ISO 4287:1997 - figure 10).

Model uncertainty

The ambiguity of this definition is shown in Figure 5.8. In this case, there are two valid profile elements with different height and width values. Thus, the height and width of this profile element could be 1) Zp_2 and Xs_2; 2) Zp_1 and Xs_1; 3) $(Zp_2 + Zp_1)/2$ and $(Xs_2 + Xs_1)/2$.

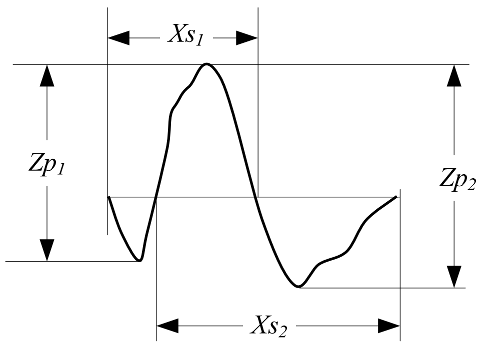


Figure 5.8 Ambiguity of the definition of a profile element

In NPL's interpretation, the profile elements are used as a concept only, and the calculations of their related parameters (e.g. *RSm/Rc*) are based on features (a peak or a valley) directly.

5.2.4.4 Crossovers

Description

Crossovers refer to as the mean line crossing-points. Crossovers are of importances which are used to define the profile feature.

Code uncertainty

Unfortunately, most crossovers are excluded in the measuring data point set. Thus the crossovers are generally estimated by their neighbour points. The disagreements caused by different interpretation algorithms should be considered.

NPL's interpretation recommends including implied mean line crossing points by interpolating the data where these occur and provide each profile peak or valley element with calculated boundary values.

5.2.5 Sampling length and evaluation length

5.2.5.1 Cut-off

Description

Most parameters are calculated over a sampling length, so the *sampling length* has been recognised as the basic "unit" length of most surface parameters (Whitehouse 2002b). This length should be long enough to include a statistically reliable amount of data. The sampling length has the same numeric value as the cut-off of filter. So the sampling length is also known as the *cut-off* length.

Model Uncertainty

Sample length of R-parameter - lp

The primary profile is the basis for evaluation of the primary profile parameters. The sampling length *lp* is numerically equal to the evaluation length. ISO document defines that *lp* is equal to the length of the feature being measured. However, no current ISO standard defines the profile filter λf. There are two interpretations of the (default) sample length for P-parameter:

1) l_p (default): The remaining profile after removing one λc cut-off at each end of a profile

2) l_p (default): All the measured points in a data file.

NPL's interpretation uses the second interpretation. For the first interpretation 1, it should be noticed that: 1) there is no standardised method to reduce the end effect of a filtration operator; 2) *P*-parameter is relied on the selection of the λc value if follows this interpretation. Thus, to avoid ambiguity, the first interpretation requires specifying the λc value when using the *P*-parameters in drawing. So this interpretation does not consistent with ISO 1302 (2002).

Sample length of R-parameter - l_r

To obtain the roughness profile, NPL's interpretation recommends the following procedure:

1) The primary profile is first filtered using the short wave Gaussian profile filter with a cut-off wavelength value λc.

2) To reduce the end-effect, one cut-off at the beginning and the end of this profile are removed.

3) The remaining profile is then partitioned into adjacent portions. Apart from possible the last portion at the end of the profile, each portion is equal in length of the sampling length. If the last portion is not equal in length to the sampling length then it is removed. The resulting profile is called the roughness profile.

In step 2, some production software packages (e.g. [CC]) remove half cut-off at each end of the profile.

Sample length of W-parameter - l_w

There is no common understanding of the meaning and use of waviness parameters (Whitehouse 2002b). ISO 4287 defines the sampling length of *W*-parameters based on the cut-off of the profile filter λ_f. Some industrial practice ignores this filter step and uses the sampling length l_w equal to the cut-off wavelength λ_c.

Code uncertainty

The number of points of a cut-off varies as the results of different length definitions (see Table 5.3). An example is given in Table A2.1.

5.2.5.2 Evaluation Length

Description

Evaluation Length is the length of the data used for analysis, which contains several (usually five) consecutive sampling lengths (see Figure 5.9). Some parameters are defined within the evaluation length directly, e.g. parameter *Rt*.

Model uncertainty

Evaluation length and sampling length are specified in ISO 4288(1996). However, some of the terms (such as measurement length, traverse length in Figure 5.9), used widely in practice, are not standardised.

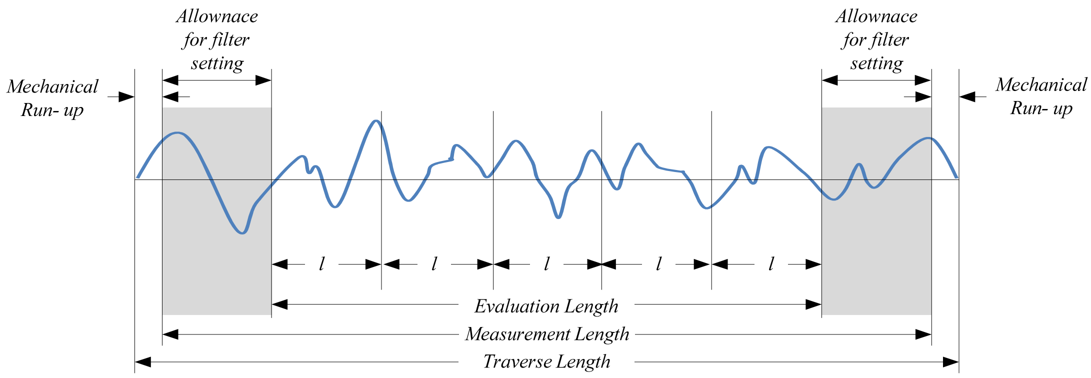


Figure 5.9 Sample length *l*, evaluation length, measurement length and instrument traverse length.

Code uncertainty

Different length definitions (see Table 5.3) affect the number of points used to define the evaluation length.

5.2.6 Segmentation of portions

Description

Segmentation is the operation to remove the "insignificant" portions due to noise, etc.

Model uncertainty

A segmentation method for motif parameters is provided in ISO 12085 (1996). For ISO 4287 parameters, however, there is no specified segmentation method. Many algorithms exist.

The insignificant portions can be classified into five types by their position in the sampling length and the evaluation length (Li, Leach et al. 2009). According to its type, an insignificant portion can be discarded or merged into its neighbour portions. Table 5.4 summarises five methods for removing the insignificant portions in the middle of a sampling length. Figure 5.10 illustrates the different results produced by those methods.

Table 5.4 Five segmentation methods

NO	*Search strategy*	*Segmentation method*
1	From left to right	Merging with next portion
2	From left to right	Merging with half of next portion
3	From right to left	Merging with next portion
4	From right to left	Merging with half of next portion
5	From the smallest to biggest	Merging with the smaller one of its neighbouring portions

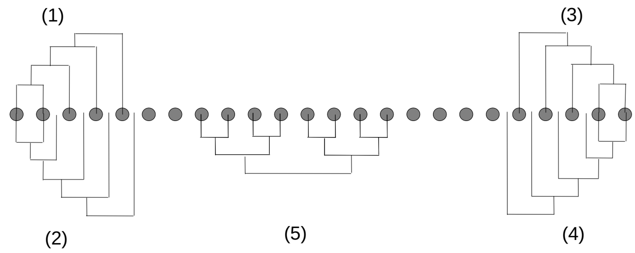


Figure 5.10 Significant results produce by different segmentation methods (the black points represent the crossing points of a profile)

The variation of parameter *RSm*, arisen from the difference of the method 1,2,3,4, are significant (Leach and Harris 2002). Scott (2006) proposed the method 5 and proved its stability by the representation theory of measurement. NPL's interpretation implements the method 5.

5.2.7 Parameters

According to the bandwidth of the profiles, there are three types of the surface parameters currently defined in ISO 4287, namely *P*-parameters, *R*-parameters and *W*-parameters. Same parameter algorithms are given for three profiles (ISO 4287 1997). Thus, this section only discusses the algorithms of *R*-parameters.

5.2.7.1 Field parameters (mean)

Description

Those parameters calculate the mean value of ordinate values *z(x)* within a sampling length.

Parameter Ra

Ra is the arithmetic mean of the absolute ordinate values *z(x)* within a sampling length. It is simply defined as the average height of the surface deviations in the z direction.

$$Ra = \frac{1}{l}\int_0^l |z(x)|dx \quad \textbf{(5.2)}$$

Parameter Rq

Rq is the root mean square roughness of the surface.

$$Rq = \sqrt{\frac{1}{l}\int_0^l z^2(x)dx} \quad \textbf{(5.3)}$$

Parameter Rsk

Rsk is the skewness of the assessed profile.

$$Rsk = \frac{1}{Rq^3}\left[\frac{1}{l}\int_0^l z^3(x)dx\right] \quad \textbf{(5.4)}$$

Parameter Rku

Rku is the kurtosis of the assessed profile.

$$Rku = \frac{1}{Rq^4}\left[\frac{1}{l}\int_0^l z^4(x)dx\right] \quad \textbf{(5.5)}$$

Model uncertainty

There are two methods to take the mean value of the profile parameters over the evaluation length, they are listed below.

1) One method calculates the profile parameters over each sampling length, and takes the means of those results.

2) Another method calculates of the profile parameters over evaluation length directly.

The first method is used in ISO 4288, while the second method is implemented in American standard document ASME B46. Two methods deliver same results on parameter *Ra*, while produce different results on parameter *Rp, Rdq*, *Rsk*, and *Rku* (Bui, Vorburger et al. 2003).

Code uncertainty

These parameter algorithms involve the addition of thousands of point, so the truncation errors should consider. In NPL's implementation, Kahan's method (Kahan 1965) is used for computer addition. Kahan's method increases computation by a factor of 4 but yields more accurate results, especially when adding a very small number on a quite large number.

Note the total number of points, used to calculate those parameters, is slightly different according to the length definitions of the software packages (see Section 5.2.4.1).

5.2.7.2 Field parameters (max)

Description

These parameters deliver the max value of ordinate values *z(x)* within a sampling length.

Parameter Rp

Rq is the maximum profile peak height of the assessed profile.

Parameter Rv

Rq is the maximum profile valley depth of the assessed profile.

Parameter Rz

Rz is the maximum height of the assessed profile.

Parameter Rt

Rt is the difference between the highest peak and the lowest valley within the evaluation length (see Figure 5.11).

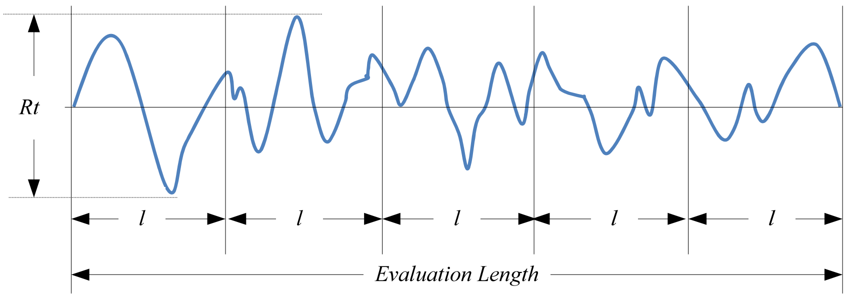


Figure 5.11 *Rt* is the total height of a profile over the evaluation length

Model uncertainty

Currently, these parameters are evaluated over a sampling length and pay no attention on the location of features. Thus, a significant feature, at the end of a sampling length, has more weight than a feature at the middle. For example, the peak A in Figure 5.12 is the highest profile peak in both sampling length l_1 and l_2. One peak (e.g. the peak A) can be counted two peaks (e.g. part of peak A in l_1 and reaming part of the peak A in l_2). A slightly shift of the start point of the sampling length could lead significant change of parameter value (e.g. the value of Rp_2 in Figure 5.12 depends on the start point of sampling length l_2).

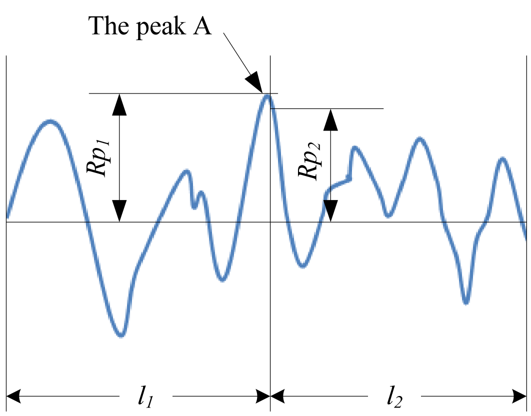


Figure 5.12 A significant feature at the end of the sampling length

Code uncertainty

The parameter value is slightly greater if these parameters calculate over the reconstructed profile.

5.2.7.3 Feature parameters

Description

These parameters deliver the mean value of height and width of the profile elements after removing insignificant features.

Parameter RSm

RSm is the average spacing of profile elements (A profile element is a valley and its adjacent peak). The peaks and valleys are found by using both height and width discrimination criteria. The minimum height and minimum spacing of profile peaks and profile valleys is set as a percentage of an amplitude parameter (the red line indicated in Figure 5.13)

$$RSm = \frac{1}{m}\sum_{i=1}^{m} Xs_i \tag{5.6}$$

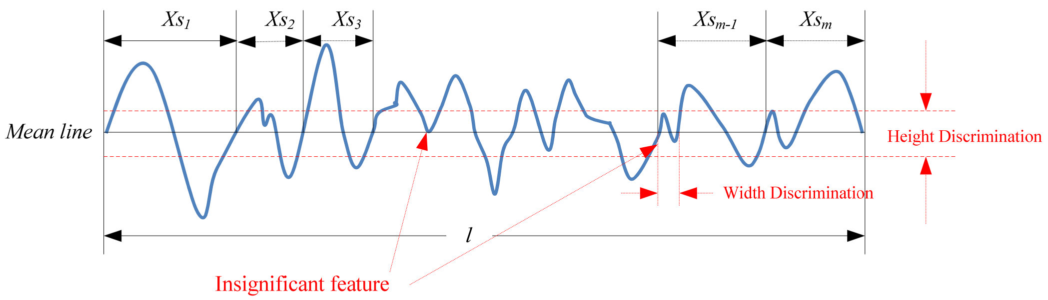


Figure 5.13 Width of profile elements

Parameter Rc

Rc is the average height of profile elements.

Model uncertainty

The elements of parameter *RSm* and *Rc* have significant model uncertainty (see the previous part of this chapter). Parameter *RSm* and *Rc* are defined over the sample length (ISO 4287: 1997). However, NPL, PTB, and NIST recommend that *RSm* and *Rc* should be assessed over the evaluation length directly to reduce the effect of incomplete features.

5.3 Estimating the effect of software uncertainty

The previous section identified the model and code uncertainty of ISO 4287 parameters. For different profiles, their contributions are varied. Their effects on three F2 softgauges and four commercial software packages (listed in Table 5.2) are estimated in Table 5.3 – Table 5.5.

Table 5.5 Estimating the effect of the software uncertainty of parameter *Ra*[32]

Reference	*Operation*	*Estimating Effect* *(Weight in the final result)*
5.2.2.3	Other operations	[CB] *** [CC]
5.2.2.1	Form removal	[PTB] *
5.2.3.1	End effect of λc filtering	[CC] *
5.2.2.2	*λs* filtering	[CC] *
5.2.4.1	Length Definition	
5.2.4.4	Crossover	

Table 5.6 Estimating the effect of the software uncertainty of parameter *Rz*[32]

Reference	*Operation*	*Estimating the Effect* *(Weight in the final result)*
5.2.2.3	Other operations	[CB] *** [CC]
5.2.2.1	Form removal	[PTB] *
5.2.3.1	End effect of λc filtering	[CC] *
5.2.2.2	*λs* filtering	[CC] *
5.2.4.1	Length Definition	
5.2.4.4	Crossover	

[32] Note: ***** More than 100 % variation;
**** More than 10 % variation;
*** More than 1 % variation;
** More than 0.1 % variation;
* More than 0.01 % variation

Table 5.7 Estimating the effect of the software uncertainty of parameter *RSm*[32]

Reference	*Operation*	*Estimating the Effect* *(Weight in the final result)*
5.2.2.3	Other operations	[CB] *** [CC]
5.2.2.1	Form removal	[PTB] *
5.2.3.1	End effect of λc filtering	[CC] *
5.2.2.2	*λs* filtering	[CC] *
5.2.4.1	Length Definition	
5.2.4.4	Crossover	
5.2.4.3 & 5.2.4.2	Profile element	
5.2.4.3	Joint Direction	[NIST] ***
5.2.4.2	Incomplete portion	[ALL] ***
5.2.6	Segmentaion	[ALL] *****

5.4 Conclusions

This chapter has analysed the errors and uncertainties in the software modelling and coding procedure by studying the case of ISO 4287 parameters. This is the first detailed analysis of model and code uncertainty of surface metrological software. It showed that software uncertainties can be significant. Software uncertainty will be evaluated in Chapter 7 by using type F1 softgauges developed in Chapter 6.

6 Development of type F1 softgauges

The objective of this chapter is to develop type F1 softgauges for surface texture, as the realisations of ISO definitions at the national level in the UK. Type F1 softgauges have two components, the reference dataset and the reference results. Section 6.1 presents the scope of the reference dataset in good coverage. Section 6.2 addresses the development of the reference dataset. Section 6.3 focuses on the production of the reference results, and uncertainty is covered in Section 6.4.

6.1 Scope of type F1 softgauges

Type F1 softgauges are developed for calibrating both F2 softgauges and production software packages. The scope of the type F1 softgauges is of critical importance. It is influenced by prior knowledge and experience in the use of relevant standard documents, and targeted applications based on the user consultation exercise as discussed in Chapter 2. Type F1 softgauges are focused on three areas.

1) General manufacturing engineering

In general manufacturing engineering, the surface texture features are closely related to the manufacturing process. So the type F1 softgauges need to cover the surfaces created by those processes. The broad categories of manufacturing processes used are as follows:

- Casting and primary forming.

- Forming and shaping: rolling, forging and sheet forming, etc.
- Machining: turning, milling drilling, planning, grinding, EDM, etc.
- Finishing: honing, lapping, polishing, coating, etc.

The surface texture produced directly from casting in particular, and to a lesser extent forming, are precursor surfaces for further processing. Additional operations such as machining and fine finishing are normally employed. Consequently, relevant surfaces can be narrowed down to two broad classifications as shown in Figure 6.1.

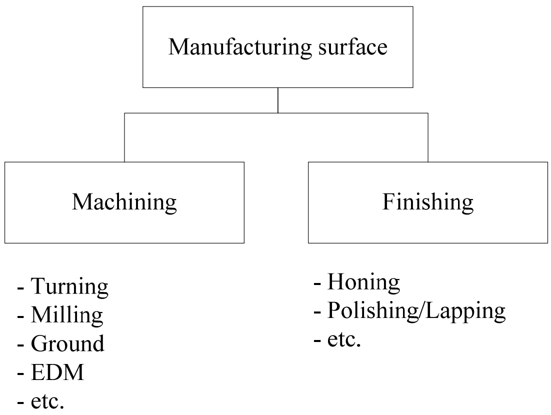


Figure 6.1 Processing routes for manufacturing surfaces

2) Relevant standard documents

In addition, type F1 softgauges should cover specific surfaces referred to in relevant standard documents. Hardgauges are listed in ISO 5436-1 and include types A to E for calibration surface profile measurement. A number of these profiles are also very useful for software calibration. This is especially true for type C hardgauges and type D hardgauges. Type C hardgauges are sine and triangular waves, and type D hardgauges represent measurement of the practical ground profile.

3) Industrial consultation exercise

Finally, and also most importantly, type F1 softgauges should centre on surfaces which industry considers widely used and of particular importance. From the industry point of view, some manufacturing processes are used much more frequently than others. As discussed in Chapter 2, precision finishing of metal are highlighted as the main manufacturing process where metrology is of primary importance. These processes focus on grinding and lapping/polishing of steels as being of high importance.

Many standard manufacturing workpiece surfaces can be obtained commercially - the measurements undertaking on these surfaces are considered ideal as reference data. In addition, the simulation of the manufacturing processes (e.g. turning, grinding and milling, etc.) is quite mature in the research field. Simulated surface profiles are very close to the real processed surfaces.

Some of the profiles, used in the previous comparison or testing, are good examples as well (Thomas and Charlton 1981; Haitjema 1998; Leach and Harris 2002; Bui, Vorburger et al. 2003; Koenders, Andreasen et al. 2004; Chen, Hsieh et al. 2005; Bui and Vorburger 2007). These profiles are in the scope of reference data presented above.

Overall, type F1 softgauges, as shown in Figure 6.2, is proposed and includes two parts, that of functional reference profiles for practical and simulated manufacturing surface, and that of evaluation reference profiles.

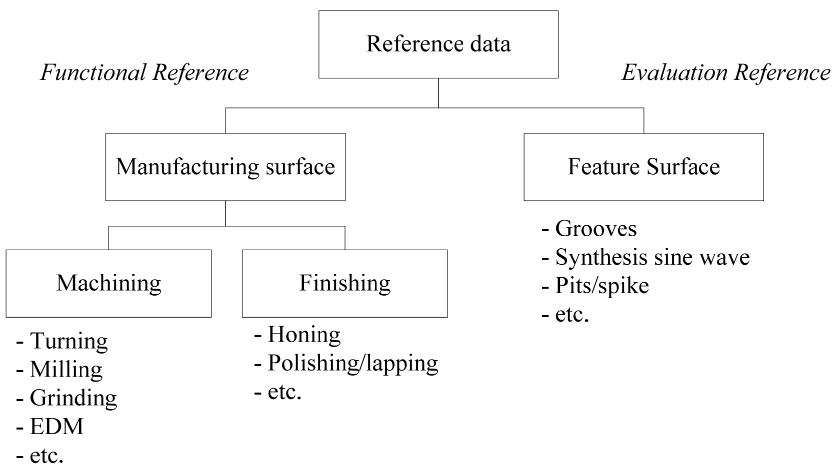


Figure 6.2 Scope of the type F1 softgauges

6.2 Reference datasets

Overview of the existing techniques, there are four ways to produce a reference datasets. They are: 1) measuring an engineered surface; 2) generating the simple profiles by a known function; 4) simulating the manufacturing profiles; and 4) modifying the measured profiles or simulated profiles. Figure 6.3 illustrates these methods together with their links to manufacturing surface, type C and type D hardgauges. Their advantages and disadvantages are compared in Table 6.1.

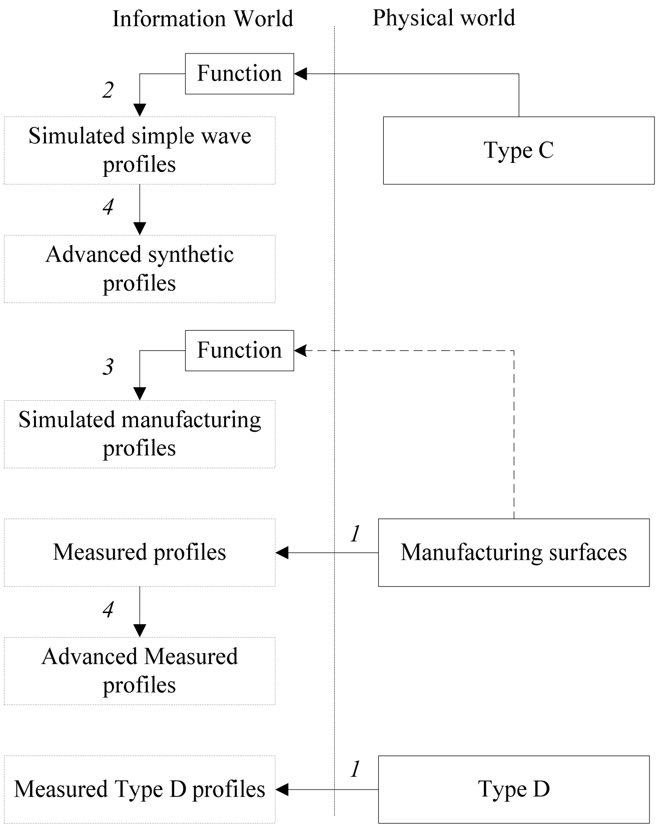


Figure 6.3 The methods for producing the reference datasets

Table 6.1 Comparison of the methods for producing a reference dataset

No	*Method*	*Advantage*	*Disadvantage*
1	Measuring standard workpieces	Easily obtained; A real surface profile	Measurement uncertainty and different instruments; No theoretical support for the reference results
2	Generating simple wave profiles	Easy to generate profiles and the reference results	Not close to real profiles
3	Simulating manufacturing profiles	Close to real profiles and the reference results cross check	Complicated algorithms
4	Modifying measured and simulated profile	Predict the future performance, simulate the special measurement condition	Only partly close to real profiles.

Following the developed methodology and using existing techniques, a minimum set of 14 reference datasets have been proposed for this set of type F1 softgauges (see Table 6.2).

Table 6.2 Scope of type F1 softgauges

Reference Data Sets				
	Tool cutting	Abrasive cutting	Non-traditional	Feature
Measured profile	Milling, turning	Grinding, lapping, honing	EDM	
Simulated profile	Turning	Grinding, honing (pits and noise)	EDM	
Mathematical model	Harmonic wave			Grooves and steps
Min number of profiles for ISO 4287	4	5	2	3

Except for the measured profiles, the simulated manufacturing profiles and the mathematical defined profiles will be generated in Matlab. For all profiles, the measurement condition will be consistent in order to minimum of effect of sampling (see Table 6.3).

Table 6.3 Profile "measuring" conditions

Condition	*Setup*
Sampling interval	0.25 um
Sampling length	0.8 mm
Evaluation length	0.8mm*7 = 5.6 mm
Total number of points	22401

6.2.1 Mathematical defined reference dataset

The basic waveforms (such as sine waves, saw waves, pulses and square waves) will be used for generating reference datasets. Combination of different frequencies and modification of those waveforms are applied to address special feature and fault focus. This subset of reference dataset consists of the following datasets:

1) Synthetic sine & saw wave profiles

    a. Single frequency

    b. Multiple frequencies (inc. phase shifts)

2) Advanced synthetic sine & saw wave profiles

    a. Truncated wave form (sine & saw)

    b. Padded wave form (sine & saw)

3) Pulsed & spiked profiles

    a. Single pulsed

    b. Multiple pulsed with different widths

4) Square wave profile

    a. Advanced square wave

    b. Single and multiple steps

5) Gaussian white noise

Synthetic sine & saw wave profiles

Based on the lessons learnt from the use of hardgauges (See Chapter 2), simple sine and saw wave profiles are the first choice for evaluating both roughness parameters and filtering. The combination of the simple and synthetic wave profiles provides full cover of the reference dataset for the characteristic transmission curve of the Gaussian filter. The functional testing is further enhanced by the addition of two phases shifted synthetic profiles. Table 6.4 shows the mathematical functions used to generate sine and saw wave profiles and Figure 6.4 gives some examples of the profile generated.

Table 6.4"Mathematical" surface profiles

Filename	***Function***
Sin1.smd	$f(x) = \sin(\frac{2\pi x}{\lambda})$, $\lambda = 0.16mm$
Saw1.smd	$f(x) = \text{saw}(\frac{2\pi x}{\lambda} + \frac{\pi}{2})$, $\lambda = 0.16mm$
Sin1_2.smd	$f(x) = \sin(\frac{2\pi x}{0.5*\lambda})$, $\lambda = 0.16mm$
Saw1_2.smd	$f(x) = \text{s}\,aw(\frac{2\pi x}{0.5*\lambda} + \frac{\pi}{2})$, $\lambda = 0.16mm$
Sin123.smd	$f(x) = \sin(\frac{2\pi x}{0.5*\lambda}) + \sin(\frac{2\pi x}{\lambda}) + \sin(\frac{2\pi x}{2*\lambda})$, $\lambda = 0.16mm$
Saw123.smd	$f(x) = \text{saw}(\frac{2\pi x}{0.5*\lambda} + \frac{\pi}{2}) + \text{saw}(\frac{2\pi x}{\lambda} + \frac{\pi}{2}) + \text{saw}(\frac{2\pi x}{2*\lambda} + \frac{\pi}{2})$, $\lambda = 0.16mm$
Sin12phs.smd	$f(x) = \sin(\frac{2\pi x}{0.5*\lambda} + \frac{\pi}{4}) + \sin(\frac{2\pi x}{\lambda})$, $\lambda = 0.16mm$
Saw12phs.smd	$f(x) = \text{saw}(\frac{2\pi x}{0.5*\lambda} + \frac{\pi}{2} + \frac{\pi}{4}) + \text{saw}(\frac{2\pi x}{\lambda} + \frac{\pi}{2})$, $\lambda = 0.16mm$

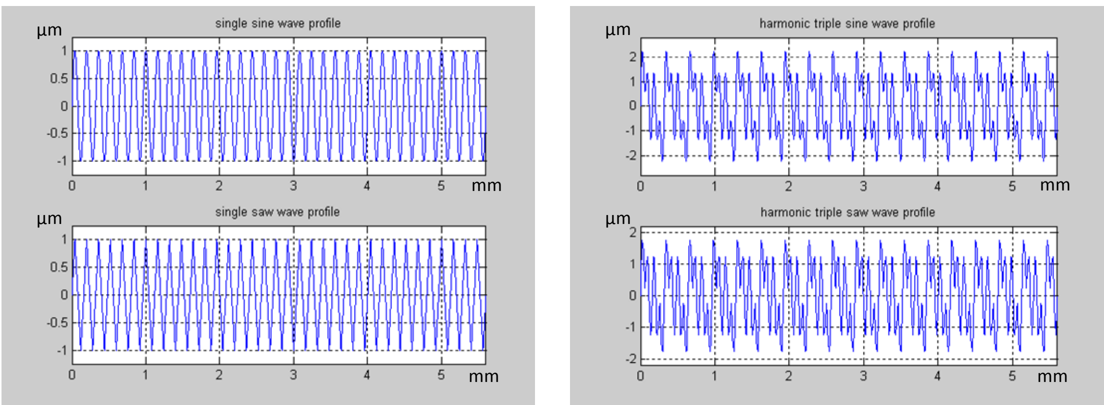


Figure 6.4 Example of synthetic sine & saw profiles

Advanced synthetic sine & saw wave profiles

The modified synthetic profiles are designed to address the deficiency in hybrid and spacing parameters, as the truncation and padding introduce uncertainty into the calculation (see Table 6.5 and Figure 6.5).

Table 6.5 "Mathematical" profiles for testing spacing and hybrid parameters

Filename	*Function*
Sin1tru.smd	$f(x)=\begin{cases}\sin(\frac{2\pi x}{\lambda}),(k+0.5)\lambda<x\le(k+1)\lambda,k\in I\\0\end{cases}$, $\lambda=0.16mm$
Saw1tru.smd	$f(x)=\begin{cases}\mathrm{saw}(\frac{2\pi x}{\lambda}+\frac{\pi}{2}),(k+0.5)\lambda<x\le(k+1)\lambda,k\in I\\0\end{cases}$, $\lambda=0.16mm$
Sin1pad.smd	$f(x)=\begin{cases}\sin(\frac{2\pi x}{\lambda}),2k\lambda<x\le(2k+1)\lambda,k\in I\\0\end{cases}$, $\lambda=0.16mm$
Saw1pad.smd	$f(x)=\begin{cases}\mathrm{saw}(\frac{2\pi x}{\lambda}+\frac{\pi}{2}),2k\lambda<x\le(2k+1)\lambda,k\in I\\0\end{cases}$, $\lambda=0.16mm$

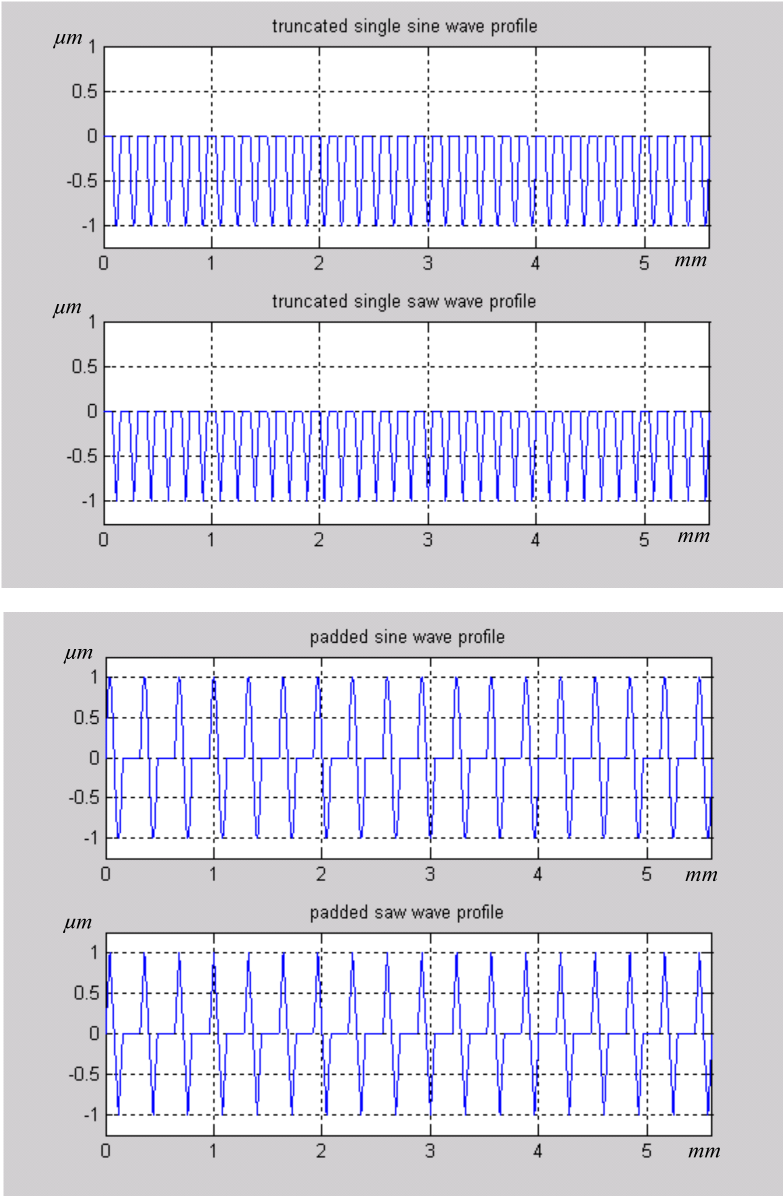


Figure 6.5 Example of advanced synthetic sine & saw wave profiles

Pulsed & spike profiles

Pulse and spike profiles are extreme wave profiles. They are an effective sample to test the response of the Gaussian filtering (see Table 6.6 and Figure 6.6).

Table 6.6 "Mathematical" spiked profiles for testing Gaussian filtering

Filename	***Function***
Pulse.smd	$f(x)=\begin{cases}1, x=l/2\\0, x\neq l/2\end{cases}, l=5.6mm$
Spike.smd	$f(x)=\begin{cases}1, & x=l/2\\-1, & x=l/4,3l/4\\0, & x\neq l/4,l/2,3l/4\end{cases}, l=5.6mm$

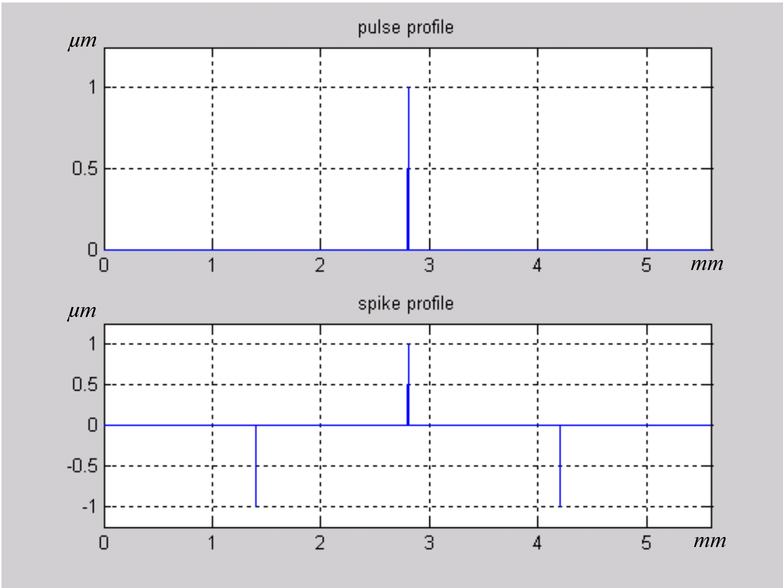


Figure 6.6 Example of spike profiles

Square wave and white noise profile

Square wave and step profiles are effective in the calibration of the Gaussian filter. The white noise profile is used for testing parameter calculations (see Table 6.7 and Figure 6.7).

Table 6.7 Square wave and white noise profiles

Filename	***Function***
Squ1.smd	$f(x)=\begin{cases}1, & k\lambda < x \le (k+0.5)\lambda, k\in I\\ -1, & (k+0.5)\lambda < x \le (k+1)\lambda, k\in I\end{cases}, \lambda = 0.16mm$
Steprf.smd	$f(x)=\begin{cases}0, x<l/2\\ 1, x\ge l/2\end{cases}, l=5.6mm$
Stepsrf.smd	$f(x)=\begin{cases}1, & l/5\le x< l/5+500pts\\ -1, & 2l/5\le x<2l/5+500pts\\ -1, & 3l/5\le x<3l/5+500pts\\ 1, & 4l/5\le x<4l/5+500pts\\ 0, & other\end{cases}, l=5.6mm,$ $\Delta x = 0.25\mu m$
Normrand.smd	$f(x)=normrand(0,1,l), l=5.6mm$

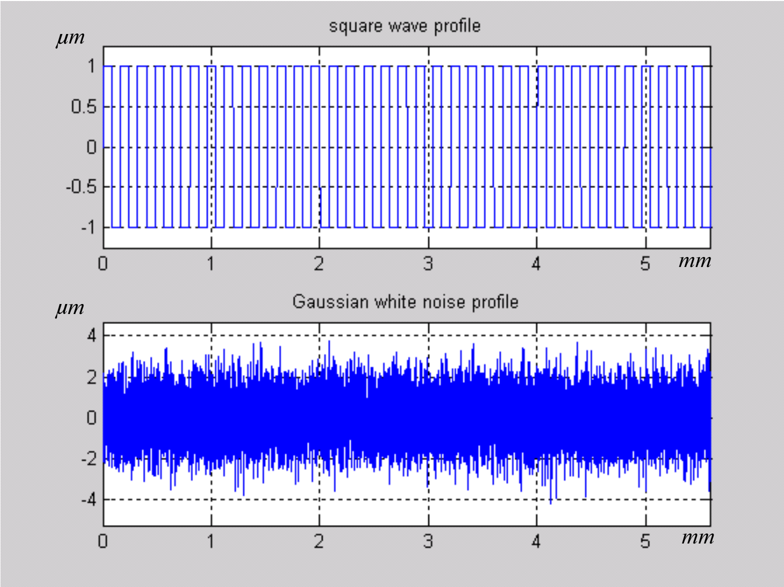


Figure 6.7 Examples of square wave and white noise profiles

6.2.2 Simulated manufacturing reference dataset

Surface profile parameters are often used to validate the simulation of manufacturing process. It is of importance to limit the software error for the validation of simulation. Thus, some simulated manufacturing reference dataset are developed.

Simulated manufacturing reference datasets are generated from numerical models of manufacturing processes. Profiles cannot be described in a simple mathematical form. In accordance with the classification of the manufacturing processes, three processes have been simulated. These were:

1) Grinding, a typical example of abrasive cutting.

2) Milling, a typical example of tool cutting.

3) EDM, random surface processing.

Another reason to choose these three processes is because the techniques for their simulation are quite mature and the simulated surface profiles are very close to real surfaces. A method to simulate dressing and grinding was described by Chen et al (1996; 1996). The method developed here provides a way to simulate the wheel surface for further simulation of the grinding process. The results from the simulation demonstrate the features of a dressed grinding wheel surface, which qualitatively agrees with practical measurement. In the simulation model used in this project, the following machining conditions of the grinding process have been taken into account:

- Dressing condition, i.e. length and width of the grinding wheel, dressing depth, dressing feed rate, density of grains, etc.

- Cutting condition, i.e. grinding wheel spindle speed, workpiece feed-in rate, depth of cut, contact length of the wheel, etc.

A comparison of measured and simulated ground surface profiles is shown in Figure 6.8.

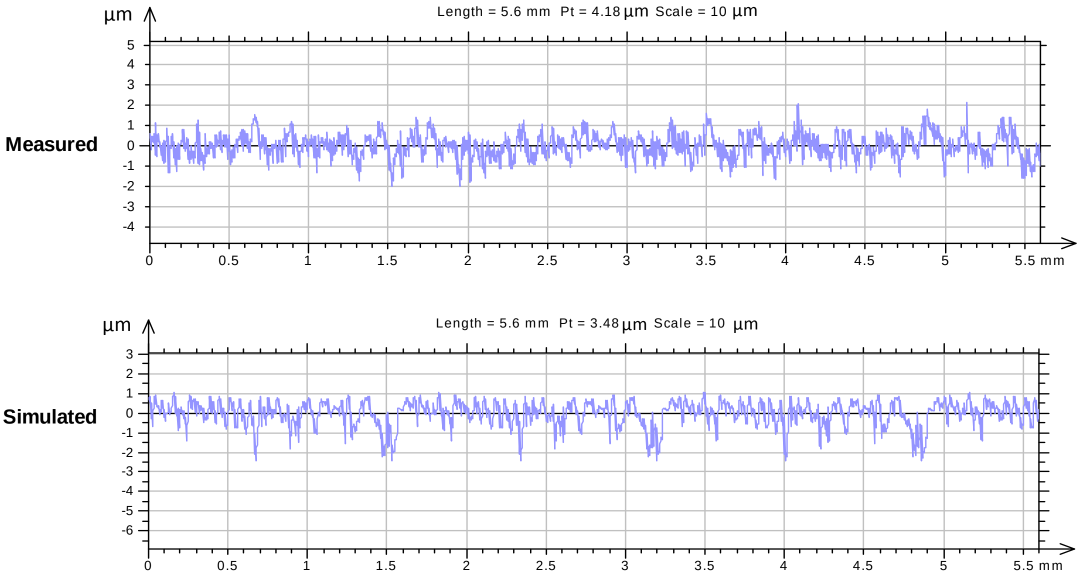


Figure 6.8 Comparison of measured and simulated ground surface profiles

Simulating a milled surface profile is based on a model developed by Liu et al (2002; 2004). The simulation and experimental results demonstrate the effect of the machine stiffness, axis forces and vibrations on the final finished surface. The simulation and experimental results show a reasonably good agreement between the measured and simulated surface profiles. In the simulation, the following machining conditions for the milling process have been taken into account: radius of workpiece; tool nose radius; cutting speed rpm; cutting angular velocity; feed rate; end cutting edge angle; and side cutting edge angle.

A numerical procedure for the simulation of a range of surface profiles has been developed by Wu (2000; 2004). The method is based on the Fast Fourier Transform (FFT), and can effectively simulate surfaces with given spectral density or auto-correlation function (ACF). Furthermore, for simulating non-Gaussian distributed surfaces, the *Rsk* and *Rku* parameters can be specified. Profiles with both Gaussian and non-Gaussian distribution spectral densities have been simulated. The Gaussian distribution and spectral density profile have a strong relationship to an EDM processed surface profile whilst a non-Gaussian distribution spectral density profile is similar to polishing or honing processes as shown in Figure 6.3. The test results prove that the *Rsk* and *Rku* parameters of simulated profiles are very close to the nominal values (see Table 6.8).

Table 6.8 Specifications used for simulated surfaces (EDM and honed) surfaces

Filename	***Function***
Cor2gau.smd	$ACF(x) = e^{-x/2}$, $Rsk = 0$, $Rku = 3$; (EDM)
Cor5gau.smd	$ACF(x) = e^{-x/5}$, $Rsk = 0$, $Rku = 3$; (EDM)
Cor5ngau.smd	$ACF(x) = e^{-x/5}$, $Rsk = -1$, $Rku = 4$; (Honed)
Cor10gau.smd	$ACF(x) = e^{-x/10}$, $Rsk = 0$, $Rku = 3$; (EDM)
Cor10ngau.smd	$ACF(x) = e^{-x/10}$, $Rsk = -1$, $Rku = 4$; (Honed)

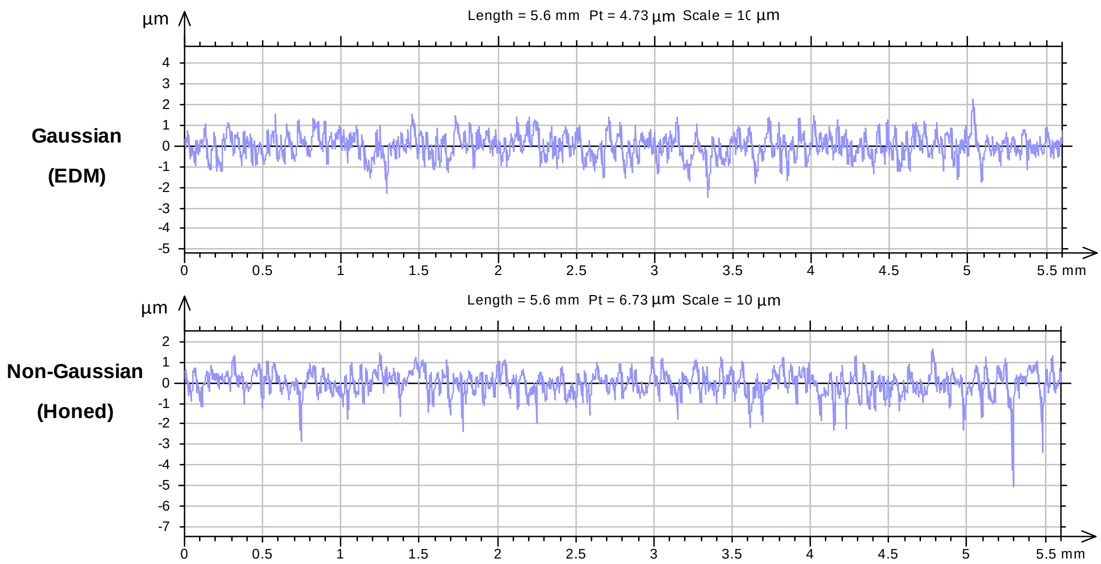


Figure 6.9 Examples of the simulated profiles with specified *Rsk* and *Rku*

6.2.3 Measured profile for reference dataset

Measurements of master workpieces are based on a good coverage of processes and emphasis is given to the consultation document (see Chapter 2). Therefore, the following manufacturing processes are given prominence as reference datasets: grinding; turning; milling; lapping; honing; EDM. For each process, three different rough surface profiles have been measured and uploaded into the reference dataset bank (see Figure 6.10 for examples).

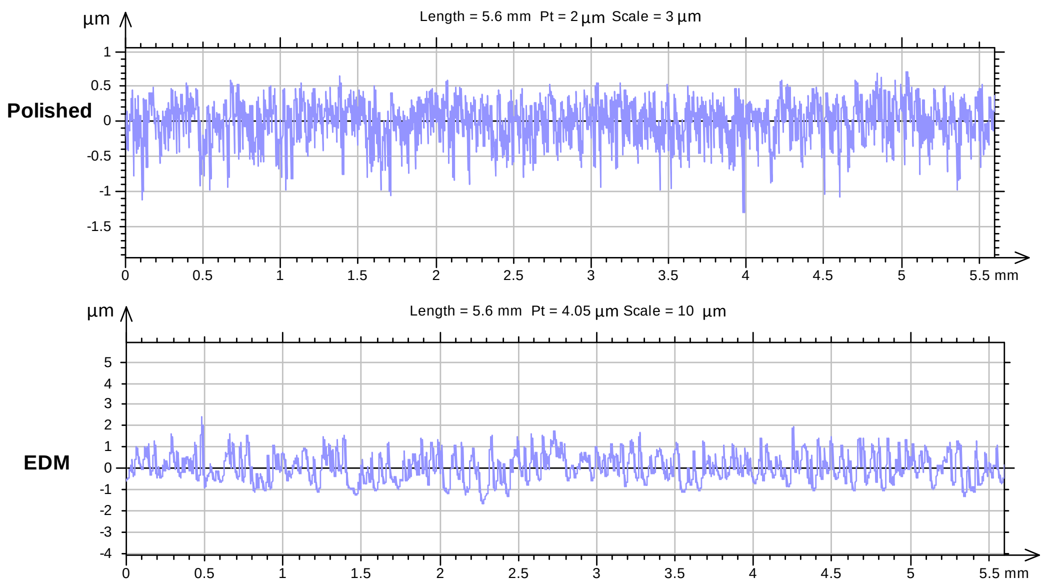


Figure 6.10 Example of the master workpiece measurements for reference datasets

6.2.4 Advanced measured profiles for reference dataset

Undertaking special modification on a measured profile is an effective method to predict the performance of an engineered surface. It can also be used to check the robust and stability of a software algorithm by comparing the results obtained from a measured profile with its modified counterpart. The data modifications include the following.

Inversion

Inversion provides a detailed view of the surface valleys in the inverted form. The feature is of particular use in revealing features in lubrication and wear analysis where the extent of the surface structure is of importance. It also reveals the effect of using of replica on engineered surfaces.

Truncation

The truncation is often used both to predict controlled wear behaviour of surfaces in a tribological environment and to examine sub-surface textures. A measured surface profile can be truncated to any pre-determined level and then analysed in any of the previously mentioned modes. Stout et al (1990) revealed the effects of 30% and 70% truncation on most of the machined surfaces. The pre-determined level, 30% and 70%, are used to produce the truncation counterpart of the measured profiles in this project.

Revision

This reveals the stability of a parameter algorithm by changing the order of measured data point to simulate different measurement direction.

One point shifting

This provides evidence on the robust of the algorithm by applying a tiny change on a measured profile, removing the first measurement point and adding an extra point at the end of file.

A modification tool is developed and provided in this project website. A user can upload their measured data file and download the modified counterparts.

6.3 Reference results

One of the key issue needs to be addressed is how to produce the reference results for reference datasets. The certified values, provided in type F1 softgauges, give an absolute reference for all production software in the UK. Thus, their accuracy and reliability are of critical importance.

In a mathematically well-defined model, the higher accuracy can be achieved by using both a high precision processor and data. NIST implemented this method to produce the Statistical Reference Datasets (StRD) to benchmark statistical software package. The reference results were obtained from a multiple precision FORTRAN pre-processor and reference data sets with 500 decimal digits of accuracy. It has been used to benchmark many well-known statistical software packages such as Microsoft Excel (version: 97, 2000, XP, 2003, 2007) (McCullough 1998; McCullough and Wilson 1999; McCullough and Wilson 2005; McCullough and Heiser 2008). Another method is to start with some reference results and produce the corresponding reference data set by a data generator through the null-space approach (Cox and Harris 1999). NPL has implemented this approach to test a range of software packages (Harris, Lines et al. 2006; Lines, Onakunle et al. 2007).

These methods are too advance and unsuitable for this project due to the following:

- These methods are developed for investigating the fitness for the purpose of a software implementation of an algorithm to solve a specified, and well-defined, mathematical model. Unfortunately, there are significant model uncertainties of the software of surface measuring systems as discussed in Chapter 5.

- The indication of a surface texture parameter is normally only needed two or three decimal digits of accuracy. Thus, using an extra high precision method (both processor and data) is too advanced for this project.

Based on the lessons learn from the use of hardgauges (see Chapter 2), there are three methods to provide reference values.

1) In a national measurement system, reference values are produced by a primary software package, i.e. a type F2 softgauge.

2) In international comparisons among NMIs, the reference values are often produced by the mean of the results obtained from different primary software.

3) In addition, for type F1 softgauges in the simple form of function, the reference values can be calculated by algebraic calculation.

The first method is widely used for providing certified value for hardgauges. As discussed in Chapter 2, a primary instrument provides an absolutely interpretation of concept of the unit. In this project, all reference values of type F1 softgauges are produced by NPL's type F2 softgauge which is the primary software in the UK.

Due to the model uncertainty and code uncertainty as discussed in Chapter 5, varied certified values could be obtained from different type F2 softgauges when they assess a type F1 softgauge. The second method will be used to produce reference values in inter-comparison, which will be presented in Chapter 7. However, this value is unsuitable as certificated value of type F1 softgauges due to it contain the model uncertainty and code uncertainty among NMIs.

The third method will be used in internal test of the F2 softgauges. According to the duality principle, the measurand is defined in a specification chain as results of a specification operator. Modern computing tools like MAPLE (algebraic computation) and MATLAB (a numerical computation and visualization program) make it possible to solve realistic nontrivial problems in scientific computing. Using MAPLE, algebraic calculation can provide an initial result to cross-check results with the type F2 softgauges. The procedure is illustrated in Figure 6.11. Firstly, Matlab generates the discrete reference dataset according to the defined function; then the same function is calculated in Maple and takes the algebraic form of both profile and parameter functions. The most important aspect of this algebraic calculation is that a 'true value' is calculated from MAPLE by use of the algebraic form of the function.

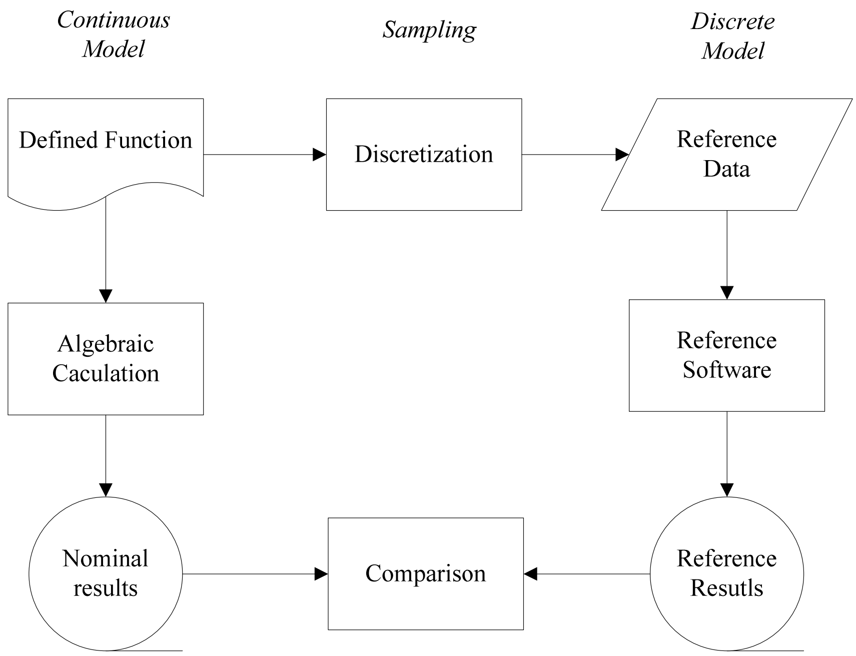


Figure 6.11 Diagram of the use of algebraic calculation

For example, in the case of algebraic calculating the *Pa* parameter of the "sin1" profile, the executed code in the MAPLE will compute the profile parameter given the definition of the *Pa* parameter as

$$Pa = \frac{1}{l}\int_0^l |Z(x)|dx = \frac{1}{l}\int_0^l \left|\sin(\frac{2\pi}{\lambda})\right|dx \text{, with } l = 5.6 \text{ mm; } \lambda = 0.16 \text{ mm.}$$

However, the algebraic calculation is limited to those generated profiles with simple functions. For the more complex functions, the equivalent MAPLE function (in algebraic form) of the MATLAB function (in numerical form) is too difficult to apply. The results obtained from the algebraic calculations are used for cross checking the values obtained from the reference software and are purely used as an internal tool for development of type F1 softgauges.

6.4 Uncertainty

The associated uncertainty is key part of a measurement standard. However, as discussed in Chapter 3, the software uncertainty (i.e. model uncertainty and code uncertainty) is different from the traditional meaning of measurement uncertainty (i.e. data uncertainty). The introduction of definitional uncertainty in the VIM3 and specification uncertainty in the GPS make difficult in the evaluation, even understanding, of measurement uncertainty.

To make it clearer, the measurement uncertainty can be decomposed in several dimensions as shown in Figure 6.12. The data uncertainty is traditional meaning of measurement uncertainty in the metrical dimension. The specification uncertainty is the uncertainty in the communication level in the translational dimension. The definitional uncertainty is the uncertainty in cognise level in structural dimension.

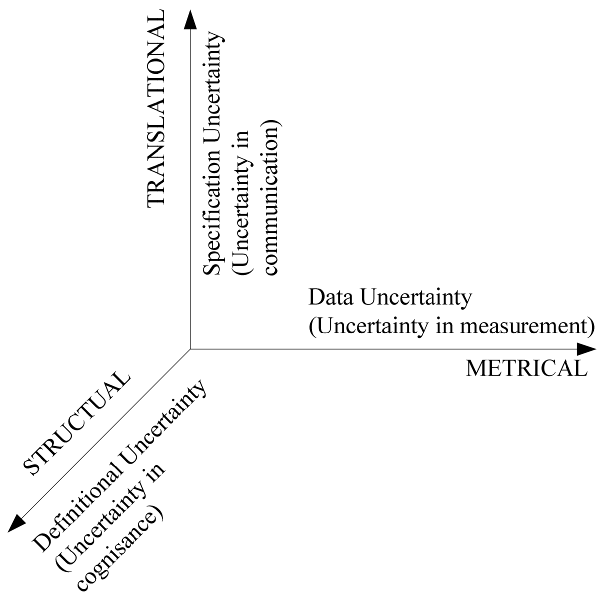


Figure 6.12 Dimensions of measurement uncertainty [Adapt from Rowe (1994)]

It is different of the nature of each class of uncertainty. Rowe (1994) summarises their parameters and evaluation methods as shown in Table 6.9. They should be addressed separately first, then assessing their interaction. For the uncertainty in translational and structural dimension, many modern theories of uncertainty-based information have been developed, such as possibility theory, evidence theory, fuzzy set theory, and imprecise probability theory. However, these theories are not well developed when compared with probabilistic inference (Oberkampf, DeLand et al. 2002). So none of these theories, except fuzzy set theory, has been applied the engineering analysis problems.

Table 6.9 Parameters of the classes of uncertainty (Rowe 1994)

Uncertainty class	*Unknown information*	*Discriminator parameter*	*Valuation parameter*	*Evaluation methods*
Metrical	Measurement	Precision	Accuracy	Statistics
Translational	Perspective	Goals/Values	Understanding	Communication
Structural	Complexity	Usefulness	Confidence	Models

Some case studies have been proposed to study the uncertainty in communication level. For example, Lu et al. (2008) proposed an evaluation approach for compliance uncertainty through a case study on the diameter characteristics. As illustrated in Figure 6.13, the compliance uncertainty is evaluated by three steps. They are: 1) listing all possible interpretations of a specification; 2) evaluating the implementation uncertainty of each method by the GUM's method; and 3) combining uncertainty by the GUM's method.

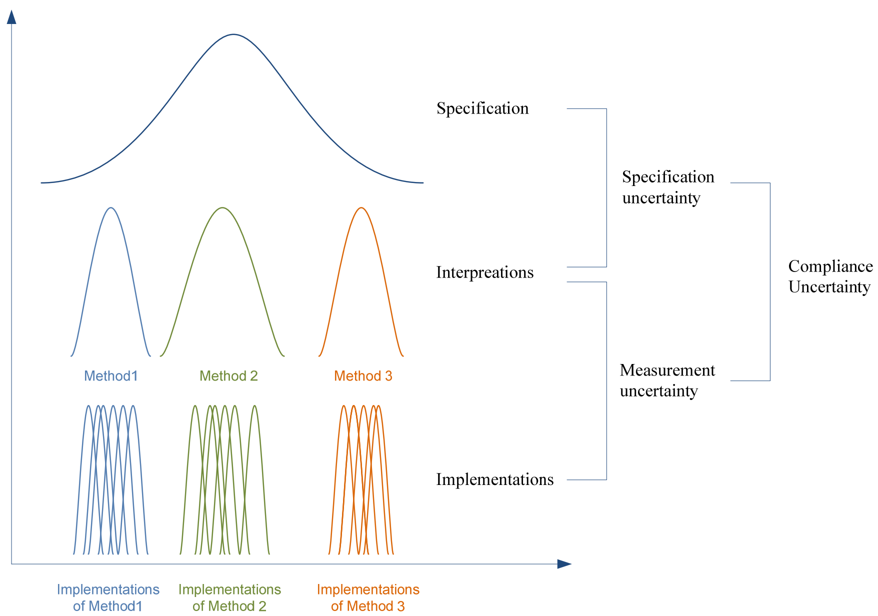


Figure 6.13 A method to calculate compliance uncertainty

This approach shows a possible way to estimate the effect of model uncertainty and code uncertainty of software on the measurement results. However, this approach is relative immature and the calculation is time-consumed. Some of the questions for this approach are: 1) it is impossible to predict all interpretations in complex case such as surface measurement; 2) each interpretation should have different weight according to the possibility of their appearance (this approach assumes all interpretations has same weight; Thus, a rarely used interpretation could have the same effect as a dominated interpretation on the final uncertainty result). In addition, the effect varies on applications.

Therefore, it is too advanced to calculate rigorous uncertainty value for the model uncertainty and code uncertainty. Fortunately, a procedure for uncertainty Management (PUMA) is proposed in ISO/TS 14253-2 (1999). In a given measurement process, it is used iterative method to refine the estimation of the dominate contributors to move towards to a true estimate of uncertainty components. For design and development of a measurement procedure, a procedure is developed based on a given measuring task and a given target uncertainty. This project will use the PUMA method to manage the model uncertainty and code uncertainty by setting up a task uncertainty (a certain ratio of data uncertainty) via some case studies.

6.5 Conclusions

Based on the reviewing results from the industry consolation and general manufacturing surface, a methodology of designing type F1 softgauges has been developed and a subset of F1 reference datasets has been generated. The method of the producing the reference value has been proposed. The concept of algebraic calculation has been introduced to provide theoretical and traceable results for the mathematically generated reference datasets. The algebraic calculation strictly follows the parameter definitions as given in ISO standards and is an important tool for cross-checking with type F2 softgauges.

7 Use of softgauges

This chapter purpose to demonstrate the usage of the developed type F1 softgauges. Section 7.1 develops guidance for a user to set up minimum requirements for the calibration of surface metrological software. The developed type F1 softgauges are used to verify the type F2 softgauges in Section 7.2. The verified type F2 softgauges are utilised to calibrate the commercial software packages in Section 7.3. Section 7.4 addresses end-users' requirements by undertaking two case studies to demonstrate the evaluation of measurement uncertainty with the aid of softgauges.

7.1 Calibration procedure for surface metrological software

The calibration procedure of surface profile (stylus) instrument has been standardised (ISO 12179 2000). In areal surface texture characterisation, calibration procedure of stylus instruments, optical instruments and AFM has been proposed (Kuhle 2003; Ville 2003). These publications focus on calibration of surface measuring instruments by using hardgauges only. Their calibration strategy is to identify the main components, to calibrate each of components separately, to estimate of corresponding uncertainty of each component, to combine these uncertainties and to report it. In addition, influential condition needs take into consideration (for example, temperate is not a component, but an influential condition, of length measurement).

The requirements of software calibration have been emphasised (Song and Vorburger 1991; Vorburger, Song et al. 1996). Mainsah et al. (1995) proposed a holistic approach in the calibration procedure of areal surface texture measuring instruments. This approach advocated a routine in the following order: 1) validating software; 2) calibrating translational table; 3) calibrating magnification and condition of the probe; 4) calibrating overall performance. Based on these studies, it can be agreed that software should be the first component to be calibrated in the calibration procedure of any type surface measuring instruments. The reasons are listed as follows:

1) The reliability of measurement results of a hardgauge is greatly relied on the reliability of the software. Many hardgauges, such as type C and type D, provides the certified value in the form of surface parameters.

2) Softgauges can replace some functions of the hardgauges with less cost both in time and labour.

In the calibration of software, the major method is through black-box testing. *Black-box testing* refers to the testing when only the inputs and outputs of the software are observable (it requires no detailed knowledge of the software code, although such knowledge can certainly help) (Beizer and Wiley 2002).

As discussed in Chapter 3, there are two ways to calibrate production software by the aid of softgauges: 1) via the use of type F2 softgauges; 2) via the use of type F1 softgauges. The end-users often only want to know the overall performance of their software. It is recommended that end-users calibrate their software via first way. Instrument manufacturers should calibrate their instruments via both ways in order to gain much evidence of traceability of the software of their instruments.

7.1.1 Scope

This proposed procedure applies to the calibration of the metrological characteristics of the software employed within contact (stylus) instruments for the measurement of surface texture by the profile method as defined in ISO 3274 (1996), the parameters defined in ISO 4287 (1997), the filter defined in ISO 11562 (1996) and the measurement conditions defined in ISO 4288 (1996). The calibration is to be carried out with the aid of software measurement standards, i.e. type F1 softgauges.

For the ambiguous concepts within above ISO standard documents, NPL's interpretation, distributed in this project website, is the key reference which provides the absolute interpretations of these concepts.

7.1.2 Condition of use

Surface metrological software shall be calibrated when an update is undertaken.

7.1.3 Software measurement standards

The following software measurement standards, i.e. type F1 softgauges, are applicable to the calibrations given in the following sections:

- Synthetic sine & cosine wave profiles;
- Measured profiles on a typical engineering surface with their modified counterparts, such as the treatments of inversion, truncation, revision and shifting.

7.1.4 Calibration

7.1.4.1 Preparation for calibration

Before calibration, the software shall be checked to determine if it operates correctly as described in the manufacturer's operation instructions. For surface (profile) software the following shall be complied with.

- The protocol of softgauges, in the form of SMD file format, is defined in ISO 5436-2 (2000). A conversion tool can be used to convert this standardised file format to a file format used by the software. It should bear in mind that error may be introduced by this operation.
- The conditions used to assess type F1 softgauges shall be compatible with these used to certify those softgauges. The conditions are expressed via an ordered set of operations which is adhered the latest GPS language.

7.1.4.2 Calibration of Gaussian filter

Overall objective

Determine the deviations from the use of Gaussian filter.

Procedure

The filtration is calibrated by comparing the amplitude parameters (e.g. *Ra* and *Pa*) of a series of sine wave profiles produced by using mathematical simulations with their nominal value. An alternative is to use a series of cosine wave profiles in order to avoid the possible distortions caused by levelling operation.

In addition, a spike profile can provide useful information of respond of the filter. However, software packages may not deliver the results for this profile.

7.1.4.3 Calibration of the field parameters

Overall objective

Determine the deviations from the implementation of the algorithms of field parameters.

Procedure

The algorithms of field parameters are calibrated by comparing the amplitude parameters of mathematical defined profiles with their nominal values.

An alternative is to use some measured profiles obtained from some typical surfaces. It should limit the possible deviation contributed by the filtration operation.

7.1.4.4 Calibration of the feature parameters

Overall objective

Determine the deviations from the implementation of the algorithms of the feature parameters.

Procedure

The algorithms for feature parameters are calibrated by comparing the amplitude parameters obtained from the following type F1 softgauges with their nominal values.

- A cosine wave profile is used to check the algorithm for incomplete feature;
- Some measured profiles obtain from some typical surfaces. It should limit the possible deviation contributed by the filtration operation.

7.1.4.5 Calibration of total software

Overall objective

Determine the reliability and stability from the implementation of algorithms.

Procedure

The software is calibrated by comparing all parameters obtained from the following type F1 softgauges with their expected values.

- Measured profiles obtained from some typical surfaces with their revision counterpart. A reliable software package should deliver very closer results.
- Measured profiles obtain from some typical surfaces with its one point shifting counterpart. It expects no significant difference between their results.

7.1.5 Uncertainty

Since uncertainty varies from application to application and depends on the user's instrument and measurement condition, type F1 softgauges only provide certified values without associated uncertainty. The uncertainty of software is studied within the specified environment via the case studies that are undertaken in Section 7.4.

7.1.6 Decision rule

A key question concerns the comparison between the test results (obtained from the test software) and certified value (provide by Softgauges). The comparison should be objective and address the requirements of the application. The result of the comparison is the means by which a decision is made about the fitness-for-purpose of test software.

If y^{test} and y^{ref} denote, respectively, the test and reference results, then

$$d_A\left(y^{test}, y^{ref}\right) = \left|y^{test} - y^{ref}\right|,$$

and, for $y^{ref} \neq 0$,

$$d_R\left(y^{test}, y^{ref}\right) = \frac{\left|y^{test} - y^{ref}\right|}{\left|y^{ref}\right|},$$

are metrics for the numerical correctness of the test result that measure, respectively, the absolute and relative differences between the test and reference results. It is unnecessary (and perhaps unreasonable) to expect that the absolute difference between the test and reference results is comparable to the computational precision of the arithmetic used to deliver the test result. If the developer of the software has made a claim about the numerical correctness of the results returned by the software, then this can be used as the basis for setting a tolerance against which to compare the calculated value of the absolute difference. If the user of the software has documented a requirement on the numerical correctness of the result, then this can also be used as a basis of the comparison. If the data uncertainty associated with the test result is available (evaluated in terms of the uncertainties associated with the measured data defining the surface profile), then it may be sufficient to require that the calculated value of the absolute difference is smaller (by several orders of magnitude, say) than this data uncertainty.

A well known principle in metrology is the "weakness chain" principle - a chain is as strong as its weakness part. Therefore, fitness for the purpose can also mean that the effects arising from the use of the approximate mathematical model, approximate algorithm, *etc.* are quantitatively small compared to those effects arising from the data.

7.2 Verification of the type F2 softgauges

7.2.1 Objectives

As discussed in Chapter 2, some web-based type F2 softgauges have already been developed separately by NMIs in the UK, Germany, the United States and China (Jung, Spranger et al. 2004; Nie, Liu et al. 2006; Bui and Vorburger 2007; Blunt, Jiang et al. 2008). These type F2 softgauges claimed that they have been developed to high standards and been thoroughly tested with some self-evidence. NIST also compared its type F2 softgauge with some commercial packages (Bui, Renegar et al. 2004). The results of this comparison showed that there is agreement in some parameters and disagreements on others. Therefore, there are some of the questions that need to be addressed before these type F2 standards can safely and reliably be used. Some important questions are:

1) Is it safe to ignore calibration software?

2) Do those type F2 standards qualify to be used as calibration tools?

3) How does one make a judgement when there is a discrepancy between an industrial software package and a type F2 standard, or even between two type F2 standards?

To address those questions, this section undertakes an inter-comparison between the three NMI's type F2 softgauges with the aid of type F1 softgauges. The next section undertakes a calibration of four commercial software packages by NPL's softgauges.

This comparison follows the proposed calibration procedure in the previous section with the aid of some developed type F1 softgauges. It purposes to provide evidence on the following objectives:

– **Adherence to ISO documents**: As the realisations of the ISO standardised metrology concept, it should strictly adhere to the ISO document.

– **Accuracy and Reliability**: As the primary software, their accuracy and reliability are of extremely importance. It expects that they deliver the results closer to the "true value" than commercial software.

7.2.2 Preparation of calibration

The measurement conditions used in this comparison are detailed in Appendix 2. [NIST], [PTB] and [NPL] have some differences in their interpretations of the ISO standard documents. Most of them were detailed in Chapter 5. The detailed descriptions of the type F2 softgauges are available online (see Table 5.2). In addition, three widely commercial software packages, developed in three different countries, were used in this comparison. They are named as CA, CB and CC for commercial protection. In this thesis, the square brackets refer to the associated software packages.

7.2.3 Selected type F1 softgauges

Six type F1 softgauges (see Table 7.1), as transfer standards, were selected in this comparison. Type F1 softgauge cos.smd is a cosine wave with a wavelength of 160 μm and amplitude of 2 μm. Its reference results are obtained from an algebraic calculation in Maple 10.03. Four measured surface profiles were selected to represent industrial requirements according to the survey (see Chapter 2). Their *reference results* are the non-weighted mean of results obtained from the three type F2 softgauges.

Table 7.1 List of selected type F1 Softgauges

Softgauges	*Description*
Cos.smd	A cosinusoidal profile
EDM.smd	Measured profile of an EDM surface
Mill.smd	Measured profile of a milled surface
Ground.smd	Measured profile of a ground surface
Ground2.smd	Same data set as Ground.smd with the order of the data points reversed to simulate the opposite measuring direction.
Polish.smd	Measured profile of a polished surface

7.2.4 Calibration

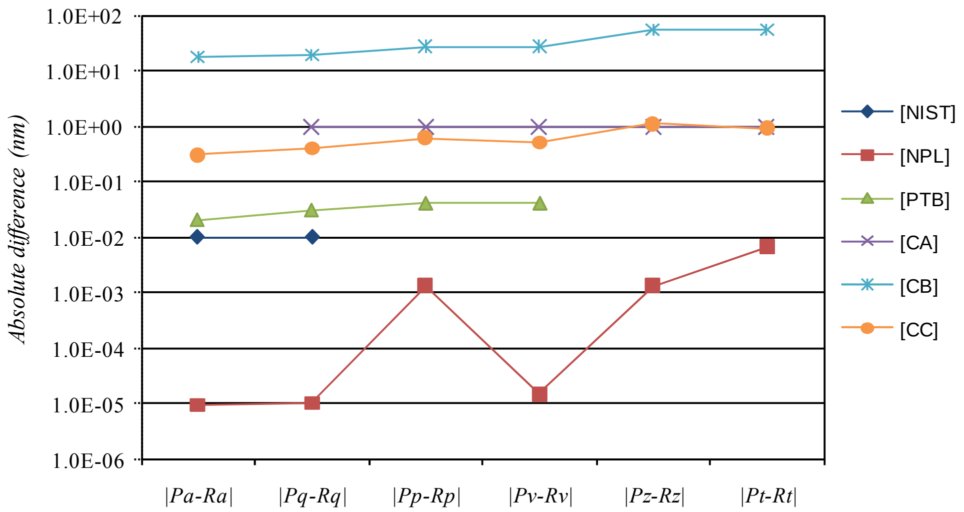
7.2.4.1 Calibration of Gaussian filter

The transmission characteristic of a filter indicates the amount by which the amplitude of a sinusoidal profile is attenuated as a function of wavelength. According to ISO 11562, the filter characteristic of the data file Cos.smd is calculated as

$$\frac{a_2}{a_0} = 1 - e^{-\pi\left(\frac{0.4697\times 0.8mm}{0.16mm}\right)^2} \approx 0.999999970175$$

where a_2 is the amplitude of the filtered profile, and a_0 is the amplitude of the cosine wave profile before filtering.

The measured data only provides six significant digits. Thus, there is no significant difference between the results of *P*-parameters and *R*-parameters obtained from the data file Cos.smd. Figure 7.1 presents these testing results. Three type F2 softgauges perform well with less than 0.1 nm absolute differences. They all deliver fewer errors than commercial packages.



Note: 1.There are some missing points due to zero values cannot be plotted in this log chart.
2. Some results may be overstated or understated due to rounding effect.

Figure 7.1 Assessment of Gaussian filtering

7.2.4.2 Calibration of field parameter

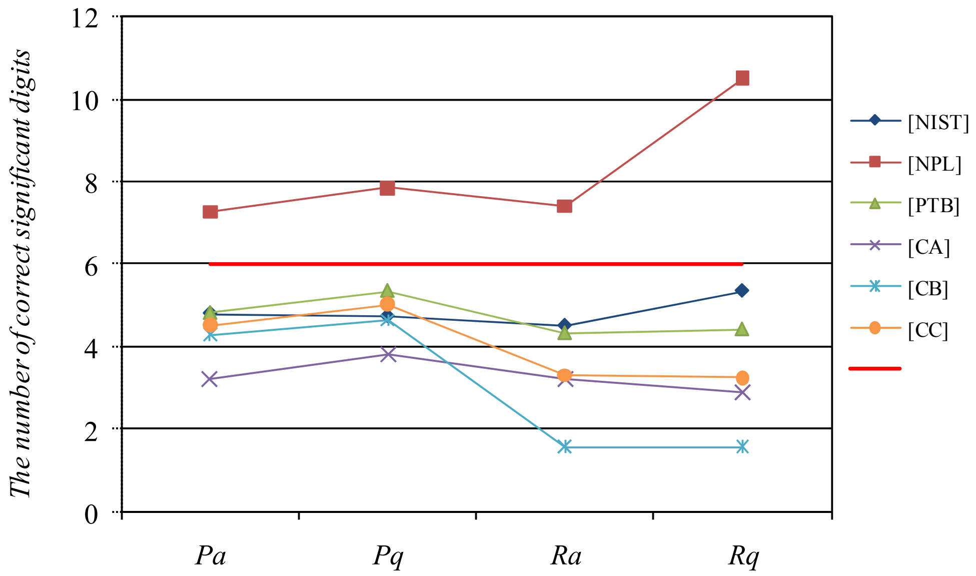
Accuracy

The number of correct significant digits obtained from the test software is calculated by the *log relative error* (LRE) as

$$LRE = -\log_{10}\left(\frac{y_{test} - y_{ref}}{y_{ref}}\right) \quad \textbf{(7.1)}$$

where the y_{test} is the result obtained from the test software, and y_{ref} is the expected results obtained from an algebraic calculation (e.g. if y_{ref}= 0.636619 and y_{test} = 0.6363, then LRE=4.8) [33].

Figure 7.2 shows the LRE obtained from all software implementations. [PTB] and [NIST] give results where only last digits are inaccurate. [NPL] delivers seven to ten accurate significant digits in this case, even higher than the precision of measuring data. They all perform better than commercial packages.



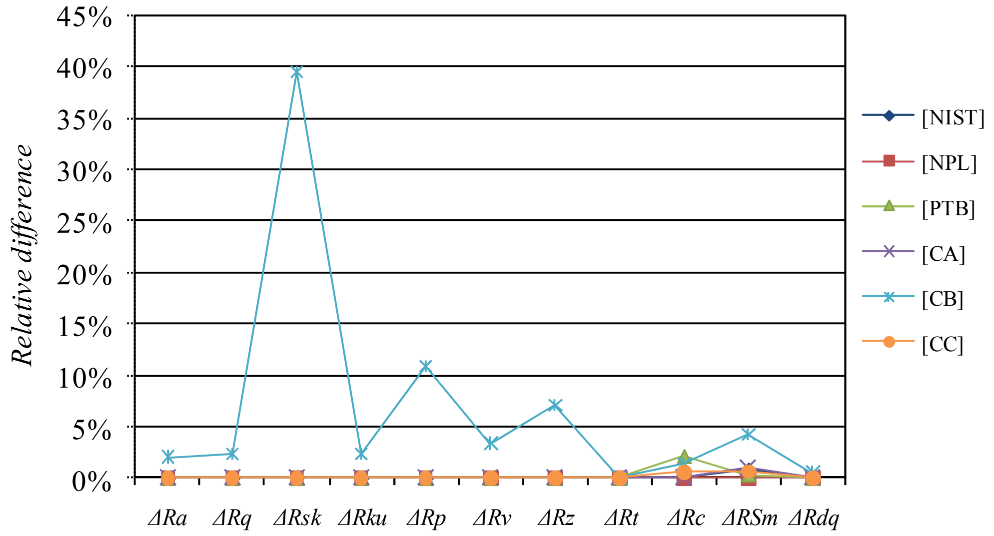
Note: The red line indicates the significant digits of the measuring data within data file

Figure 7.2 The number of the correct significant digits

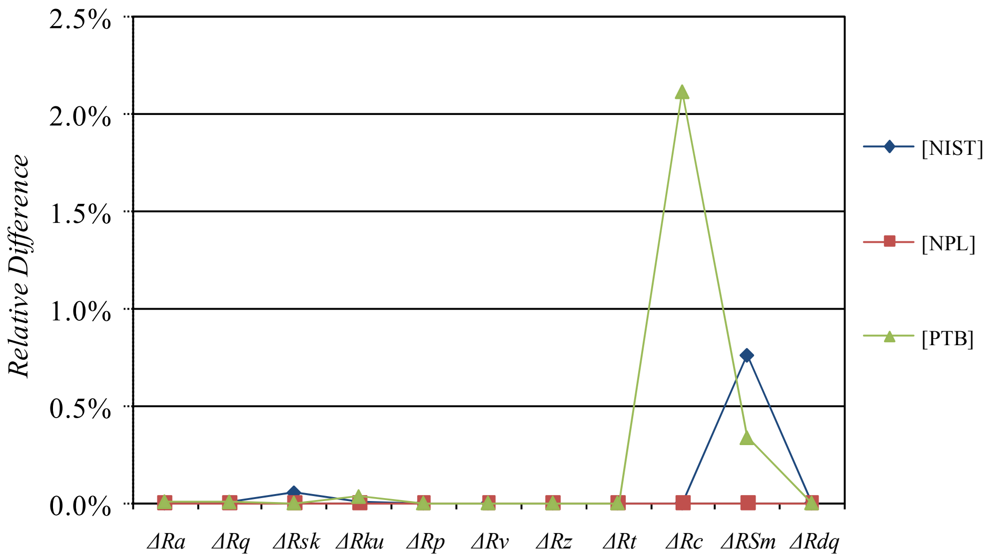
Stability

Figure 7.3 presents the stability of parameters by comparing the results obtained from Ground.smd and Ground2.smd that are same data set with a different order to simulate difference measurement directions. For [NIST] and [PTB], the relative difference of *Ra*, *Rq*, *Rsk*, *Rp*, *Rv*, *Rz*, *Rt* and *Rdq* fall with the range of 0.05 %. [NPL] performs well in this test with same results obtained from the pair of profiles.

[33] McCullough (1999) provides further details on measuring numerical accuracy.



(a)



(b)

Figure 7.3 The effect of the direction

7.2.4.3 Calibration of feature parameters

PSm/RSm

The value of PSm/RSm should be 160 µm, which is the "true" value for this cosine wave. If we strictly adhere to ISO 4287: 1997, to evaluate within every sampling length and discard incomplete portions at the end of sampling length,

RSm = 152 µm and PSm = 158.857 µm.

If, following ASME B46.1-2002, we evaluate within the evaluation length and discard incomplete portions at the end of evaluation length,

RSm = 158.4 µm.

If we use the interval-based length definition to define the sampling length, and the point-based length definition to calculate the width of a profile element within each sampling length, and discard the incomplete portions at each ends,

RSm = 159.95 µm.

If we use the interval-based length definition to define the evaluation length, and the point-based length definition to calculate the width of a profile element within the evaluation length, and discard the incomplete portions at each ends,

RSm = 159.99 µm.

Table 7.2 presents the PSm/RSm results for Cos.smd. [PTB] and [NPL] performs well in this test. [PTB] delivers a small error due to a different length definition. The results obtained from three type F2 softgauges are closer the "true value" than the commercial package [CB] and [CC].

Table 7.2 Influence of the incomplete portion for *RSm* and *PSm*

	PSm (µm)	*RSm (µm)*
NIST	160.00	160.00
NPL	160.00	160.00
PTB	159.99	159.99
CA	-	160.00
CB	**158.89**	**156.01**
CC	**158.86**	**158.40**

Stability

As illustrated in Figure 7.3, there are noticeable difference results of *Rc* and *RSm* delivered by [NIST] and [PTB] (in the range of 0.76% and 2.1%). [NPL] performs well in this test.

7.2.4.4 Calibration of total software

Table 7.3 and Table 7.4 present the percentage of coefficients of variation among the three type F2 softgauges and three commercial packages. For the three type F2 softgauges, most of the relative differences are less than 0.5 %. [NPL] delivers slightly greater values of *Rp*, *Rv*, *Rz*, *Rt*, *Pp*, *Pv*, *Pz* and *Pt* due to its interpolating method, and only one result is greater than 0.5 % (*Rp* for Polish.smd). For *PSm*, *RSm*, *Pc* and *Rc*, variations are significant (Figure 7.4 - Figure 7.7) as the result of ambiguous definition (see Chapter 4). Together with the three commercial packages, most of the relative differences for *R*-parameters are more than 0.5 %.

Table 7.3 Percentage of coefficients of variation among three type F2 standards

Softgauges	*Ra*	*Rq*	*Rsk*	*Rku*	*Rp*	*Rv*	*Rz*	*Rt*	*Rc*	*RSm*	*Rdq*
Cos.smd	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
EDM.smd	0.00	0.14	0.19	0.06	0.05	0.06	0.06	0.05	**3.18**	**6.95**	0.02
Mill.smd	0.00	0.15	0.12	0.01	0.14	0.18	0.16	0.13	**3.78**	**7.10**	0.07
Polish.smd	0.01	0.13	0.03	0.02	0.38	0.13	0.17	0.15	**10.76**	**24.98**	0.04
Ground.smd	0.00	0.25	0.13	0.00	0.05	0.03	0.04	0.02	**6.39**	**16.66**	0.01

Table 7.4 Percentage of coefficients of variation among three type F2 standards and commercial packages

Softgauges	*Ra*	*Rq*	*Rsk*	*Rku*	*Rp*	*Rv*	*Rz*	*Rt*	*Rc*	*RSm*	*Rdq*
Cos.smd	**1.03**	**1.02**	-	0.00	**1.03**	**1.03**	**1.02**	**1.02**	**1.72**	0.93	**1.13**
EDM.smd	**1.03**	**1.36**	**30.17**	0.89	**7.10**	**5.65**	**2.71**	0.60	**6.10**	**9.08**	**2.31**
Mill.smd	**2.60**	**2.32**	**8.19**	**2.85**	**5.59**	**12.28**	**1.69**	**1.19**	**6.25**	**45.41**	**17.17**
Polish.smd	**1.03**	**1.21**	**1.29**	**1.98**	**7.30**	**7.95**	**3.11**	**1.24**	**13.66**	**33.77**	**9.12**
Ground.smd	0.80	0.84	**15.90**	**2.12**	**13.90**	**7.03**	**1.24**	**0.62**	**9.91**	**22.30**	**4.37**

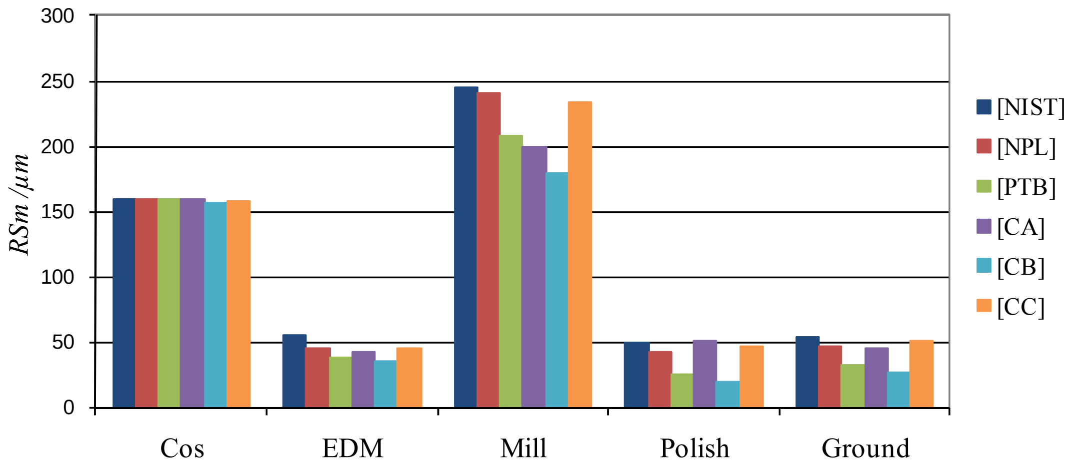


Figure 7.4 Results of parameter RSm

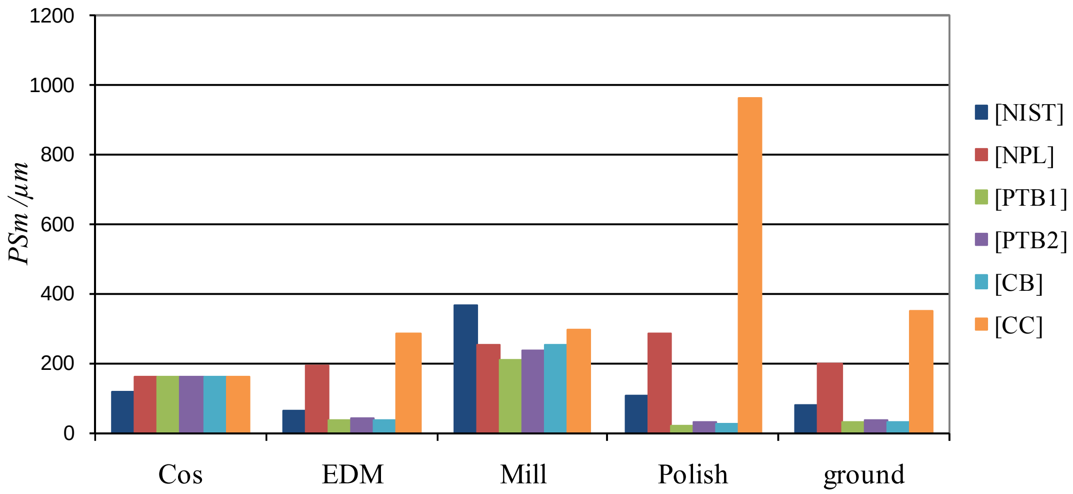


Figure 7.5 Results of parameter PSm

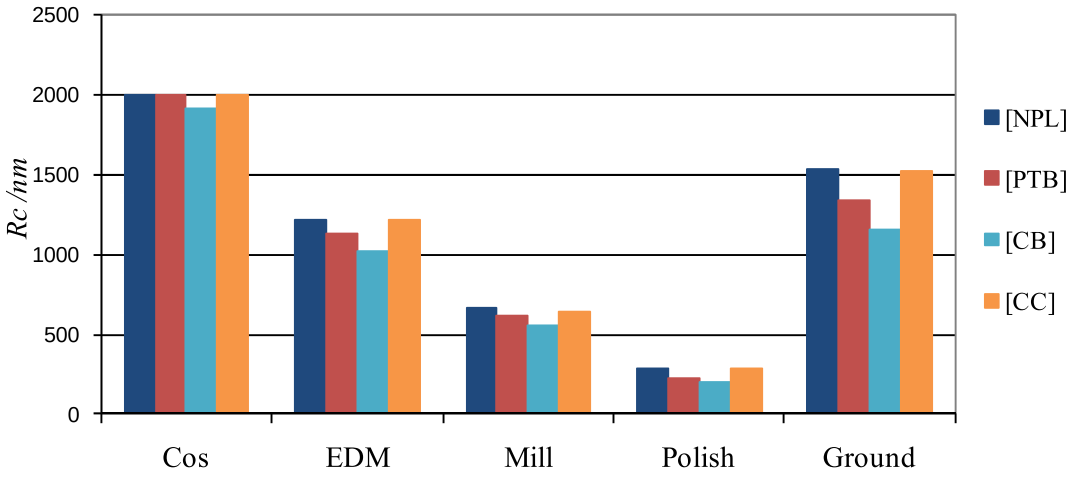


Figure 7.6 Results of parameter Rc

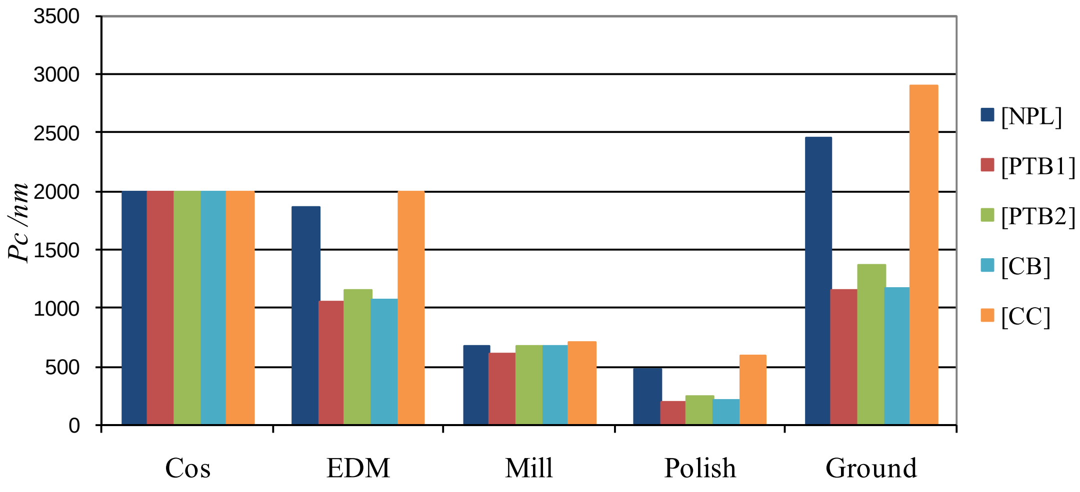


Figure 7.7 Results of parameter Pc

7.2.5 Performance metrics

Sinusoidal artefacts have been widely used in the calibration of surface measuring instruments, since they were introduced by Sharman (1967). Sinusoids are insensitive to many measurement conditions. Some research comparison results are listed in Table 7.5. To reproduce these research results, the effect of software should be of insignificance. The metric for *Ra* is set based on the reproducibility of those results from the software aspect.

Table 7.5 The performance metrics for Cos.smd

No	Reference[1]	Metric for Ra[2]
1	Haitjema (1998) has estimated the uncertainty of roughness parameters using a styles instrument. It shows that the uncertainty of *Ra* and *RSm* for a sinusoidal artefact (nominal *Ra*: 2.9 µm and *RSm*: 100 µm) are 0.25 % and 0.03 % (at 95 % confidence).	0.04 %
2	[NIST] is able to simulate the measurement error by adding the normal distributed random noise to each data point. The uncertainty of *Ra* and *RSm* for Cos.smd (nominal *Ra*: 636.62 nm and *RSm*: 160 µm) is ± 2.68 nm and ± 6.97 µm (at 95 % confidence).	0.07 %
3	Vorburger et. al.(2007) has undertaken a comparison between optical and stylus methods. For a sinusoidal specimen (nominal *Ra*: 500 nm and *RSm*: 50 µm), the difference of *Sa value and Ra* value is 6 nm obtained from difference type of instruments.	0.1 %
4	Thomas and Charlton (1981) has investigated the (in)homogeneity of some typical manufactured surfaces. The variation of 1.8~3 % for *Ra* are found on RTH reference standards (Two-dimension sinusoidal surfaces, nominal *Ra*: 0.27 µm).	0.6 %

Note: [1]. Based on the assumption that software used in this research work is qualified.

[2]. The pass margin set as 1/3 of value of uncertainty and 1/10 of absolute difference.

Table 7.6 presents the performance of test software for *Ra* of Cos.smd. It indicated that the three type F2 softgauges could be used to reproduce all the measurement tasks listed in Table 7.5.

Table 7.6 The performance of software implementations, assessed by the effect of the reproducibility of measurement tasks listed in Table 7.5

	Tasks
[NIST]	1;2;3;4
[NPL]	1;2;3;4
[PTB]	1;2;3;4
[CA]	2;3;4
[CB]	NONE
[CC]	2;3;4

Table 7.7 lists the percentage coefficients of variation from place to place on a manufactured surface studied by Thomas (1981). ISO 4288 introduces the "The 16 %-rule" and "The max.-rule" for comparison of the measured values within tolerance limits. For the measured profiles used in this comparison, we provide six significant digits that include false precision and guard digits. For measured profiles, the software effect is considered as insignificant when the relative difference of results obtains from the test software and a reference result is less than 0.5 %. Therefore, we set the "pass margin" as 0.5 % in this comparison. Most of results obtained from three type F2 softgauges have passed (see Table 7.3 and Table 7.4).

Table 7.7 Percentage coefficients of variation from place to place on a manufactured surface (Thomas and Charlton 1981)

	Milled	*Ground*
Ra /%	17 ~ 65	7~80
Rq /%	15 ~ 61	9 ~ 56
Rsk*	0.35 ~ 0.75	0.22 ~ 0.73

Note: * which is an absolute value)

7.2.6 Conclusions

To address the questions arisen at beginning of this section, conclusions of the comparison are listed as follows:

1) Is it safe to ignore calibration software?

For commercial packages, the results indicate that software is a primary contributor to variability in the results of surface profile measurement. One commercial software package delivered significantly different results. The variation of the results obtained from these software packages is even greater than the variation caused by the surface inhomogeneity, variation of measurement environment and different data collection methods. Therefore, it is not safe to ignore the calibration of software embedded within a surface measuring instrument

2) Do those type F2 standards qualify to be used as calibration tools?

In general the results for *R*-parameters obtained from the three type F2 softgauges are in good agreement. The exceptions are the *RSm* and *Rc* parameters. The three type F2 softgauges performed better than the three commercial packages by giving high precision results and their specifications adhere closely to ISO standards. Some particular conclusions are as follows:

- The current specifications of parameters *Ra, Rq, Rsk, Rp, Rt* and *Rz* are clearly defined and stable. The three type F2 software standards are qualified to provide accredited results for those parameters of commercial packages.

- The specifications of parameters *RSm* and *Rc* are ambiguous and unstable. The variation of *RSm* is significant. The revised specification of *RSm* in NPL's interpretation is mathematically stable in this test.

- The specifications of *P*-parameters are unambiguous in standard documents. However, there are different understandings of the meaning of *P*-parameters, which leads to different interpretations.

- The effect of rounding error is insignificant in the test. The major contributor to the variation is the specification variation.

- In addition, there are significant variations on the results of *W*-parameter as well[34].

3) How does one make a judgement when there is a discrepancy between an industrial software package and a type F2 standard, or even between two type F2 standards?

This is depends on the requirements. Examples are given in section 7.2.5 to illustrate how to make a judgement.

[34] We do not present the results of W-parameters in this report because they are seldom used and have same "nature" as R-parameters and P-parameters. Moreover, the specifications of W-parameters defined within ISO standards do not accepted by industry.

7.3 Calibration of commercial software packages

This comparison result (Li, Leach et al. 2009) was noticed by the instrument manufacturers. We received a respond from the company B. This company claimed that the latest version, refers to as [CBv2], has fixed all reported issues.

This section presents the calibration results of four commercial packages, all latest version of [CA], [CBv2], [CC], and one more of commercial software package [CD]. Same type F1 softgauges were used in this calibration. Note that the reference results were produced by NPL's type F2 softgauge. Same calibration procedure and measurement condition were used (see the previous section). Only a brief report for each software package is given as follows.

[CA]

Figure 7.8 shows that the difference is relative small in parameter *Ra, Rq, Rz, Rt*, while significant in parameter *Rsk, Rku, Rp, Rv* and *RSm*.(The significant disagreement on parameter *Rp* and *Rv* is due to [CA] follows American Standard ASME B46).

In the case of Cos.smd, [CA] delivers three correct significant digits (see Figure 7.9). This software can be use to reproduce most of the measurement tasks listed in Table 7.5.

It delivers stable results on most of the parameters (except *RSm*) (see Table 7.8).

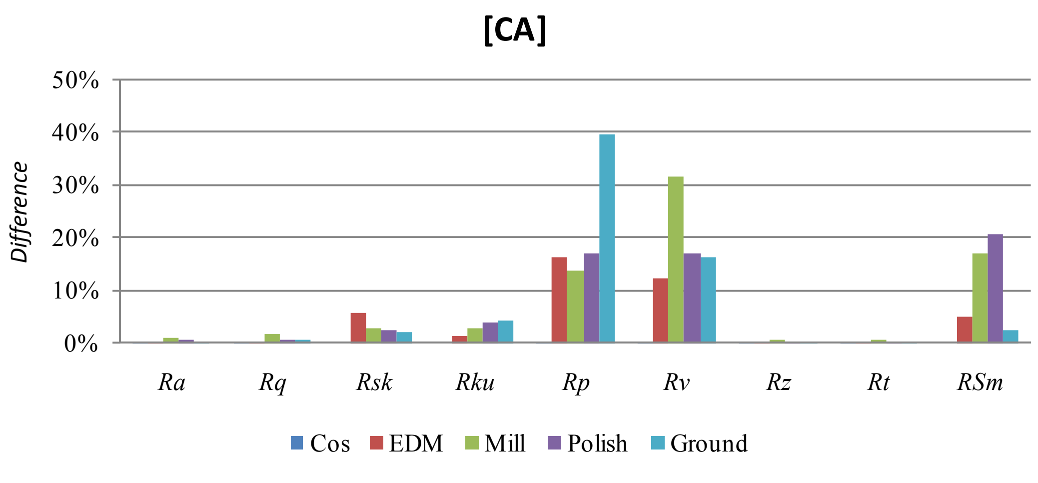
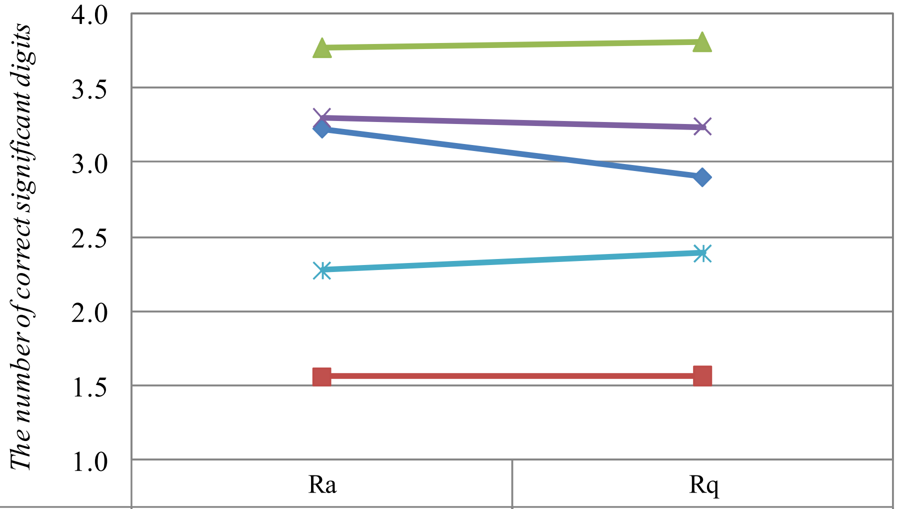


Figure 7.8 Calibration results of [CA]



	Ra	Rq
[CA]	3.2	2.9
[CB (v1)]	1.6	1.6
[CB (v2)]	3.8	3.8
[CC]	3.3	3.2
[CD]	2.3	2.4

Figure 7.9 The number of the correct significant digits

Table 7.8 Percentage of relative difference between results obtained from the same software on the same profile with reversed order of data points.

	Ra	*Rq*	*Rsk*	*Rku*	*Rp*	*Rv*	*Rz*	*Rt*	*Rc*	*RSm*	*Rdq*
CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*	**1.1**	0.0
CB (v1)	**2.1**	**2.4**	**39.4**	**2.4**	**10.9**	**3.4**	**7.1**	**0.0**	**1.4**	**4.3**	**0.5**
CB (v2)	**2.0**	**2.9**	**108.1**	**3.0**	**15.8**	**5.2**	**4.2**	**0.0**	**1.1**	**1.2**	**1.6**
CC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.6**	**0.6**	0.0
CD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*	**0.9**	0.0

(Note: * signifies that the result is not available).

[CB(v1)] and [CB(v2)]

Figure 7.10 and Figure 7.11 show that [CB(v1)] and [CB(v2)] produce significant differences on all parameters.

In the case of Cos.smd, [CB(v2)] delivers two correct significant digits (see Figure 7.9). [CB(v2)] can be use to reproduce most of the measurement tasks listed in Table 7.5.

Both [CB(v1)] and [CB(v2)] deliver significant unstable results (up to 108% difference) on nearly all *R*- parameters (see Table 7.8).

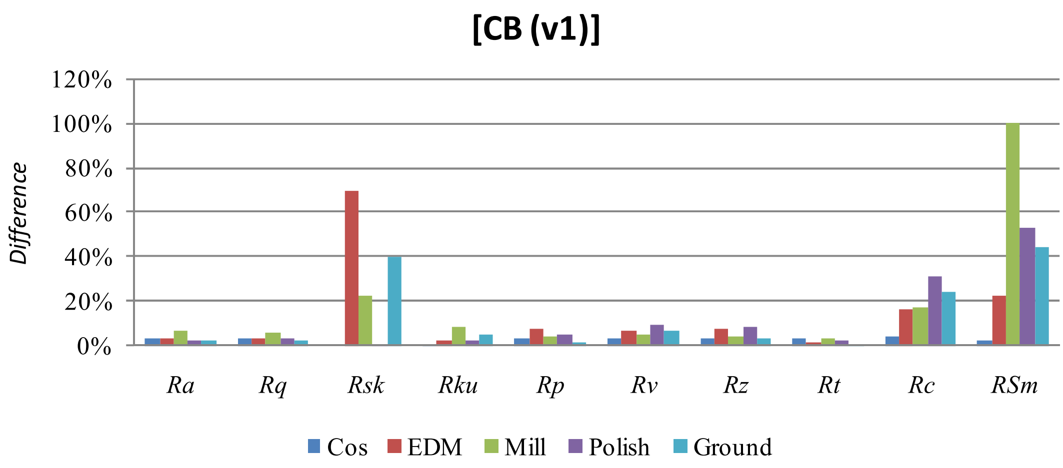


Figure 7.10 Calibration results of [CB(v1)]

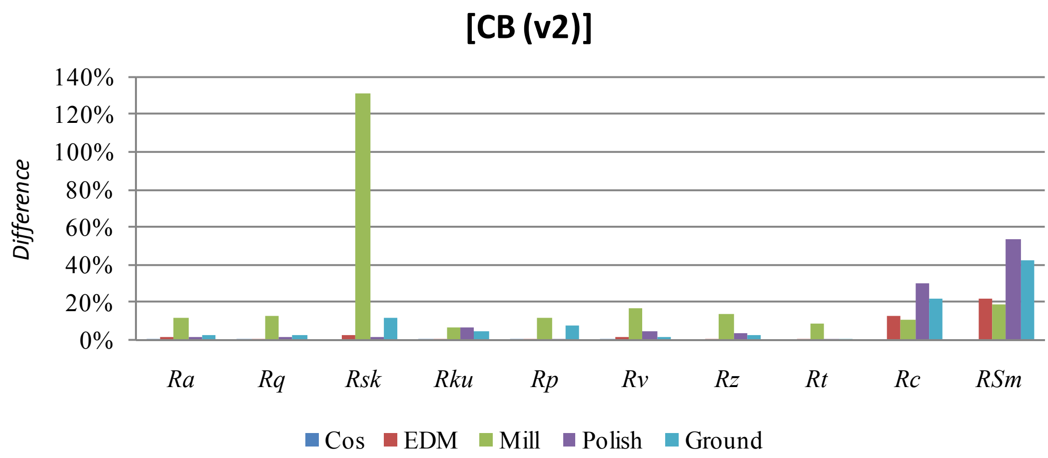


Figure 7.11 Calibration results of [CB(v2)]

[CC]

Figure 7.12 shows that [CC] produces significant differences on all parameters. This should be contributed mainly by using the λs filter and the end-effect of the λc filtering.

In the case of Cos.smd, [CC] delivers more than 3 correct significant digits (see Figure 7.9). [CC] can be use to reproduce most of the measurement tasks listed in Table 7.5.

It delivers stable results on most of the parameters (except *RSm* and *Rc*) (see Table 7.8).

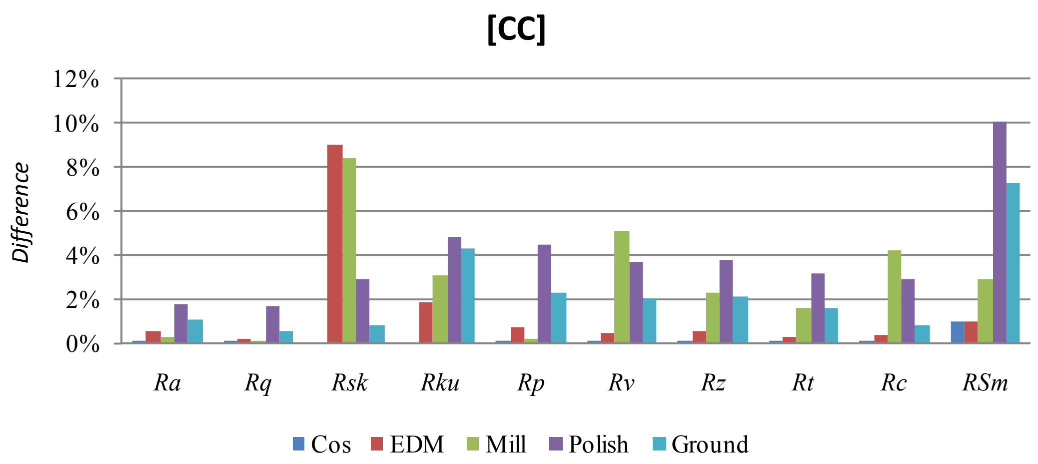


Figure 7.12 Calibration results of [CC]

[CD]

Figure 7.13 shows that the difference is relative small in parameter *Ra, Rq, Rp, Rv,Rz, Rt*, while significant in parameter *Rsk, Rku,* and *RSm.*

It delivers stable results on most of the parameters (except *RSm*) (see Table 7.8).

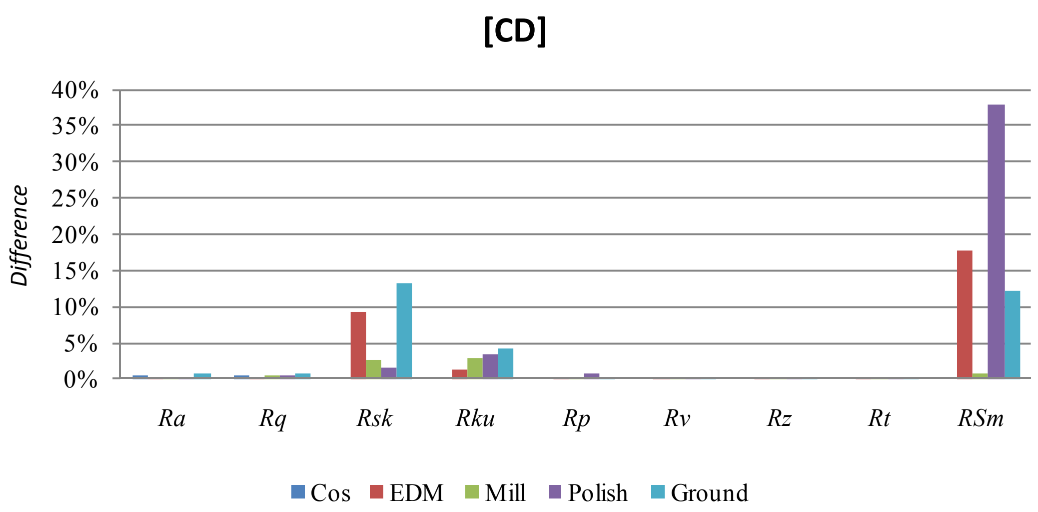


Figure 7.13 Calibration results of [CD]

This comparison highlights the need to verify surface texture software using softgauges. Furthermore, when carrying out comparisons of surface texture measuring instruments, it would make sense to use the same software package to filter the data and to calculate all parameters (Even in this situation, some software packages may still produce unreliable results, e.g. [CB]).

7.4 Estimating the measurement uncertainty

In order to understand the uncertainty of surface profile measurements, this section undertakes two case studies. These case studies show uncertainty estimation methods for roughness measurement in the workshop environment. These case studies implemented two methods, the ANOVA method and a computer simulation method.

7.4.1 ANOVA method

ISO 12179 (2000) introduces the ANOVA method into the field of surface metrology to analysis the variations in surface measurement. In this section, ANOVA method is implemented to estimate the Type A uncertainties. And type F2 softgauge is used to assess a component of the Type B uncertainties. The combination of different type uncertainties follows the GUM's method.

7.4.1.1 Case study 1: A type D1 hardgauge

As discussed in chapter 2, the type D hardgauges are the only hardgauges for calibrating the whole measurement procedure. This standard is characterised by the parameters *Ra* and *Rz*. The minimum number of traces required is 12, which are evenly distributed across the measuring window. The measurement of this sample, a type D1 hardgauge 1271, details in this author's publication (Li, Blunt et al. 2009) .

Evaluate the random effect

The hardgauge 1271 was evaluated five times in twelve positions according to the measuring plan given in Figure 2.8. The results of *Ra* values on this sample are given in Table 7.9.

Table 7.9 Ra values on type D1 measurement standard 1271

Ra /nm		*Evaluation (j)*					*Mean*
		1	*2*	*3*	*4*	*5*	
Position (i)	1	667.0	667.0	667.2	667.2	667.0	667.08
	2	672.7	672.6	672.2	672.4	672.7	672.52
	3	671.9	671.9	671.6	671.7	671.8	671.78
	4	672.3	671.9	672.0	672.0	671.9	672.02
	5	665.4	665.3	665.5	665.5	665.5	665.44
	6	669.7	669.7	669.6	669.8	669.6	669.68
	7	662.9	662.6	662.5	662.7	662.5	662.64
	8	669.3	669.3	669.3	669.4	669.2	669.30
	9	663.0	663.0	663.2	662.8	663.1	663.02
	10	670.7	670.6	670.5	670.6	670.5	670.58
	11	658.1	658.4	658.2	658.4	658.1	658.24
	12	668.2	668.1	668.3	668.4	668.0	668.20
Mean		667.60	667.53	667.51	667.58	667.49	667.54

The random effects contributing to the observed variability of the measurements are listed in Table 7.10. According to ISO 12179 (2000), each of these random effects is assumed to have associated with it an unknown variance, denoted by σ_R^2, σ_E^2 and σ_M^2.

Table 7.10 The random effects (ISO 12179 2000)

Symbol	*Variation*
σ_R^2	Variation between each individual roughness measuring position
σ_E^2	Variation of between evaluations (at same position)
σ_M^2	Repeatability of the instrument

Associated with these means are the sum-of-square S_1, S_2 ,S_3 and S_4, and the results are summarised in Table 7.11.

Table 7.11 Summary of ANOVA

Source of variability	*Sum of squares* S_l	*Degree of freedom* v_l	*Mean square* $M_1 = \frac{S_l}{v_l}$	*Variance estimated by mean square*
Mean	$S_1 = 60\overline{X}^2$ = 26736712.6	1	M_1 =26736712.6	-
Across measurement standard	$S_2 = 5\sum_{i=1}^{12}(\overline{X_i} - \overline{X})^2$ = 1078.773833	11	M_2 =98.0703484	$\sigma_M^2 + 5\sigma_R^2$
Between evaluations	$S_3 = 12\sum_{j=1}^{5}(\overline{X_j} - \overline{X})^2$ = 0.098333333	4	M_3 =0.02458333	$\sigma_M^2 + 12\sigma_E^2$
Instrument repeatability	$S_4 = \sum_{i=1}^{12}\sum_{j=1}^{5}(X_{ij} - \overline{X_i} - \overline{X_j} + \overline{X})^2$ = 0.813666667	44	M_4 =0.01849242	σ_M^2

Denoting the estimates of by σ_R^2, σ_E^2 and σ_M^2 by s_R^2, s_E^2 and s_M^2 respectively, it follows from the last columns of the table that:

$$s_R^2 = \frac{(M_2 - M_4)}{5}$$

Thus, s_R = 4.428 nm;

$$s_E^2 = \frac{(M_3 - M_4)}{12}$$

Thus, s_E = 0.023 nm;

$$s_M^2 = M_4$$

Thus, s_M = 0.136 nm.

Calibration Uncertainty

The calibration certificate gives a nominal value of *Ra* = 669 nm with “an uncertainly of ±4 nm with *k* = 2,17 ”. Assuming that the results have a Gaussian distribution this gives a standard uncertainty estimate of:

$$u_{cal} = \frac{4}{k} = 1,9nm$$

The calibration certification states that this uncertainty already includes the variation of the parameter values across the measurement standard so this will not have to be included a second time in the combined standard uncertainty.

Software Uncertainty

One of the measurement data files for a type D1 1271 hardgauges were evaluated by NPL’s type F2 softgauge. The difference of Ra is 4nm. The uncertainty is assumed to be uniformly distributed. Dividing by the half-width of the uncertainty by $\sqrt{3}$ gives the standard uncertainty of:

$$u_s = \frac{2}{\sqrt{3}} = 1,2nm$$

Combined Uncertainty

The calibration cortication states that this uncertainty already includes the variation of the parameter values across the measurement standard so this will not have to be included a second time in the combined standard uncertainty. The combined standard uncertainty is thus:

$$u_c = \sqrt{s_E{}^2 + s_M{}^2 + u_s{}^2 + u_{cal}{}^2} = 2,2nm$$

And the expended uncertainty, U, is 4,4 nm with k = 2.

7.4.1.2 Case study 2: A honed surface

Automotive cylinder bores are an important class of technical components. The specification and control of their surface texture is an important manufacturing requirement. Compared with other areas of dimensional metrology, surface roughness is relatively immature in terms of the provision of the statements of uncertainty (Leach 2009). In the workshop, it is usually the case that no statement is provided at all. The objective of this case study is to illustrate how to produce a traceable surface roughness result in the workshop environment with the aid of softgauges.

Evaluate the random effect

The measurement of this sample, the honed surface of an automotive cylinder bore, details in (Li, Blunt et al. 2009). This honed surface was evaluated five times at six different positions across the surface. "16%- rule" sets of the default tolerance zone for surface. In this case, we assume it specified the USL only. Thus, we simply remove results obtained from position 6 (the biggest) to reduce the effect from the outlier of the tolerance zone (see Table 7.12).

Table 7.12 Results of parameter Ra (nm) used in assessment

Ra /nm		*Evaluation*					
		1	*2*	*3*	*4*	*5*	*Mean*
Position	1	650.2	641.1	645.7	651.3	664.0	650.46
	2	643.1	657.9	658.5	662.8	701.9	664.84
	3	676.1	691.6	697.1	666.7	679.9	682.28
	4	587.6	614.9	637.7	616.4	610.3	613.38
	5	640.2	661.1	645.7	641.3	636.0	644.86
Mean		639.44	653.32	656.94	647.70	658.42	651.164

Using the ANONA method detailed in the previous section, the random effects are evaluated.

$$s_R = 24{,}8nm;$$

$$s_E = 4{,}4nm;$$

$$s_M = 14{,}3nm.$$

Calibration Uncertainty

The instrument has been calibrated. From the specification of this instrument, it stated that the surface peak parameter uncertainty is: 2% + 4nm at 95% confidence. Assuming that the results have a Gaussian distribution this gives a standard uncertainty estimate of:

$$u_I = \frac{(Ra \times 2\%) + 4nm}{k} = 9nm$$

Software Uncertainty

One of the measurement data files was evaluated by NPL's type F2 softgauge. The difference of *Ra* is 14 nm. The uncertainty is assumed to be uniformly distributed. Dividing by the half-width of the uncertainty by $\sqrt{3}$ gives the standard uncertainty of:

$$u_s = \frac{7}{\sqrt{3}} = 4nm$$

Combined Uncertainty

According to ISO 4288:1996, the uncertainty of measurement shall be estimated without taking into account the inhomogeneity in the surface which is already accounted for in the 16% allowance. Thus, the combined standard uncertainty is calculated without the variation between positions.

$$u_c = \sqrt{s_E^2 + s_M^2 + u_s^2 + u_I^2} = 18nm$$

And the expanded uncertainty, U, is *36 nm* with k=2.

7.4.1.3 Discussions

These two case studies show that:

$$S_R > S_M > S_E$$

Key: S_R – Variation between position
S_M – Variation between evaluations (at same position)
S_E – Repeatability of the instrument

Thus, surface inhomogeneity is the major contributor to the variation of the results. It influences repeatability of the instrument on this surface as well (S_M is several times greater than S_E). Clearly, the instruments' variations are far less than that of the surface. In addition, attention should be paid to the software uncertainty. It is greater than repeatability of the instrument.

7.4.2 Computer simulation

Computer simulations are the next frontier for uncertainty assessment. A surface metrology algorithm testing system is provided NIST in the USA (Bui and Vorburger 2007). This software is a free access at the web site: http://syseng.nist.gov/VSC/jsp/Filter.jsp. This software can estimate the propagated uncertainty arisen from data errors by using computer simulations. Figure 7.14 shows a diagram of NIST's model.

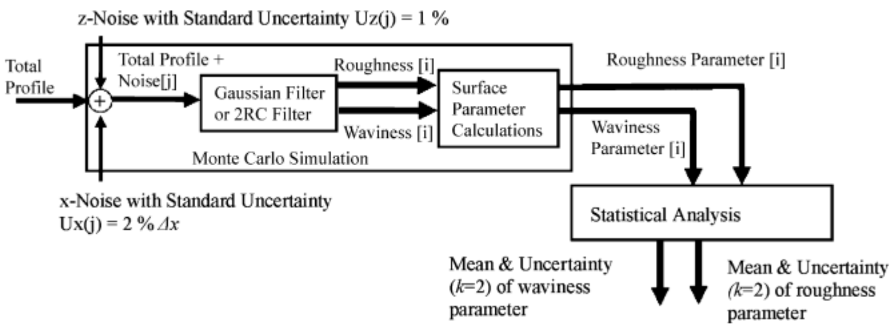


Figure 7.14 The NIST's model for calculating the uncertainty of surface roughness (Bui et.al 2007)

One of the measurement data files from a Type D1 1271 measured was uploaded to the NIST system. Five evaluations were undertaken and results are listed in Table 7.13. This table also provides the results obtained from [NIST], [CC] (the software package used in this measurement instrument) and NPL's F2 softgauges directly (i.e. without adding noise on profile).

Table 7.13 Results of one profile obtained from Type D1 hardgauge 1271

	[NIST]						[CC]	[NPL]
	Evaluation 1 (default)	Evaluation 2	Evaluation 3	Evaluation 4	Evaluation 5			
Z-Noise Uz(j)	1% of Pq[1]	0,5% of Pq	0,5% of *Pq*	1% of Pq	2% of Pq			
X-Noise Ux(j)	2,0% of spacing	1,0% of spacing	2,0% of spacing	1,0% of spacing	2,0% of spacing			
Parameter	Mean ± U	Mean ± U	Mean ± U	Mean ± U	Mean ± U	Nominal		
Ra /nm	675,8 ± 6,7	677,1 ± 4,3	675,9 ± 6,8	676,9 ± 4,7	676,1 ± 6,4	677,9	672,5	676,4
Rq /nm	798 ± 24	798 ± 24	799 ± 24	798 ± 24	799 ± 24	822	829	820
Rt /nm	4462 ± 65	4446 ± 33	4452 ± 67	4460 ± 43	4481 ± 78	4447	4393	4443
Rz /nm	3448 ± 84	3432 ± 90	3443 ± 76	3437 ± 93	3470 ± 89	3447	3446	3510
RSm /µm	237 ± 22	244 ± 15	245 ± 15	238 ± 21	-	221	266	269

Figure 7.15 shows the *Ra* results with the uncertainties produced by the simulation and ANOVA. It shows that evaluation 2, obtained from simulation, delivers uncertainty value close to the value produced by ANOVA method (see Section 7.4.1.1). However, the disagreement of the measured values of *Ra* obtained from two methods is significant. Some of reasons are listed below.

1) *The inconsistence of the measurand*: Only one profile is used to represent the whole surface in simulation, while 60 profiles are used in ANOVA method. So the disagreement could be arisen from to the inconsistence on the surface.

2) *The software uncertainty*: The absolute difference of the *Ra* values obtained from [CC] and [NIST] is 5.4 nm.

3) *The difference between the nominal and mean value*: The absolute difference of the *Ra* values obtained from [NIST]-Evaluation 1 and [NIST]-Nominal is 2.1 nm.

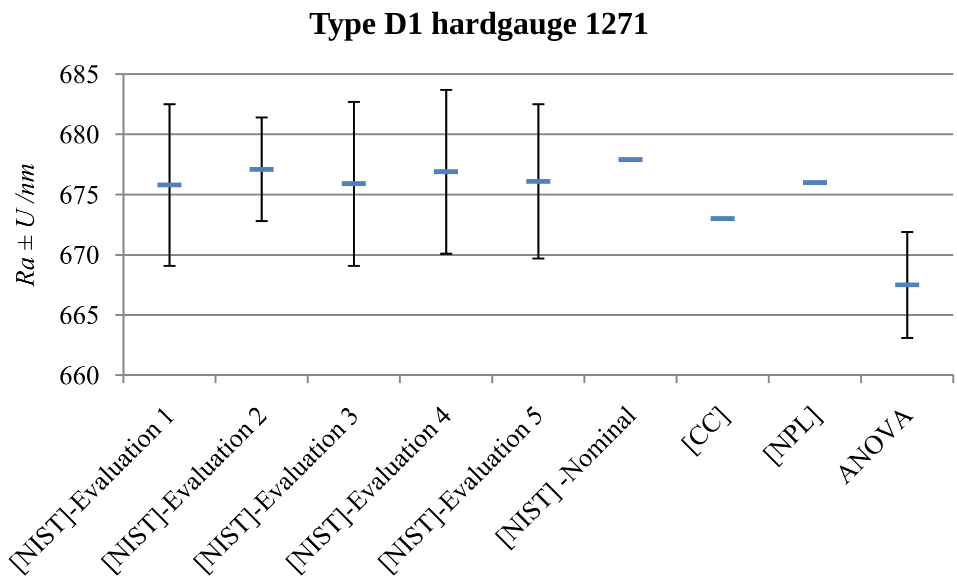


Figure 7.15 Comparison of parameter Ra values with uncertainties

Table 7.13 shows that parameter *Rq*, obtained from different the level of noise, has close measured value (only 1nm difference). Compared with the random effect, software uncertainties are relatively significant.

In addition, associated uncertainties of parameter *Rq*, obtained from different the level of noise, have same value (see table 7.13). This is due to parameter *Rq* has more weight on significant features and less weight on insignificant features. Parameter *Ra* gives same weight for both significant and insignificant feature, thus, its uncertainty values are increased (from 4.3 to 6.7, shown in table 7.13) when noised level is enlarged.

7.5 Conclusions

This chapter has attempted to bring together the main practical issues involved in the use the softgauges for surface texture.

A calibration procedure for surface metrological software has been developed with the aid of softgauges. This has been carried out by assessing filtration operations, field parameters, feature parameters and whole software packages.

This procedure and some developed type F1 softgauges has been used to verify three type F2 softgauges. The inter-comparison shows that three type F2 softgauges are more accurate and stable than selected commercial software packages. These F2 softgauges can be used as references to calibrate commercial software packages.

This chapter also presented the calibration results of four commercial software packages. This work shows that it is not safe to ignore the software calibration as some software packages deliver very unreliable results.

The uncertainties of surface roughness measurement have been presented via two case studies. This work has assessed the random effect by ANOVA method and systematic effect with the aid of softgauges. This study provided a practical method to evaluate the uncertainty for roughness measurement in the workshop environment. The random effect is also estimated by computer simulation. This work showed that the computer simulation can be used to study the data uncertainty, but attention should be paid to its software uncertainty.

8 Conclusions and future work

This chapter summarises the outcomes of this project and highlights the contribution to knowledge in the relevant research domains. Further work on the softgauges, especially for areal surface texture characterisation, is also discussed.

8.1 Summary of contributions

The first main contribution of this project is the development of a new traceability route of surface texture measurements. This route includes two important components, hardgauges to check the data collection process, and softgauges to calibrate the data processing process. This route has some distinctive advantages over the conventional one, and they are listed below.

- It provides a sound solution for maintaining metrological traceability of surface texture measurements. This new route enables to check metrological traceability of all parameters of surface measurement, while the current route only can check the traceability of two parameters within limited conditions.

- It significantly reduces the cost of using national measurement standards.

The second contribution of this project is the development of a methodology to estimate software uncertainty, which is based on the latest uncertainty concepts and philosophy of metrology. Uncertainty is used as an economical tool to balance the requirements in each stage of the use and design of surface measuring instruments. In addition, a guide is provided to evaluate the measurement uncertainty in workshop level by using of ANOVA and softgauges.

The third contribution of this project is the development of type F1 softgauges for surface profile parameters as the national standards in the UK. They have been used to verify type F2 softgauges developed in the UK, Germany and the United States.

8.2 Future work

Detailed work in the development of software measurement standards in this thesis revealed more interesting issues, some of which need to be investigated further:

1) In this thesis, a framework for softgauges was focused on the surface profile measurements. With areal surface texture measurements becoming an industry norm, a further work is needed to extend the knowledge gained here to cover them.

2) The information model developed in Chapter 4 requires more related components, such as the XSLT components for transforming the SMD file, other XML formats into SMTL and vice versa. A continuous update to stay in current is also needed.

3) This project has investigated the software uncertainty in modelling and coding process in the case of ISO 4287 parameters. The study of the uncertainty of other parameters (e.g. Motif parameters, areal surface texture parameters) is required.

4) Chapter 6 has developed the type F1 softgauges and Chapter 7 has presented the use of softgauges. The extending is also needed to cover areal surface texture measurements. Using computer simulation to evaluation of measurement uncertainty has been developed significantly, and BIPM[35] will fully release new version of the GUM in 2012. A study is required to evaluate the measurement uncertainty more rigorously.

[35] http://www.bipm.org/en/publications/guides/gum.html

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Appendix 1

Examples of the messages in STML

This section lists the example file of standardised message in the Surface Texture Markup Language (STML), developed in Chapter 4.

A.1.1 IndicationSample.XML


```
<?xml version="1.0" encoding="UTF-8"?>
<Indication xmlns="http://www.surfacetexture.info/schemas/indication"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.surfacetexture.info/schemas/indication.xsd">
	<SurfaceTextureRequirement>
		<Parameter>
			<SpecificationLimitType>U</SpecificationLimitType>
			<FilterType>Gassian</FilterType>
			<TransmissionBand>
				<LowLimit Unit="mm">0.0025</LowLimit>
				<UpLimit Unit="mm">0.8</UpLimit>
			</TransmissionBand>
			<ParameterName>Ra</ParameterName>
			<EvaluationLength Unit="mm">4</EvaluationLength>

	<SpecificationLimitInterpretation>16%</SpecificationLimitInterpretation>
			<ParameterValue Unit="um">0.9</ParameterValue>
		</Parameter>
		<Parameter>
			<SpecificationLimitType>L</SpecificationLimitType>
			<FilterType>Gassian</FilterType>
			<TransmissionBand>
				<LowLimit Unit="mm">0.0025</LowLimit>
				<UpLimit Unit="mm">0.8</UpLimit>
			</TransmissionBand>
			<ParameterName>Ra</ParameterName>
			<EvaluationLength Unit="mm">4</EvaluationLength>

	<SpecificationLimitInterpretation>16%</SpecificationLimitInterpretation>
			<ParameterValue Unit="um">0.4</ParameterValue>
```

```xml
				</Parameter>
				<Parameter>
					<SpecificationLimitType>U</SpecificationLimitType>
					<FilterType>Gassian</FilterType>
					<TransmissionBand>
						<LowLimit Unit="mm">0.0025</LowLimit>
						<UpLimit Unit="mm">0.8</UpLimit>
					</TransmissionBand>
					<ParameterName>Rz</ParameterName>
					<EvaluationLength Unit="mm">4</EvaluationLength>

			<SpecificationLimitInterpretation>16%</SpecificationLimitInterpretation>
					<ParameterValue Unit="um">5.0</ParameterValue>
				</Parameter>
				<ForAllOutlineSurface>No</ForAllOutlineSurface>
			</SurfaceTextureRequirement>
			<MaterialRemoval>MRR</MaterialRemoval>
			<SurfaceLayAndOrientation>Perpendicular</SurfaceLayAndOrientation>
			<ManufacturingMethod>turned</ManufacturingMethod>

</Indication>
```

A.1.2 MeasurandLRa0.4.xml

```xml
<?xml version="1.0" encoding="UTF-8"?>
<Measurand xmlns="http://www.surfacetext.info/Schemas/SpecificationOperator"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.surfacetext.info/Schemas/SpecificationOperator
L:\Projects\STML\FullSpecificationOperator.xsd">
	<Partition/>
	<Extraction>
		<NumCutoff>5</NumCutoff>
		<SamplingLength Unit="mm">0.8</SamplingLength>
		<EvaluationLength Unit="mm">4</EvaluationLength>
		<Instrument>
			<Type>Stylus</Type>
			<MaxSamplingSpacing Unit="um">0.5</MaxSamplingSpacing>
			<MaxTipRadius Unit="mm">2</MaxTipRadius>
		</Instrument>
	</Extraction>
	<Filtration>
		<Filter>
			<FilterName>Gassuian</FilterName>
			<UpLimt Unit="mm">0.8</UpLimt>
			<LowLimit Unit="um">2.5</LowLimit>
		</Filter>
	</Filtration>
	<Evaluation>
		<ParameterName>Ra</ParameterName>
		<ParameterValue Unit="um">0.4</ParameterValue>
		<Tolerance>
			<Limits>L</Limits>
			<ComparisonRule>16%</ComparisonRule>
		</Tolerance>
	</Evaluation>

</Measurand>
```

A.1.3 MeasurevalueRa0.5.xml


```xml
<?xml version="1.0" encoding="UTF-8"?>
<MeasuredValue xmlns="http://www.surfacetext.info/Schemas/SpecificationOperator"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.surfacetext.info/Schemas/SpecificationOperator
L:\Projects\STML\AcutualVerificationOperator.xsd">
	<Partition/>
	<Extraction>
		<NumCutoff>5</NumCutoff>
		<SamplingLength Unit="mm">0.8</SamplingLength>
		<EvaluationLength Unit="mm">4</EvaluationLength>
		<MeasurementLength Unit="mm">4.8</MeasurementLength>
		<Instrument>
			<SamplingSpacing Unit="um">0.25</SamplingSpacing>
			<TipRadius Unit="um">2</TipRadius>
			<InstrumentType>Stylus</InstrumentType>
		</Instrument>
		<MeasurementInfo>
			<CreatedBy>Tukun Li, Univeristy of Hudderfield</CreatedBy>
			<MeasurementDate>2010-12-8</MeasurementDate>
		</MeasurementInfo>
	</Extraction>
	<Filtration>
		<FOperator>Remove residual tilt by Linear least square method</FOperator>
		<Filter>
			<FilterName>Gassian</FilterName>
			<UpLimt Unit="mm">0.8</UpLimt>
			<LowLimit Unit="um">2.5</LowLimit>
			<EndEffect>Remove half cutoff at each end of sampling
length</EndEffect>
			<SoftwareID>Taylor-Hobson Ultra v4.6</SoftwareID>
		</Filter>
	</Filtration>
	<Evaluation>
		<ParameterName>Ra</ParameterName>
		<ParameterValue Unit="um">0.5</ParameterValue>
		<Tolerance>
			<Limits>L</Limits>
			<ComparisonRule>16%</ComparisonRule>
		</Tolerance>
	</Evaluation>
</MeasuredValue>
```

Appendix 2

Measurement conditions for comparison of type F2 softgauges

This section lists the measurement condition used in the comparison of three type F2 softgauges, which is discussed in Chapter 7.

Form Removed

The form removal operation is set as standard in PTB's F2 standard, is an option in NIST's F2 standard, and is not used in NPL's F2 standard. Therefore, in this test, all measured reference data sets were levelled by the least-squares straight line method on NIST F2 standards before input into all F2 software standards and commercial packages.

Filtering

At the filtration stage, we used only a Gaussian filter with long-wavelength cut-off λc of 0.8 mm calculated by the convolution method.

Sampling Length and Evaluation Length

To minimise the distortion due to the convolution filter, one cut-off at each end of the roughness profile is normally removed. All data sets include 7 cut-offs and the evaluation of the R-parameters is based on the middle five cut-offs. P-parameters are calculated based on all data points in files and, therefore the evaluation length of P-parameters is equal to 5,6 mm in these profiles.

Parameters

The parameters to be compared here are defined in ISO 4287 (1996). The waviness profile is not well defined in current ISO standards due to there is no common understanding of the meaning and use of waviness parameters. Thus, the comparison of W-parameters calculation is not very meaningful and is not discussed in the report.

File format

It should be noted that some test used different data file format due to some software packages do not support SMD data format. In some case, data type is converted and precision is reduced.

The variation of measuring condition

The variation of measuring condition is listed in the following table.

Table A2.1 Variation of measuring conditions

	[PTB]	[NIST]	[NPL]	[CA]	[CB]	[CC]
Levelling	LSQ				LSQ	
Profile filtering λs						2,5 μm
The number of data points	22400	22400	22401	22400	22400	22400[a] 19200[b]
The number of removed cut-offs at each end of the profile (End effect of λc profile filtering)	1	1	1	1	1	0,5

Note: [a]. The number of points of *P*-profile,
[b]. The number of points of *R*-profile