University of Nottingham
Faculty of Engineering
Department of Mechanical, Materials and Manufacturing
Manufacturing Metrology Team

Calibration of focus variation microscopy for surface texture measurement

Ph.D. thesis written by
Anas Ibrahim Alburayt

Supervisors:
Prof. Richard K. Leach
Dr Wahyudin P. Syam

September 2019

Abstract

Developments in manufacturing technologies have led to the ability of product fabrication with complex deterministic surface topography, designed to have specific functions. The measurement of surface topography has become increasingly important in recent years. In industry and research environments, the most popular methods for surface texture measurements are i) profile measurement (line profiling) and ii) areal measurement with either contact (tactile) or non-contact (optical) instruments.

Profile measurements have been used for many decades, whereas areal measurements are relatively recent technique, compared to profile measurement, that can cover large areas of surface textures to have more comprehensive information about a surface. Areal measurements can be conducted using contact and non-contact surface texture instruments. Measurements using optical instrument are still less understood compared to contact stylus instruments; but optical measuring instruments have significant advantages over contact instruments in terms of relatively short measuring times, accessibility for small delicate surface features and minimal damage to surfaces. Therefore, establishing the traceability of optical measuring instruments is very important to have reliable areal surface topography measurements.

Focus variation microscopy (FVM) instrument is an optical areal surface topography measuring instrument. The measurement traceability of the FVM can be established by determining its metrological characteristics. Measurement traceability is achieved when an unbroken chain of calibration processes to the definition of metre, with stated measurement uncertainties at each step. The Organisation for International Standards (ISO) has proposed metrological characteristics for optical areal surface texture measuring instruments, including for FVM instruments. These metrological characteristics, which directly affect measurement results, should be quantified to calibrate the FVM instrument for surface topography measurement.

FVM is a popular instrument used for various type of surface topography measurements obtained from various manufacturing processes, including both subtractive and additive, and various surface coating processes. However, the establishment of FVM's traceability to get reliable measurement results is still challenging. Because, most of FVM instruments cannot, or at least are very difficult, to measure very smooth surfaces with Ra < 10 nm. Due to this reason, the available calibration infrastructures (including reference artefacts, and calibration procedures and methods) for areal surface topography measuring instruments cannot be applied for FVM because the infrastructures are based on the use of very smooth reference artefacts.

This research project aims to develop novel calibration infrastructures, including novel artefacts, procedures and methods to quantify the metrological characteristics of the FVM. The project provides calibration infrastructures by using novel low-cost material measures and novel practical procedures to determine the metrological characteristic for FMV. The metrological characteristics of focus variation microscopy include: measurement noise, residual flatness, amplification coefficients, linearity deviations and perpendicularity deviations and topographic spatial resolution. The Low-cost material measures were calibrated with more accurate and traceable measuring instruments to create the traceability link to the metre.

Key words: traceability, surface texture, focus variation microscopy, calibration, measurement uncertainty, metrological characteristics.

Contents

List of Figures

List of Tables

Publications

- Alburayt A, Syam W P and Leach R K 2017 Detecting the signature of motion stage non-linearity for focus variation microscopy using measurement noise and surface topography repeatability *The 16'th Conference on: Metrology and properties of engineering surfaces in Göteborg Sweden 26-29'th of June 2017*
- Alburayt A, Syam W P and Leach R K 2018 Lateral scale calibration for focus variation microscopy *Meas. Sci. Technol.* **29** 065012
- Alburayt A, Syam W P and Leach R K 2019 lateral image sensor calibration for focus variation microscopy in *preparation*
- Alburayt A, Syam W P and Leach R K 2019 Methodology to determine topographical spatial resolution with a random surface artefact for focus variation microscopy *in preparation.*

Acknowledgment

I want to take this opportunity to acknowledge all who have supported and helped me throughout my PhD journey; I could not have achieved this PhD without their contribution. All the guidance and advice I have received have led me to where I am now. I owe my appreciation to the following people:

- I want to start with my parents: my mum, for her encouragement ever since I was little and for her patience while I was studying abroad. All that you wish for me serves as a guiding path to success. My dad, who had passed away at the beginning of my studies abroad; he was the first one to support and advise me to do so. His advices remain on my mind even now. I believe that thanking my parents is not enough, but am trying to do my best to show my full appreciation of their efforts and patience with me.

- I cannot move forward without mentioning the person who has been sharing her life with me for over ten years. I appreciate my wife, Noorah, for all her support. Her patience during the busy and hard days that we faced together is unforgettable. I hope I can return her effort with me and my children as a family; the time she took to look after me and our children is obvious. I believe that Noorah and my children deserve more than what they got from me. Whatever I do for them, I will feel that my efforts towards my wife will not live up to her own.

- I am immensely grateful for the chance to complete my PhD under the valuable supervision of Professor Richard Leach and Doctor Wahyudin Syam. Advancement in my research could not have been achieved without their pertinent comments and guidance. My life during my PhD journey has, under their supervision, been filled with the most knowledge I have ever known. This extended to any mistakes that I have made, as I have learnt from their own wealth of knowledge and experience. The knowledge that I in turn have obtained from them is rich and covers a breadth of different disciplines, including the subject of my own research, personal growth and science in general. I will always be proud that I did my PhD with them and hope I can continue to benefit more from them.

- No doubt, a huge thank you to the scholarship program of the Saudi Arabian government for their support and investment in Saudi citizens for the purpose of them gaining knowledge. Their full funding of my postgraduate studies in the UK cannot be ignored. Their belief in my efforts has not only made me a new person, but has also affected my family members, even my little daughter. I will always be indebted to them for support. The King Abdulaziz City for Science and Technology (KACST) of the Saudi government must be mentioned here; their support is hugely appreciated.

- Engineering and Physical Sciences Research Council (EPSRC), Alicona GmBH and Digital Surf Company have also supported me during my PhD. The EPSRC grant EP/M008983/1 has partially funded my work and most measurements for my thesis have been carried out using a focus variation optical method, based on the Alicona InfiniteFocus G5 instrument. In turn, the data from these measurements has been analysed using Mountainsmap software provided by the Digital Surf Company.

- It is difficult to cover all those who have contributed to my postgraduate journey. This section is a general acknowledgement to all who have not been mentioned. My appreciation reaches all those who have made even a small contribution to my work.

Chapter one: Introduction

1 Introduction

Measurements have a daily importance in our lives and are carried out across numerous disciplines, from science to engineering, using different methods. The methods range from simple to advanced, based on the work carried out. Measurement has been defined in VIM (JCGM200 2008, JCGM200 2012) as the '*process of experimentally obtained one or more quantity values that can reasonably be attributed to a quantity*'. Measurement in the manufacturing field can be used for different purposes, including studying a sample's surface texture and checking the dimensions of the sample to optimise manufacturing quality. Thus, measurement plays a vital role in manufacturing and is carried out from the design stage through to production, to final quality inspection to completed products. Leach RK, Senin N et al. (2017) recently discussed why measurement has become a fundamental aspect of manufacturing. One of its benefits is related to the improvement of the manufacturing process; for example, in the measurement of surface texture. The surfaces being measured can be of different textures due to different process conditions. From the measurement results, one can monitor the process conditions and improve the process. Studying the different types of surface texture is, therefore, important so as to overcome the issues currently preventing measurement.

1.1 Surface texture

The terminology of '*surface*' should be clarified in the beginning. ConciseOxfordDictionary (2011) presents several definitions for this word, one of them being '*the outside part or uppermost layer of something'.* This definition indicates the surface as a being the highest part of a body that can be touched. The International Standard (ISO14460-1) also defined the surface of samples as '*a set of features which physically exist and separate the entire workpiece from the surrounding medium*'. It can, therefore, be understood that the surface connects an existing feature to its surrounding environment. Blunt and Jiang (2003) Identified the surface of an engineering component as a physical boundary between the work piece and the surrounding environment. These definitions allow one to understand the significance of the surface; it is an essential part of an object that can provide information about the object's geometry (Leach, Weckenmann et al. 2014). Surfaces can form different textures, which depends on the surface material type and the process that generate the surface. Therefore, understanding the property of surfaces is important, as most of the engineering component failures are significantly affected by the condition of the component's surface (Blunt and Jiang 2003). The surface texture has been defined by Leach (2010) and (2014) as '*the features that remain once the form has been removed*'. Continuing developments in the measurement of surface texture drives continuing research in the topic. Research on the measurement of surface texture has been carried out for over a century (Leach 2010). Improvement of surface texture measuring methods is constantly required to keep up with developments in manufacturing. Nowadays, manufacturing machines use high technologies to build an array of complex parts, such as laser micro milling machine (Pham, Dimov et al. 2002). The advanced manufacturing technology is able to produce a surface that has been deterministically designed to improve the functionality of the part (Evans and Bryan 1999, Alting, Kimura et al. 2003, Bruzzone, Costa et al. 2008, Whitehouse 2010, Jiang and Whitehouse 2012, Godi and Chiffre 2014, Senin, MacAulay et al. 2014). Some products require a specific surface texture to perform their function. For example, the special patterned-surface of an engine cylinder block and the surface texture of bearing part. The engine cylinder block needs to have a deterministic pattern with valleys to preserve the lubricant on the interior surface while the engine is working. Therefore, a dimpled surface texture or stratified surface texture that has a high deep valley can be used to increase the friction resistance of the cylinder block and achieve the required function and performance (Godi, Kühle et al. 2013, Graboń and Pawlus 2016).

Figure 1 shows the surface texture of an engine cylinder block. From Figure 1, the inner surface texture of an engine cylinder block has a patterned valley that can keep the lubricant. Similarly, the inner bearing surface texture can become as oil reservoir to reduce the issues of friction. These designed surface textures can directly affect the part’s function, such as wear resistance, reduce the coefficient of friction and operational lifetime (Stout and Blunt 2001, Jiang, Scott et al. 2007, Vorburger, Rhee et al. 2007, Chand, Mehta et al. 2011, Gupta, Kumar et al. 2013). The requirements for this type of surface texture can be fulfilled using various advanced manufacturing techniques, such as laser texturing process (Etsion 2005, Grabon, Pawlus et al. 2011, Yin, Li et al. 2012, Hsu, Jing et al. 2014).

Making a specifically-designed surface texture is one of the advantages of using advanced manufacturing techniques, for example micro-scale injection moulding, laser texturing and diamond turning. The advanced manufacturing techniques manufacture the designed surface texture with high precision. Subsequently, an accurate surface texture measurement is required to be able to measure and verify the tolerance of the surfaces. Measuring the specifically designed surface texture is challenging due to some reasons, for example the measurement depends on the surface materials, features to be measured are smaller than the optical resolution limit and the measurement with already well-understood tactile instrument is not anymore suitable. Some of surface texture measuring instruments cannot measure all surface types. For instance, the reflective, translucence and high rough surfaces can be difficult to measure in optical instruments.

Leach, Bointon et al. (2018) mentioned that all surface measuring instruments are currently limited to measuring only some types of surfaces. Understanding the different surface types can help improving the measurement process.

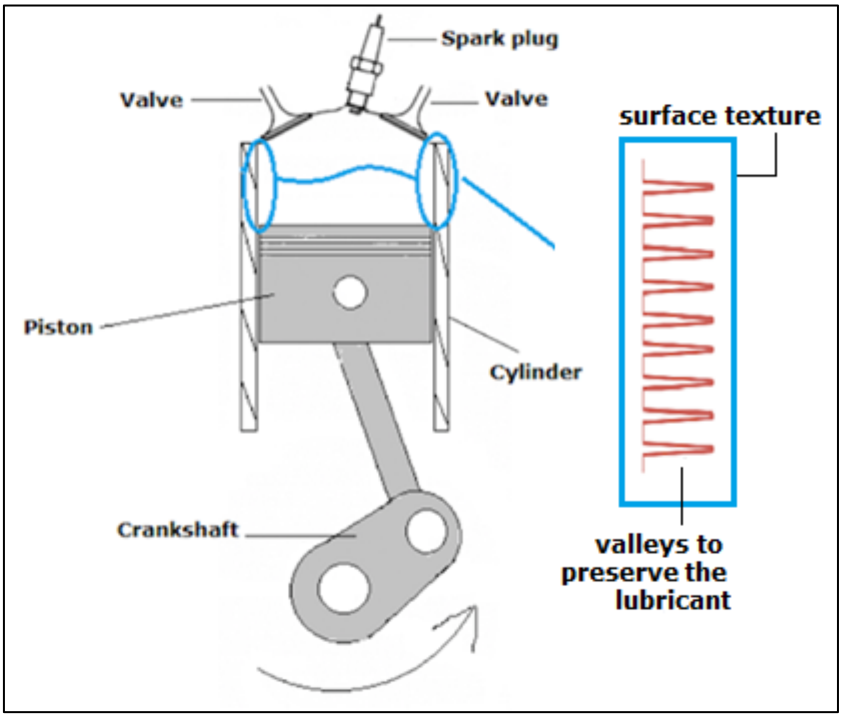

Figure 1: The engine cylinder block and the importance role of its surface

Different methods can be used to measure the surface texture based on the measurement of interest. The types of surface texture methods have been classified into: line profiling, areal topography and areal-integrating (Vorburger, Rhee et al. 2007, ISO25178-6 2010, Leach and Smith 2018). The methods of surface texture using line profiling and areal topography parameters are more popular in the industry and research sectors, as they provide the required data from the measured surface texture using surface topography measuring instruments. The areal-integrating type, on the other hand, relates more to the statistical information of the surface. Figure 2 shows the classification of surface texture measurements. Line profiling as a measurement parameter has been a subject of research focus for over a century (Leach 2013, Leach, Giusca et al. 2014) and has led to numerous publications. Although many measurements have been carried out using line profiling type, these measurement data for surface texture are inadequate. The line profiling type only provides data of a single profile form an entire surface. The areal topography measuring type, on the other hand, can cover a large area of measured surface and provide rich measurement data. For this reason, measurement of surface texture using areal topography has become more popular in research. Moreover, areal topography type can provide comprehensive information on the functional features of the surface (Jiang, Scott et al. 2007, Leach, Flack et al. 2009, Leach, Giusca et al. 2009, Giusca, Leach et al. 2011, Leach, Claverley et al. 2012, Leach and de Groot 2015). This advantage encourages further focus on the areal topography measurement, rather than line profiling. Table 1 compares line profile and areal measurements.

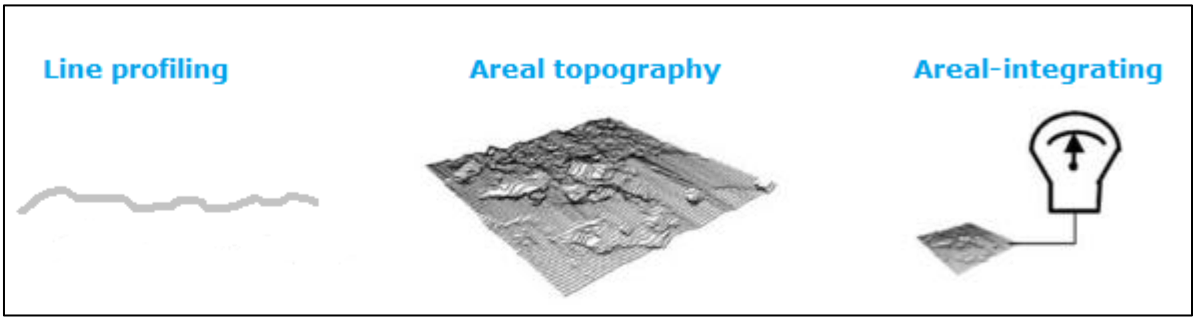

Figure 2: The classification of surface texture measurement

The measurement of surface texture is not a new concept. Areal topography measurements were first made between 1967 and 1970, with the first standard published at the end of 2005 (ISO/IEC17025 2005, Jiang, Scott et al. 2007). The considerable time delay in publishing may indicate slow development of this method. In addition, more focus may have been on line profiling measurements at that time. Jiang, Scott et al. (2007) and Kapłonek, Nadolny et al. (2016) confirmed that areal surface measuring instruments have only become available commercially in the early 1990s. Consequentially, several measurement companies have developed measuring systems that are suitable for areal topography, which have made this type of measurement more popular. The measurement of surface texture using either line profiling or areal topography can provide useful information on the manufactured surface quality; i.e. these instruments can calculate the parameters of Ra and Sa, which are frequently used for assessment of surface quality. Making accurate surface texture measuring instruments is important to obtain a reliable surface data and its surface texture parameters.

Table 1: Comparison of line profiling and areal topography measurements

Line profiling	Areal topography
Line measurement	Area measurement
More efficient data	Adequate data
2D	3D
Traditional measurement	Modern measurement
Only limited region	More real representation

1.2 The measuring instruments

The available surface texture measuring instruments for areal topography measurement operate based on different principles. Some of the instruments require contact with the measured surface, while others do not. The stylus (contact) and optical (non-contact) measuring instruments are the two techniques currently used for areal surface topography (Leach, Giusca et al. 2009, Leach and Smith 2018). The stylus instrument measures the surface texture using a stylus tip. The stylus instrument is commonly used as a reference measuring instrument. The reason is that a mature mathematical model that describes a profile obtained from rolling a ball, that is a stylus tip, across a surface is available. The model allows the prediction of the measuring results with high confident (Leach and Haitjema 2010, Leach and Giusca 2013). However, certain long-standing issues make the stylus instruments undesirable for measurement, in spite of its widespread use in research and industry. For this reason, the advantages of the stylus instrument do not outweigh its limitations. First, the stylus instrument can damage the surface being measured through contact with the stylus tip – this especially concerns measurement of soft surfaces. Moreover, this leads to reading of wrong data. The damage also can be to the stylus itself; for instance, it can break when contacting a surface with high impact. In addition, the stylus instrument proves time-consuming for certain measurements. Leach, Giusca et al. (2014) argued that areal surface texture measurements using a stylus instrument is time-consuming, as it requires multiple setup and calibration steps prior to the measurements. Furthermore, the stylus tip collects the measured data by touching all the determined points on the surface – this not only takes time, but also make the measurement difficult as large areas with complex topography are meant to be covered using areal surface texture measurement. Thus, the stylus instrument is an inappropriate method of areal measurement. Optical instrument, on the other hand, is the preferred alternate method for areal measurement as it overcomes the limitations of the stylus instrument. The optical instruments do not damage the measured surfaces and the short measuring times make this method easier to employ

(Whitehouse 2002, Leach 2004, Hansen, Carneiro et al. 2006, Leach and Haitjema 2010, de Groot 2015, Tosello, Haitjema et al. 2016). Table 2 shows the differences between the stylus and optical instruments. From table 2, optical instruments are more preferable to be used as areal surface texture measuring instrument. For instance, mounting the stylus component onto the system prior to measurement is not a requirement when using the optical instrument. Instead, the surface is measured using the instrument's illumination source through the objective lens or other methods, such as ring light. Although the optical instrument overcomes the stylus instrument in a number of ways, it is currently difficult to interpret the measurement results obtained using the optical instrument. The electromagnetic wave interaction between the light source and measured surface has no analytical solution to estimate the measured surface (Leach and Haitjema 2010, Foreman, Giusca et al. 2013, Leach, Giusca et al. 2014).

Table 2: Differences between stylus and optical instruments

Stylus	**Optical**
Stylus can be broken	No damage
Geometrical measurement	Optical path measurement
Slow measurement	Fast scan

Optical instruments for surface texture measurement operates using several techniques – similar in their measurement principles, but different in how they operate. optical instruments, available commercially to measure surface topography, comprise coherence scanning interferometry, confocal microscopy, digital holography, light scattering and focus variation (Leach and Giusca 2013, Leach, Giusca et al. 2013). Light scattering, notably, is used to statistically measure the surface parameter (area-integrating measurement) (Leach and Haitjema 2010). These optical instruments have been increasingly used in research and industry. The traceability of optical instrument has become important. To realise measurement traceability, an unbroken chain of calibration to the definition of a metre has to be established. The optical instrument should be calibrated against a more accurate measuring instrument and the measurement uncertainty of the calibration procedure should be stated for traceability. The calibration of areal surface texture instruments has received significant attention in research (Jiang, Scott et al. 2007, Leach and Giusca 2013, Leach, Giusca et al. 2015) and this has led to an international standard used to define specific characteristic for optical instrument calibration. The ISO25178 series is the international standard used for the calibration of areal surface texture instruments. The ISO25178 includes metrological characteristics (MCs) for the calibration process; these comprise measurement noise, flatness deviation, linearity deviation, amplification coefficient, *X-Y* mapping deviations, topographic spatial resolution and topographic fidelity (ISO25178-601 2010, Leach 2011, ISO25178:600 2012, ISO25178-606 2015, Leach, Giusca et al. 2015, ISO25178:600 2017, Haitjema and Leach 2018, ISO25178:600 2018). The details of these characteristics will be discussed in the next chapters. The optical measuring instruments such as for coherence scanning interferometry and confocal microscopy have been calibrated by determining the MCs. However, the calibration of FVM has not previously been completed using the MCs determination. This research will calibrate the FVM by completing the MCs determination.

To have a reliable surface texture measurements, the traceability of the measurement results should be established. To establish the traceability, optical measuring instruments for areal topography measurement should be calibrated by determining their MCs. Specifically for common FVM instruments, common available reference artefacts have very smooth and reflective surfaces so that the common FVM instruments cannot obtained the measurement of the artefact surfaces to calculate the MCs. Hence, new artefacts along with certain practical procedures (easy to carry out in a reasonable period of time) should be proposed to be able to determine MCs for FVM instruments.

1.3 Research aims

The thesis aims to investigate the traceability framework by determining the metrological characteristics (MCs) for a focus variation microscopy (FVM) instrument, as an optical areal surface texture measuring instrument. The investigation will comprise both development and manufacturing processes for a novel suggested reference artefact to determine the MC of the FVM. In addition, development of the calibration procedures will be included in this investigation. The research objective is to estimate the uncertainty of the measurement results. The aims of the thesis will be addressed by the following process. Each MC for FVM will be determined separately by measuring a suitable artefact in a separate experiment. If a suitable artefact for FVM is not available, a new low-cost artefact will be designed and manufactured. The new artefact will be calibrated with a more traceable measuring instrument to achieve traceability. The results for the new artefact with the more traceable instrument will be compared with the FVM and the uncertainty estimated.

1.4 Research questions

The method used to determine the MCs for FVM is important. Most of the available artefacts cannot be measured with FVM because of its measuring limitations with measuring smooth and transparent surfaces. Therefore, measuring a suitable artefact is important in this research project. The artefact used to determine the MCs for FVM will influence the choosing of good practical procedures. This research project focuses on FVM calibration by determining its MCs and has been motivated by the following research questions:

1- How can the MC of FVM be determined?
2- What are the suitable artefacts to determine the MCs for FVM?
3- What are good practical procedures to determine the MC with the suitable reference artefacts?

In this thesis, each MC of FVM can be determined by addressing some experiments. Four experiments will be implemented in the determination of measurement noise and measurement repeatability using the replica of an optical flat surface and flat surface artefacts. The determination of measurement noise will be with different measurement parameters, that are illumination parameters, contrast and brightness parameters. In addition, the determination will be with different scale location of the vertical motion stage and objective lenses. The residual flatness determination will compare ISO filtering rule and the proposed filtering method using two objective lenses of 50x and 100x. The proposed filtering method is applied by multiplying the sample distance of the field of view of each objective by ten. The ISO filtering process is a low pass Gaussian filter as stated in the ISO standard to generate an SF-surface with a cut–off the value that is equal to one-tenth of the field of view. The amplification, linearity and perpendicularity characteristics will be determined in three novel experiments, using novel and low-cost reference artefact. The determination will be performed for the lateral scale with multiple-image field measurements; vertical scale; and measuring the lateral scale with single image field measurement. Three new low-cost artefacts will be proposed to determine characteristics in vertical and lateral scale calibration. The cross-grating artefacts will be for the lateral scale calibration experiment and step height artefact will be for vertical scale calibration. The lateral period limit (LPL) will be determined using a novel method. The novel method will be presented using an artefact with a random surface.

1.5 Thesis structures

The following chapters will discuss the details of this project. Chapter 2 reviews the literature regarding the research project and is divided into two sub-sections: the calibration of areal surface texture measurements and the working principle of the optical instrument technique used here (FVM). The details of proposed artefacts used in the experiments of determining the MCs for FVM are in Chapter 3.Chapters from 4-7 will present the experimental results (proposed artefacts and procedure) to determine the MCs of the FVM. Measurement noise calibration will be reported in Chapter 4. Chapter 5 will report residual flatness calibration and Chapter 6 will report the calibrations of amplification, linearity and perpendicularity. Topographic spatial Resolution calibration will be reported in chapter 7. The final chapter will conclude and summarise the results of this thesis, including suggested future works.

Chapter two: Literature review

2 Literature Review
2.1 Metrological traceability

Traceability is an important terminology used in metrology, and, as being stated by Leach and Giusca (2013), it is as one of the most fundamental concepts. Traceability is indicated as one of the metrological pillars of the field. Leach (2010) and Leach (2014) claimed that any measurement in any manufacturing system must be traceable and documented. Traceability should be available in any measurement processes so that its value should be clearly demonstrated. Traceability assures in obtaining reliable and trustable measurements (Leach and Giusca 2013, Moroni, Syam et al. 2018) – i.e. it ensures measurement accuracy. Therefore, the subject of traceability is a fundamental topic when discussing metrology.

The international vocabulary of metrology (VIM) (JCGM200 2008, JCGM200 2012) has defined metrological traceability as '*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'*. This definition highlights that traceability can be achieved using a calibrated reference through an unbroken chain of calibration at all stages. This reference can be a calibrated material measure and/or traceable measuring instrument. Often, the instrument calibration achieves the traceability using a calibrated artefact (Leach 2010, Leach 2014). In addition, the mention of measurement uncertainty in the above definition shows the importance of traceability. Leach and Giusca (2013) and Leach, Giusca et al. (2015) stated that uncertainty is essential to and always an aspect of traceability; traceability cannot be established without stating uncertainty. Morel (2006) mentioned that measurement uncertainty is an essential element in traceability and that measurements cannot be compared if the uncertainty is not stated. Without stating the measurement uncertainty, the traceability chain cannot be constructed and a measurement may not yield a meaningful result. The method used to demonstrate the measurement traceability is a calibration (ISO25178:700 2018). Calibration along with measurement uncertainty are the essential part of metrological traceability.

Traceability can be achieved to different instruments for both profile and areal measurements; this has been discussed for stylus instruments for some years (Leach, Giusca et al. 2015). However, current traceability for areal surface topography instruments is, as yet, unsatisfactory, as the measurement conducting using stylus instrument takes relatively longer time (Leach and Giusca 2013, Leach, Giusca et al. 2015).

The unbroken chain mentioned in the metrological traceability definition is a '*sequence of measurement standards and calibrations that is used to relate a measurement result to a reference*' (JCGM200 2008, JCGM200 2012). This definition confirms the importance of the unbroken metrological traceability chain; moreover, Whitehouse (2003) and (2010) demonstrated that traceability is a measurement procedure employed for both national and international measurement standards. Once an instrument is traceable, it can be claimed that the measurement it provides will be accurate and reliable. The traceability chain infrastructure starts from the definition of the metre, which is the highest level in the traceability chain, to measurements conducted in the industry. The definition of metre is '*the length of the path travelled by light in a vacuum in a time interval of 1/c of a second, where c is the speed of light given by 299 792 458* $m{\cdot}s^{-1}$' (Petley 1983). Figure 3 shows the unbroken chain of the metrological traceability infrastructure.

The traceability process can be carried out using a primary instrument that has already been traceable – i.e. an instrument that is traceable and more accurate than the calibrated secondary measurement. Any instrument that is being calibrated with a primary instrument can be an example of a secondary instrument. The primary instrument can be used to calibrate a material measure and, then, to estimate the measurement uncertainty of the calibration results. When the calibration of material measure with primary instrument is completed, the secondary instrument can measure the calibrated material measure. The results of material measurements with the secondary instrument can be compared with those of the primary instrument. It should be noted that the definition of a metre has high accuracy and low measurement uncertainty. Thus, when the metrological traceability chain is moving down from the definition of a metre to the instrument that is being calibrated, the measurement accuracy decreases and the measurement uncertainty increases.

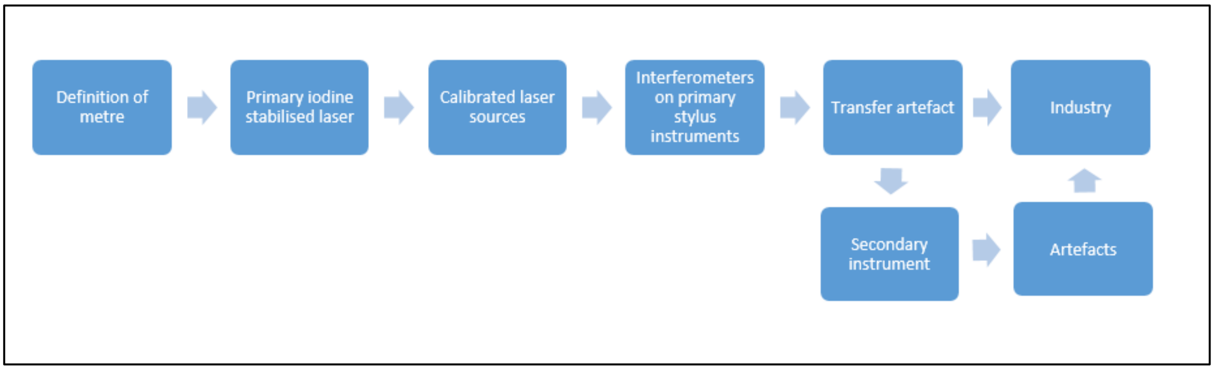

Figure 3: The traceability chain infrastructure

The metrological traceability chain can be applied through a calibration hierarchy (ISO/VIM 2004, JCGM200 2008, JCGM200 2012, ISO/WD25178-700.2 2014, ISO25178:700 2018, Leach and Smith 2018). The calibration process compares two measuring instruments, one of which is more accurate than the other, and the traceability to the metre is established by comparing against the measurement with the higher accurate instrument, that is, commonly the instrument at a national measuring institute (NMI) (Alan 2001, Cox and Harris 2006, Czichos, Saito et al. 2011, Smith 2013, NPL 2018). This calibration process creates the unbroken chain of metrological traceability. Thus, the unbroken chain of metrological traceability confirms that the measurement results obtained are referenced to a high level of traceability metrological chain (definition of metre) (ISO/IEC17025 2005, Hemming 2007, Czichos, Saito et al. 2011, Valery, Anna et al. 2013). When the measurement is linked to the national standard of known accuracy, traceability can be established. Each step in the calibration process should be supported by documented evidence to confirm the linked chain of traceability (Alan 2001, Czichos, Saito et al. 2011, Leach 2011, Estler 2014). Figure 4 depicts the calibration hierarchy according to the national metrology.

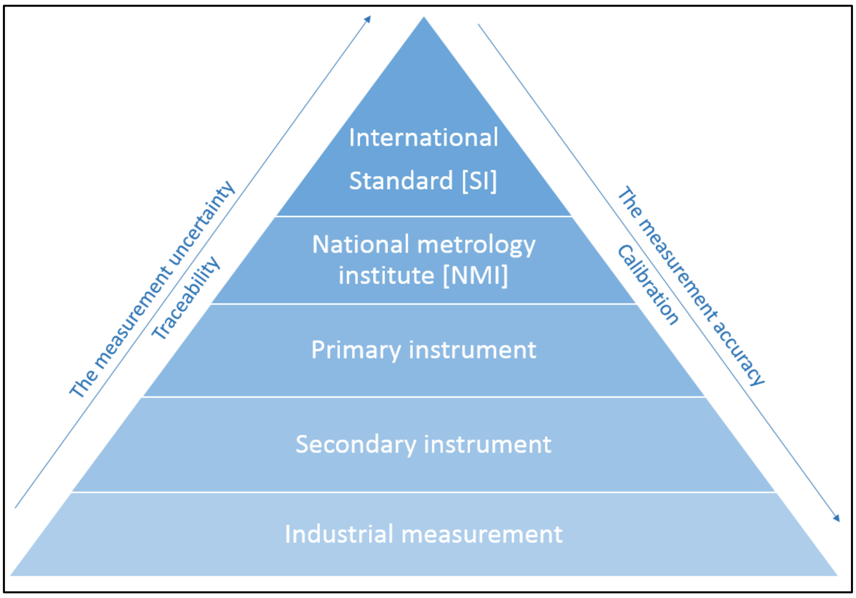

Figure 4: Calibration hierarchy

2.2 Calibration

The term 'calibration' can be used in different disciplines. However, Whitehouse (2003) and (2010) state that 'metrology is only as good as the calibration procedure', demonstrating the importance of calibration in metrology. The calibration of an instrument is one of the fundamental processes in metrology used to maintain measurement traceability (Mathioulakis and Belessiotis 2000, Raghavendra and

Krishnamurthy 2013, Advanced Instruments 2015). VIM (JCGM200 2008, JCGM200 2012) has defined calibration as an '*operation that, under 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 uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication'*. This definition clarified calibration as a practical procedure that follows required conditions so as to achieve a relationship from the results. Leach and Giusca (2013) and Raghavendra and Krishnamurthy (2013) mentioned that the conditions of an instrument calibration should be the same as those applied on a daily basis. For example, performing the measurement on the same temperature in controlled lab. The definition also emphasised that *the measurement uncertainty* is of importance in calibration. Smith (2013) and Syam (2018) mentioned that the measurement uncertainty should be stated when performing a calibration process to instruments and its result must be reported and appropriately certified.

The calibration process was explained by Ville (2003) as an operation applied to an element of already known dimensions to assess the measurement of the instrument. Although this explanation is correct, some crucial details relating to the calibration process are missed. Czichos, Saito et al. (2011) and Leach (2011) clarified that the calibration process can be achieved using a direct comparison against a more accurate measuring instrument, or certified material reference. Raghavendra and Krishnamurthy (2013) and Richard et al. (2015) agreed that calibration is a comparison operation between two measurements: one is used as a primary standard of a known value, while the other as the tested value. This method is used to demonstrate measurement traceability (ISO/WD25178-700.2 2014) and to established the traceability chain. Once the traceability with an unbroken chain is achieved, it can be assumed that the calibration process is valid. The results of calibration can then be presented in different ways, such as using a calibration diagram, curve, spreadsheet table or statement (JCGM200 2008, JCGM200 2012, ISO/WD25178-700.2 2014). One or more presentation types for calibration results are acceptable to use, depending on requirement.

The time it takes to perform calibration of a full instrument is the main barrier for industry to apply a calibration process (Leach 2011). The measuring time for the calibration using stylus instrument is time-consuming. Leach (2011) suggests using the optical measuring instrument to reduce the measurement time when measuring areal topography to overcome this issue. ISO25178 provides guide for the calibration process of surface measuring instruments by determining MCs (Giusca, Leach et al. 2011, Leach

2011, ISO25178-606 2015, ISO25178:700 2018). JCGM200 (2012) and ISO25178:700 (2018) state that calibration should not be confused with adjustment, which follows a different process. Giusca and Leach (2013) and Leach, Giusca et al. (2015) mentioned that the aim of the calibration process is commonly misused with adjustment. Instrument adjustment is only performed after the calibration process, typically by the manufacturers of an instrument to correct systematic errors (Raghavendra and Krishnamurthy 2013, ISO25178:700 2018). It is important to consider the differences between the two processes and avoiding misused terminologies.

2.3 Measurement uncertainty

Measurement uncertainty is one of the important terms in metrology that cannot be ignored. The measurement uncertainty can be used in a wide range of measurement results of metrology processes (Bell 2001). Any measurement taken by an instrument carries risks of errors and the true value can be difficult if not impossible to achieve. Measurement uncertainty is instrumental for conducting precise and accurate measurements that allows metrologists to confidently interpret the results and also to established measurement traceability (Bucher 2012, Smith 2013, Chen and Chen 2016, Leach and Smith 2018). Otherwise, the measurement results are ambiguous or not reliable when presented without information about the uncertainty. A level of uncertainty sources accompanies all measurements (Leach 2010, Raghavendra and Krishnamurthy 2013, Leach 2014); and can represent a specific margin with a level of confidence. VIM defined the measurement uncertainty as '*non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used*' (JCGM200 2008, JCGM200 2012). The non-negative parameter mentioned in this definition could be a standard measurement uncertainty. The measurement uncertainty is also defined as the range around the measurement results that contains the true value (Sładek 2015). The measurement results should, therefore, be presented as an interval within which the true value is expected. This degree of deviation in the measurement is described by the statement of uncertainty (Leach 2004, Leach 2014). Therefore, it is important to present the measurement results along with a statement of uncertainty – i.e. a results showing the measurement value, including the uncertainty statement and the confidence level. Leach (2004) and Morel (2006) agreed that a measurement would not be meaningful without stating the uncertainty in the result, but would only be an estimation or approximation of the measured value (Taylor 2009, Grous 2013). Stating the uncertainty shows the reliability of a measurement. In addition, with the stated uncertainty, one can then compare the differences between measurements values of the same surface carried out by different instruments.

Measurement results are deemed to be more reliable or more accurate the lower the uncertainty it has (Rabinovich 2006). The lower uncertainty of measurement results are desirable.

Measurement uncertainty can be estimated using two types of standard uncertainty evaluation, called type A and type B evaluations (Bell 2001, Kacker, Sommer et al. 2007, Czichos, Saito et al. 2011). These two types of standard uncertainty evaluation are different and should be used in any uncertainty evaluation. The guide to the expression of uncertainty in measurement (GUM) clarified the differences between two evaluations; type A is a statistical analysis from repeatability conditions, while type B does not use statistics but instead uses other sources, such as calibration certificates, expert opinions or previous published information (BIPM 2008).

GUM is a reference guide that should be followed when applying measurement uncertainty (Evans 2010, Caja, Gómez et al. 2015, Haitjema 2015, Leach, Giusca et al. 2015, Leach and Smith 2018) as it provides good methodology for estimation. For example, the calculation of uncertainty can be focussed on the parameter. More complex situation in areal surface topography measurements, the influence factor of using filtering and calculating the parameter on the measurement results should be taken into account as the contribution factors of measurement uncertainty (Leach 2011). However, applying the GUM guidelines is not that practical in practice as the procedure involves a mathematical model for surface texture measurement (Harris, Leach et al. 2010, Giusca, Leach et al. 2011, Leach and Giusca 2013) which most of the time the model is unknown or cannot be differentiated. Leach, Giusca et al. (2015) mentioned that the researches on measurement uncertainty from areal instruments is very limited; moreover, while it is available for optical instruments, some further research into this is required.

2.4 Material measure

Material measure in metrology is important to apply the measurement process. Material measures can be standard, where the value is known – such as the gauge block – and this can be used for instrument calibration to achieve measurement traceability. The standard material measure is traceable to the metre through the National Metrology Institute (ISO25178:700 2018). It is clear that when the material measure is traceable, it can be used for instrument calibration. However, different terminologies can be used to describe the material measure. ISO25178-70 (2014) stated that the material measure can also be named as an artefact, calibration sample, calibration specimen, calibration standard, standard artefact, physical measurement standard or physical standard. The last term is the most recent, one according to Leach, Giusca et al. (2015) and Leach and Giusca (2013). Despite the different terms, all terminologies have the same meaning and principles. Although there is no one rule for which term to use.

There are several definitions for material measure. VIM (2008) and (2012) has been defined the material measure as a '*measuring instrument reproducing or supplying, in a permanent manner during its use, quantities of one or more given kinds, each with an assigned quantity value*'. Furthermore, ISO25178-70 (2014) defined the material measure as '*surface texture dedicated manufactured workpiece intended to reproduce or supply, in a permanent manner during its use quantities of one or more given kinds, each with an assigned quantity value'.* Both definitions give a general explanation with a similar meaning and are useful to mention so as to cover any differences.

Several material measures are commercially available, as demonstrated by Leach and Giusca (2013) and Leach, Giusca et al. (2015), for profile and areal measurements. For example, the artefacts of NPL bento box. Different companies can provide different material measures and used for specific instrument types. However, there is currently a lack of material measures suitable for FVM. The reason is that common FVM instruments cannot measure very smooth and reflective surfaces (Leach 2011); thus, creating a new traceable artefact to overcome the FVM limitation is required for the calibration of surface texture measurements by FVM. In addition, Danzl, Helmli et al. (2008) claim that a special material measure should be designed for FVM.

2.5 Metrological characteristics

The calibration procedure should be applied following a standard approach. The MCs of areal surface topography instruments for surface texture measurements have been listed in the ISO 25178:600 series as a standard determination for areal surface texture measurement calibration. The concept of MCs is to provide simple and practical routines of calibration for areal surface topography instruments, that can be used by a non-expert user (Leach, Giusca et al. 2015). When the standard calibration is simple, any user in industry can easily perform it. This allows one to confirm that the calibration follows a standard approach and also can be applied by a non-expert user.

The MCs for all areal surface topography instruments comprise a common calibration framework (Leach, Giusca et al. 2015), which can be used to calibrate surface texture measurements. Leach (2011) and Leach and Giusca (2013) demonstrated that instrument calibration must involve MC measurements. Thus, MCs are defined as '*characteristics of measuring equipment, which may influence the results of measurement'* (ISO25178:600 2012, ISO25178-606 2015, ISO25178:600 2016). The importance of MCs lies in how they affect the measurement results. As mentioned in the calibration process section of this introduction, measurement uncertainty estimation is an integral part of this process. Leach (2011) and ISO25178:700 (2018) define the calibration process of surface texture measurements as a simple series of tasks that can evaluate the uncertainty of MCs; thus, there is a connection between calibration and MCs and the latter directly contribute to the measurement uncertainty (ISO25178:600 2012, ISO25178-606 2015, ISO25178:600 2016, Leach, de Groot et al. 2018).

The MCs involve measurement noise, flatness deviation, linearity deviation, amplification coefficient, *X-Y* mapping deviations, topographic spatial resolution and topographic fidelity (ISO25178-601 2010, ISO25178-606 2015, Leach, Giusca et al. 2015, Seewig and Eifler 2017, Haitjema and Leach 2018, ISO25178:600 2018, ISO25178:700 2018). Table 3 lists the MCs of areal surface topography instruments.

Table 3: A list of metrological characteristics for surface texture measurements

Metrological Characteristic	**Symbols**	**Axis**
Measurement noise	N_{M}	*Z*
Flatness deviation	Z_{FLT}	*Z*
Amplification Coefficient	α_x, α_y, α_z	*X,Y,Z*
Linearity deviation	l_x, l_y, l_z	*X,Y,Z*
X, Y mapping deviations	Δ_{PERxy}	*X,Y*
Topographic spatial Resolution	W_{R}	*Z*
Topographic fidelity	T_{FI}	*X,Y,Z*

The methods of determining the MCs have been developed by NPL, in particular for the stylus instrument, confocal microscopy and coherence scanning interferometry (Leach and Giusca 2013, Leach, Giusca et al. 2015). These methods can be used as a guide for other areal surface topography instruments, although individual instrument specifications should be considered. The current lack of suitable material measures for focus variation microscopy (FVM) can make determining some of the MCs problematic (Giusca, Claverley et al. 2014).

2.5.1 Measurement noise

Measurement noise, as discussed in ISO 25178, is one of the metrological characteristics of an areal surface texture instrument. The measurement noise is an essential metrological characteristic for instrument calibration (Leach, Giusca et al. 2015, de Groot 2017, de Groot and DiSciacca 2018). It has been defined in ISO25178:600 (2012), ISO25178-606 (2013), ISO25178-606 (2015) and ISO25178:600 (2018) as the 'noise added to the output signal occurring during the normal use of the instrument'. This definition means that the noise can affect the measurement analysis from an instrument and can thus affect the instrument's performance in terms of its measuring accuracy. In addition, measurement noise contributes to the measurement uncertainty (Giusca, Leach et al. 2012, ISO25178-606 2015, ISO25178:600 2018). It is clear that identifying the measurement noise inherent in the instruments can assist in estimating measurement uncertainty, since measurement noise will be one of the uncertainty contributors. When the measurement uncertainty is estimated, a measurement is reliable and traceable.

Noise within a measurement can originate from a number of different sources depending on the working area and the type of instrument. Basically, measurement noise is a combination of environmental noises (external noises) and the internal noises of an instrument, such as the noise of *Z* axis drive unit during scanning and the noise from the electronics (Giusca and Leach 2013, Barker, Syam et al. 2016, ISO25178:600 2018). Sources of noise within the environment in FVM measurements are temperature and vibration, while electronic noise from e.g. amplifiers and optical noise from e.g. stray light are the sources of internal noises. The noise from the drive units arises from the movement in the Z directions due to the imperfections of the geometry of mechanical components of an instrument.

Measuring instruments in an industrial area have different measurement noise compared to controlled laboratory, for example, NMI's laboratory. Measurement noise in an industrial area environment can be higher than that in a controlled laboratory (Barker, Syam et al. 2016). Machining operation and other rotary machineries in an industrial area is likely to be the source of vibrations which can be the main contributor to measurement noise in industrial environment. Lower levels of measurement noise are more likely obtained in a laboratory where environmental conditions are strictly controlled.

The ability of an instrument to take effective measurements performance can be affected by noises. An instrument's measurement performance capability, i.e. accuracy, is decreased when the noise level is increased. Noise, typically high frequency noise, can limit an instrument's ability to detect small-scale spatial wavelengths of a surface texture (ISO25178-606 2015, Barker, Syam et al. 2016). Noise can thus lead to a loss of information for the surface being measured. However, several process can be performed in order to reduce the noise. de Groot and DiSciacca (2018) claim that the noise can be reduced by averaging over time, smoothing filters or field averaging. Spending long measuring time by reducing the measurement speed can assist to decrease the noise. When the measurement data are averaged over time, the noise can be reduced. The long measuring time, a low measurement noise can be obtained. The noise result can be improved by reducing the measurement speed (Fleming 2013, TechNote(LT05-0010) 2014). The averaging process and using filter in the analysis can also be used to reduce the noise.

Material measure

The measurement of noise can be performed using a specifically designed artefact such as a smooth flat artefact (Giusca and Leach 2013, de Groot 2014, ISO25178-606 2015, ISO25178:700.3 2016). An example of smooth flat artefact is an optically flat material measure (Giusca, Leach et al. 2012). The deviation and roughness of optically flat material measure standard is negligible (Sa / Ra < 10 nm) and usually made of polished glass (ISO25178-70 2012, EdmundOptics 2018). However, some measuring instruments, for example, FVM have limitations to their measuring specifications and an optically flat material measure cannot be used. The FVM instrument needs to measure the surface contrast for each pixel compared to its neighbouring pixels in the image on the CCD sensor (Leach 2011). Therefore, as the optical flat material measure is smooth and transparent surfaces, its contrast cannot be measured by FVM instrument. For the FVM instrument a different process is required. For an FVM instrument, it is important to be aware of the range of roughness on a flat surface which the instrument can measure (ISO25178:700.3 2016). This is important with this type of instrument in order to avoid its limitations. FVM instruments can measure surfaces that have a surface roughness of greater than 10 nm. Leach (2011) has demonstrated that a replica process, that replicates the surface features of measuring artefact, can be used with a very smooth surface such as an optically flat artefact. Although a replica can assist in solving the surface measurement issues of FVM instruments, it is not always an appropriate method in practice because during the replication process, some features of the original surface may be lost. Macdonald (2014) argues that applying the replica method is not always possible. A reason is that replica materials cannot 100 % replicate a surface so that some feature details cannot be captured and transferred to the replica material. Gasparin, Hansen et al. (2011) confirmed that the achievement of replication degree is different from material to material. The replication degree is around 1 % for soft red-replica and 8-9 % for hard replica of a contoured artefact. Therefore, the replica operation may fail to replicate some of the features on the original surfaces that have nanoscale differences, such as very smooth or highly polished surfaces. Even when the original surfaces are very smooth, understanding the measurement noise from measuring a replica can still cause problems particularly with validity of the data obtained. Furthermore, some experiments of measurement noise have been conducted without using a smooth surface artefact. The material measure, which has been used for the measurement noise, is flat surface. de Groot and DiSciacca (2018) mentioned that the measurement noise is not limited to exceptional artefact of smooth surface. The results can also be obtained with another type of artefact that has flat surface. For example, using a structured silicon carbide reference flat surface and additive manufacturing artefact. The benefit of using flat surfaces that are far from the smooth surfaces can help to obtain low noise results if capturing the data is limited by the signal to noise (de Groot and DiSciacca 2018). The noise signal using flat surfaces can limit the ability of measuring instrument to capture the data. When the measuring instruments are limited, low measurement noise can be obtained.

Analytical background

Measurement noise is characterised by the parameter Sq_{noise} that is an Sq parameter, the root mean square (RMS) of the surface height measurements, can be used to estimate the amount of measurement noise (ISO25178:700.3 2016) and should be used when conducting measurement noise experiments. Measurement noise can be calculated using two techniques: subtraction and averaging (ISO/WD25178-700.2 2014, de Groot and DiSciacca 2018). These techniques can be applied to identical collected data but are different in their calculation methods. Giusca and Leach (2013) state that the results of the subtraction and averaging methods should be similar, therefore the same effect should be achieved by using both methods, and the most efficient method can be chosen by the user. When the results are not similar, the calculation process may not be correct or a non-stationary surface data occur that makes the averaging method fails to work (Baker et al., 2016).

For the subtraction technique, two measurements are taken at the same sample position and one is subtracted from the other (Giusca, Leach et al. 2012, Giusca and Leach 2013, ISO25178:700.3 2016). This operation removes the form and the underlying roughness of the surface. The equation that can be used after subtracting the measurements to estimate the measurement noise Sq_{noise} is:

$$Sq_{noise} = \frac{Sq}{\sqrt{2}} \quad (1)$$

Where *Sq* is the root mean square value of the scale limited surface after subtraction. To reduce the measurement noise variability, repeating the subtraction operation at least three times is advisable (Giusca and Leach 2013).

The averaging technique is another method for calculating measurement noise. According to Hiersemenzel (2013), this method for calculating measurement noise was first introduced by (Haitjema and Morel 2005). This method is based on the assumption that the contribution of instrument noise to multiple surface topography measurements at the same location can be decreased by the square root of the number of measurements (Hiersemenzel, Singh et al. 2012). When the data from several measurements can be averaged automatically by the acquisition instrument software, the average method can be useful. Using this method, the measurement noise is calculated as follows:

$$Sq_{noise} = \sqrt{\frac{Sq^2 - Sq^2_{mean}}{1-\frac{1}{n}}} \quad (2)$$

where *Sq* is the root mean square height of the un-averaged surface topography, Sq_{mean} is the root mean square height of the averaged surface topography, and *n* is the number of measurements (Giusca and Leach 2013). Recommending the most appropriate number of repeated measurements can be difficult (Giusca and Leach 2013). However, when increasing the number of topography measurements does not change the value of the estimated measurement noise appreciably, the number of measurements can be deemed to be sufficient.

Measurement repeatability can be used to estimate measurement noise and is defined in ISO25178:600 (2012), ISO25178-606 (2015), ISO25178:600 (2018), JCGM200 (2008) and JCGM200 (2012). The definition presented in ISO25178-606 (2015) is 'repeatability of topography map in successive measurements of the same surface under the same conditions of measurement'. While ISO25178:600 (2012) and ISO25178:600 (2018) have defined it as 'closeness of agreement between successive measurements of the same surface topography under the same conditions of measurement'. JCGM200 (2008) and JCGM200 (2012) defined the measurement repeatability as 'measurement precision under a set of repeatability conditions of measurement'. Although the definitions in all of these sources have the same meaning and present the same idea, there are slight differences in the explanations. The repeatability of surface topography measurements gives an indication of the likelihood of agreement between repeated measurements which can be expressed as a standard deviation (SD) (ISO25178-606 2015, ISO25178:600 2018). As this method focuses on the standard deviation between repeated measurements, it is quick to apply. For example, the value of standard deviation for ten measured surfaces can be calculated fairly rapidly. This method can be used as a complementary method for determining measurement noise (ISO25178:700.3 2016) and can thus be applied as part of analytical processes to assist in understanding the obtained values. It can be applied in the last stage of analytical processes after completing the subtraction or averaging calculations.

Previous works

Measurement noise has been studied in the past with different measuring instruments in both laboratory and industrial environments. Giusca, Leach et al. (2012) investigated measurement noise in laboratory conditions for three measuring instruments: a contact stylus, a coherence scanning interferometer (CSI) and an imaging confocal microscope (ICM). The study estimated measurement uncertainty and using the subtraction and averaging methods for measurement noise. Another work of the measurement noise is performed on point autofocus instrument (Maculotti, Feng et al. 2018, Maculotti, Feng et al. 2018). Barker, Syam et al. (2016) have conducted experiments with a coherence scanning interferometer (CSI) in an industrial environment. Measurement noise experiments using the focus variation technique has been conducted by Giusca, Claverley et al. (2014) and Hiersemenzel (2013). Previous experiments of measurement noise using FVM instruments have been carried out with the Alicona G4. Measurement noise experiments will be carried out in this research using an FVM Alicona G5 and the subtraction, averaging methods and measurement repeatability will be applied for calculations.

2.5.2 Residual flatness

Residual flatness for areal topography measuring method has been defined as ‘flatness of the areal reference’ (ISO25178:600, 2012; ISO25178-606,2015; ISO25178:600, 2018). It has been defined as ‘deviation of the measured topography of an ideally flat object from a plane’ (ISO25178:600 2016, ISO25178:600 2018, ISO25178:600 2019). These definitions demonstrate that residual flatness is related to the artefact surface and the error within the Z scale measurement rather than the measurement noise from the sensor and optical system. Therefore, the quality of the areal flat is important for this type of metrological characteristic. The flatness deviation can come from a number of sources, such as imperfections in the areal reference, residual flatness or the optical setup of the instrument (ISO25178:600 2016, ISO25178:600 2018). The residual flatness was measured using a standard Halle flat surface artefact (the details of the Halle flat surface artefact are presented in section (3.1) of chapter 3). Ninety-six sets of data of repeated measurements were collected from different locations. The measured surfaces of areal topography of different measuring locations using FVM were averaged prior to applying the measuring analysis to reduce random noises. Prior to applying the Gaussian filter to generate an *SF*-surface, form removal in term of levelling and thresholding of the averaged surfaces were applied to approximately flatten the surface so that the filtration process could be performed to obtain the result. The details of this process are described in section (5.1) of chapter 5. The parameter that is used to characterise residual flatness is *Sz*. This parameter is related to the highest and lowest points with respect to the reference plane obtained from a flat surface (Leach 2011, Leach and Giusca 2012, Giusca and Leach 2013, Leach 2013, Giusca, Claverley et al. 2014, Blateyron 2015, MichiganMetrology 2016) i.e. the highest peak and the lowest valley. Figure 5 shows the Sz value.

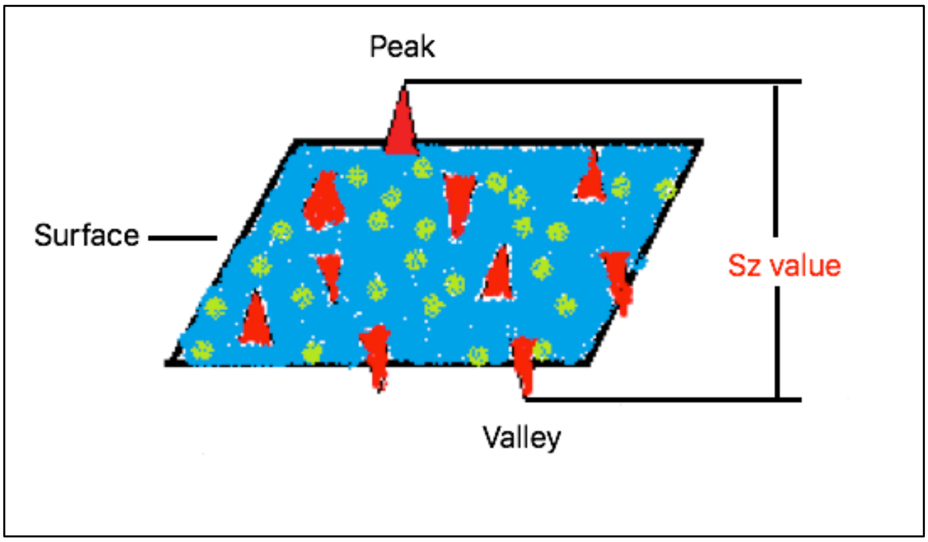

Figure 5: Sz value

Scratches and dirt are examples of local height variations on the measured surface that can affect the value of *Sz* (Leach 2011, Leach and Giusca 2012, Giusca and Leach 2013, Giusca, Claverley et al. 2014). It is obvious that when scratches or dirt are found on a flat topography, the measurement results could be affected significantly. However, measuring the surface of the artefact at a number of locations in the *X* and/or *Y* directions with the same instrument settings can assist in overcoming this problem (vdi/vde2617 2004, Leach 2011, Leach and Giusca 2012, Giusca and Leach 2013, Giusca, Claverley et al. 2014, ISO25178:700.3 2016, ISO25178:700.3 2018). As the condition of the surface at different locations will not be similar, measuring at different locations leads to a collection of different results from the surface and overcomes the problem. ISO25178:700.3 (2016) and (2018) confirm that using a number of measurement locations can decrease the effects of small deviations on the standard flat artefact. The results of this process therefore tend to be valid and more reliable than those from other processes. The point highlighted here is that it is important to maintain the perfection of the areal reference to reduce the amount of false data. ISO25178:700.3 (2016) and (2018) recommend that at least three different surface locations should be measured.

Material measure

The measurement of residual flatness concentrates on the *Z* scale errors of the vertical linear stage of an instrument. The residual flatness can be measured using a standard flat surface artefact (Leach 2011, Hiersemenzel, Singh et al. 2012, Leach and Giusca 2012, Giusca and Leach 2013, Giusca and Leach 2013, Giusca, Claverley et al. 2014, ISO25178:700.3 2016, ISO25178:700.3 2018). However, It is important to understand that the standard flat surface required for measuring residual flatness is not a perfect smooth surface (ISO25178:700.3 2016, ISO25178:700.3 2018). Therefore, the roughness of the standard flat surface used should be taken into consideration. When using optical measuring instruments, the limitations of the instrument, particularly for instruments using FVM method must be avoided. In a FVM, a certain degree of surface roughness needs to be present so that contrast values can be calculated for the FVM method to work (Leach 2011).

In practice, the ideal number of measurement repetitions cannot be recommended (Leach 2011, Giusca and Leach 2013). The number of repetitions required depends directly on the stabilisation of the *Sz* value, so recommending an exact number can be difficult. Every residual flatness experiment has different repeated measurements. The correct value of *Sz* can only be determined once the value stabilises. Therefore, it is best to simply repeat the measurements until the *Sz* value remains unchanged.

Filtering and threshold processes

The threshold and filter processes are applied during the analysis of the measured data. These processes can help to avoid spurious data and achieve effective *Sz* measurement (Ismail, Yanagi et al. 2010, Zeng, Jiang et al. 2010, Leach 2011, Giusca, Leach et al. 2012, Hiersemenzel, Singh et al. 2012, Giusca and Leach 2013, Giusca, Claverley et al. 2014). The threshold operation is used to remove irrelevant spike noises in the data. Therefore, the levelling process is carried out prior to the threshold operation. The levelling procedure can be applied as part of determining the residual flatness (ISO25178:700.3 2016, ISO25178:700.3 2018). From a practical point of view, removing the surface spikes on the levelled surface is an efficient methodology. Using a filtering process, long scale components of a surface can be separated from short scale components of a surface (Seewig 2005, Leach 2010, Whitehouse 2010, ISO25178-2 2011, Seewig 2013, Leach 2014, Blateyron 2015, ISO16610-60 2015, ISO16610-61 2015) so that different aspects such as roughness and waviness can be obtained. In addition, a filter can be used to remove the effects of high spatial frequency noise (Guan, Hirsch et al. 2016). For example, measurement noise calculations. A combination of filtering and threshold analysis can be an effective method for obtaining reliable *Sz* measurements. The filter recommended for the calibration of residual flatness is the *S*-filter (ISO25178-3 2012, ISO25178:700.3 2016, ISO25178:700.3 2018). This filter is a low-pass Gaussian filter with 1/10 cut-off on the field of view (Giusca, Claverley et al. 2014). It is important to apply a standardised procedure for calibration to ensure the correct process is followed consistently and any problems that may occur are avoided.

Previous works

Residual flatness experiments have been carried out previously with a variety of areal surface topography measuring instruments and have included estimates of measurement uncertainty. Giusca, Leach et al. (2012) Performed residual flatness experiments with a coherence scanning interferometer (CSI) and an imaging confocal microscope (ICM). Another work for residual flatness using ICM has been carried out by (Bermudez, Felgner et al. 2018). With FVM instrument, two different methods of carrying out the experiment have been implemented. In one case, the residual flatness data was compared for different averaged surfaces using a filter (Hiersemenzel, Singh et al. 2012). In the second case, a filtering procedure was applied and the results compared with the unfiltered results (Giusca, Claverley et al. 2014). All of these experiments were carried out on a FVM Alicona G4. The experiments in this research will be carried out using a FVM Alicona G5.

2.5.3 The amplification, linearity and perpendicularity

The three metrological characteristics of surface texture measurements are for scales calibration. Both the amplification coefficient and linearity deviation characteristics are focusing on the measurements of the X, Y and Z axes (ISO25178-601 2010, Leach 2011, ISO25178-606 2015, Haitjema and Leach 2018, ISO25178:600 2018, ISO25178:700.3 2018). Therefore, these two characteristics may have the same process in applying the measurement. Due to these characteristics have the same interest in calibrating the axes, the characteristics can use the same measurement data. For example, when the measurement data of used artefact are collected, both the amplification coefficient and linearity deviation characteristics can use them. ISO25178:700.3 (2018) states that the amplification coefficient and linearity deviation characteristics can use same measurement data in the determination. In addition, Leach (2011) and Giusca and Leach (2013) demonstrate that the relationship of an ideal and instrument response curve on each of the three axes can be established by the amplification coefficient and linearity deviation characteristics. This means that two metrological characteristics can be implemented together with the same experiment. While the perpendicularity characteristic is only focused on *X* and *Y* axes. In spite of the perpendicularity characteristic has different interest of axis measurements, it does not mean that the characteristic cannot use the same data of amplification coefficient and linearity deviation characteristics. As the measurement data of the amplification coefficient and linearity deviation for *X* and *Y* axes are not containing the measurements data of *Z* axis, the perpendicularity characteristic can use the same measured data of the amplification coefficient and linearity deviation characteristics in *X* and *Y* axes. ISO25178:700.3 (2018) mentioned that the perpendicularity characteristic does not need to be calibrated separately and determined directly. It can be demonstrated that the amplification coefficient, linearity deviation and perpendicularity characteristics can be applied together using the same experiment data.

The definitions can provide more understanding on these characteristics. The amplification coefficient characteristic has been defined as 'slope of the linear regression curve obtained from the response curve' (ISO25178-601 2010, ISO25178:605 2011, Giusca, Leach et al. 2012, de Groot and Beverage 2015, ISO25178-606 2015, Leach, Giusca et al. 2015, ISO25178:600 2018). The response curve here means the instruments' results that are obtained from the measurements. In order to clarify the amplification coefficient definition, an example of linear response curve can be shown in Figure 6. From Figure 6, an ideal curve, response curve and Linear curve which slope is an amplification coefficient are indicated by number (1), (2) and (3), respectively. When the collected values are equal to the input quantity values, it can be assumed as an ideal response (ISO25178-601 2010, ISO25178-606 2015, ISO25178:600 2018). This means that a slope of straight line can be equal to 1. While the linearity deviation has been defined as 'the maximum local difference between the line, from which the amplification coefficient is derived, and the response curve or function' (Giusca, Leach et al. 2012, ISO25178-606 2015, Leach, Giusca et al. 2015, ISO25178:600 2018). Both the definitions of the amplification coefficient and linearity deviation confirm the relationship between these two characteristics. Leach (2011) explained that the relationship of amplification coefficient and linearity deviation can be established by the ideal response curve and the instrument response curve on the scales of *X*, *Y* and *Z*. Therefore, when the amplification coefficient characteristic is determined, the linearity deviation characteristic should be mentioned.

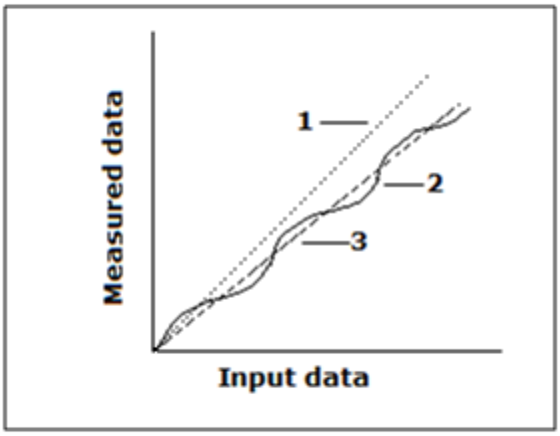

Figure 6: linear response curve

The Perpendicularity characteristic can be related to the amplification coefficient and linearity deviation characteristics. This characteristic can be applied using the same measuring data of amplification coefficient and linearity deviation that focuses on the *X* and *Y* axis. The perpendicularity characteristic that is related to *X* and *Y* axis is interested on their nonlinearity and can be performed after the amplification coefficient and linearity characteristics. These information were confirmed by the perpendicularity definition. ISO25178-601 (2010), Giusca, Leach et al. (2012) and ISO25178:700.3 (2018) defined the perpendicularity characteristic as 'the perpendicularity deviation between any two of the *X*, *Y* and *Z* axes'. It can be applied by determining the angle deviations between X and Y axis. These deviations occur by different reasons that depend on the measuring instrument type. In the imaging optical instruments, the deviations of the linearity and perpendicularity indicate to the optical distortions (ISO25178:700.3 2018). The optical distortions mean lens error which is very rare appearing perfectly (Mansurov 2015). Figure 7 shows the linearity and perpendicularity deviations.

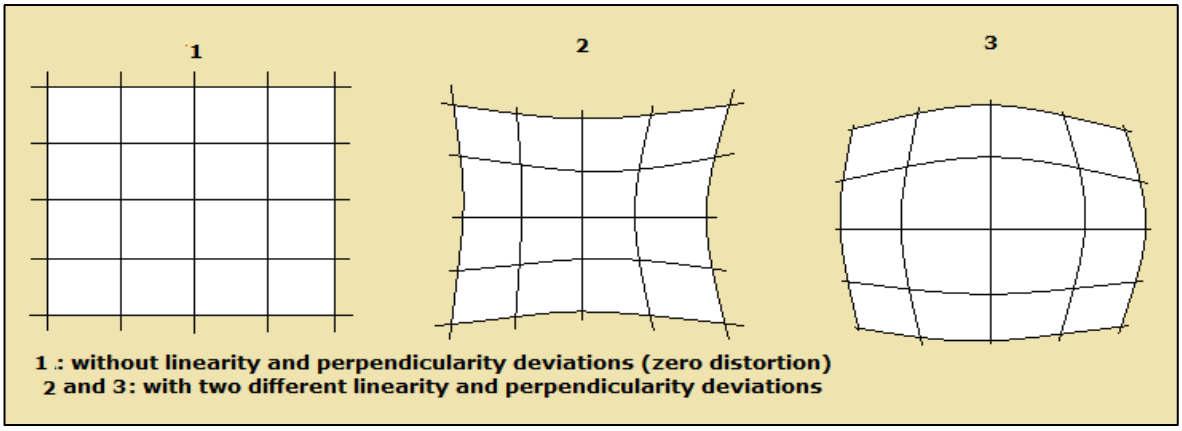

Figure 7: example of linearity and perpendicularity deviations

Material measure

The determination of the amplification coefficient, linearity deviation and perpendicularity characteristics uses a calibrated material measure to perform the experiment. ISO25178:600 (2018) and ISO25178:700.3 (2018) demonstrate that a standard material measure with calibrated depth can be used in the amplification coefficient, linearity deviation and perpendicularity characteristics. The standard material measure means that the material measure is calibrated and traceable with most accurate measuring instrument. Therefore, it is important to notes that the artefact areas should be calibrated prior to performing the measurements (Leach 2011, ISO25178:700.3 2018).

A cross grating artefact can be used for the amplification coefficient, linearity deviation and perpendicularity characteristics. Giusca, Leach et al. (2012) and Giusca and Leach (2013) and Leach, Giusca et al. (2015) state that a calibrated cross grating artefact that has different pitch values is measured to determine the amplification coefficient, linearity deviation and perpendicularity of local characteristic of the lateral scales. The measurement of centre position of gravity is required when measuring the *X* and *Y* axes. Therefore, the distances of *X* and *Y* plane and the grid positions should be calibrated (ISO25178:700.3 2018). With this type of the artefact, the measurements should cover most of the areas within *X* and *Y* axis. ISO25178:700.3 (2018) recommend that 95% is the minimum measurement area of the *X* and *Y* lengths. When the measurements are applied on the most of the artefact area, it can give reliable results.

A calibrated step height artefact is another artefact type that can be used in the measurements of *Z* axis. It is important that using an artefact should be appropriate for the characteristic. Leach (2011) provides that the calibration of *Z*-axis is often performed by using a single-step artefact, but it cannot afford a sufficient information. Therefore, using different step height artefacts with different height can be appropriate for the amplification coefficient and linearity deviation in case of measuring the *Z*-axis. The different step height artefact can provide enough information comparing with a single step height. Giusca, Leach et al. (2012) and Leach (2015) argue that the relationship between the ideal response curve and instrument response curve can be established by different step height with various heights. However, it should be noted that the current available artefacts to determine the amplification coefficient, linearity deviation and perpendicularity characteristics are not suitable for FVM instruments due to its limitation of measuring smooth surfaces. Low image contrast of smooth surfaces prevents the CCD sensor of FVM from differentiating one pixel with respect to its neighbouring pixels (Leach, 2011) (please see section 2.6.4 in chapter 2 for more details). Therefore, the FVM cannot capture appropriate measured data of smooth surfaces. To solve this issue, a new artefact must be manufactured when determining these metrological characteristics for FVM.

Previous works

The amplification coefficient, linearity deviation and perpendicularity characteristics have been done with some of areal surface texture measuring. Giusca, Leach et al. (2012) carried out the amplification coefficient, linearity deviation and perpendicularity characteristics with using three measuring instruments such as contact stylus instrument (CS), coherence scanning interferometer (CSI) and imaging confocal microscope (ICM). The calibration was applied on measuring cross grating artefact for *X* and *Y* scales and step height artefact for *Z* axis. Furthermore, these characteristics have been applied using coherence scanning interferometer (CSI) and phase shifting interferometers (PSI) by Giusca and Leach (2013). In addition, de Groot and Beverage (2015) performed the amplification coefficient using interference microscopy. The step height standard artefact and the wavelength scanning standard method have been used in the study. However, the amplification coefficient, linearity deviation and perpendicularity characteristics have not yet been investigated in FVM G5.

2.5.4 Topographic spatial resolution

According to Leach, Giusca et al. (2015), resolution is difficult to define for the areal surface topography instrument, due to problems with determination. Resolution determination uses different procedures for lateral and vertical axes, therefore, defining resolution is not straightforward. However, the latest version of ISO25178:600 (2018) includes the term *'topographic spatial resolution'* as a metrological characteristic for the lateral resolution determination of surface topography instruments. The term *topographic spatial resolution* provides a definition for different measurement methods. Topographic spatial resolution is defined in ((ISO25178:600) as a '*metrological characteristic describing the ability of a surface topography measuring instrument to distinguish closely spaced surface features'*. Although topographic spatial resolution is an umbrella term for different measurement methods, it can be quantified using several parameters and functions.

Resolution can be determined depending on the type of axis; vertical scale (*Z*-axis) resolution is influenced mostly by measurement noise and residual flatness (Leach and Giusca 2013, Giusca, Claverley et al. 2014, de Groot 2017), therefore, measurement noise can be used to determine *Z*-axis resolution. However, *Z*-axis resolution, in this case, is contributed without the lateral component. In their work, Leach, Giusca et al. (2015) agreed that measurement noise can be enough to quantify resolution of the *Z*-axis, from the measurement uncertainty point of view. Noise measurement is estimated by *Sq*, which is measured from a flat surface. To contribute to lateral resolution, the lateral period limit (LPL) or '*structural resolution*' can be used to determine *X*- and *Y*-axis resolution, i.e. the lateral resolution (Giusca and Leach 2013). The LPL closely measures the minimum space between two features, where the depth of the two features can be resolved to at least 50 % of its original depth (ISO25178:600, 2018) (ISO25178:600 2018) (ISO25178:600 2018) (ISO25178:600 2018). In their work, Xie, Lehmann et al. (2012) stated that the role of lateral resolution is becoming more important as well as the axial resolution of measuring instruments. The lateral resolution provides information on the measuring instrument, in detecting the smallest sized features in a surface. The lateral resolution in a 2D measuring instrument can distinguish between the lateral distances between two points, regardless of the depth of the two points. However, 3D measurement of areal surface texture instruments considers the height of features as an essential attribute of that feature. It should be noted that 'lateral period limit' is used instead of '*lateral resolution*'. The lateral period limit is used for 3D resolution, or the ability to distinguish two objects on one surface, including correct height measurement (Leach 2011). Therefore, LPL determination can be used in quantifying the topographic spatial resolution for areal surface topography measuring instruments.

LPL has been defined from different sources, such as ISO25178-606 (2015) and ISO25178:600 (2018). The LPL is defined as '*the spatial period of a sinusoidal profile at which the height response of an instrument transfer function falls to 50%*' (ISO25178:600 2018). 'Sinusoidal' indicates the type of artefact that can be used for resolution. Additionally, 'instrument' refers to optical and stylus instruments. The definition states that the height response of an instrument should also be considered. A useful parameter that can be used for instrument response characterisation, is the optical resolution limit which is based on the Rayleigh criterion (ISO25178:600 2018). This criterion is related to the LPL value for the theoretical quantification of the optical lateral resolution.

The LPL is useful in determining the smallest lateral feature that can be meaningfully measured. The LPL is the width limit of a feature, where its depth can still be resolved at least 50% of from its real depth (ISO25178:600 2019). An example is presented in Figure 8, where (A) illustrates LPL and its relationship with the depth of a measured feature. The depth can be reconstructed when the feature width is larger than the lateral resolution (B): the measured depth is equal to the feature depth, and the width is larger than the lateral resolution. However, when the feature width is less than the lateral resolution, the depth cannot be completely reconstructed (C): the width is less than the lateral resolution and the depth is less than the feature depth. It is important to know that the minimum lateral resolution can reconstruct the depth of groove, for example, the measured data can be obtained once the depth limit of the width of groove is constructed.

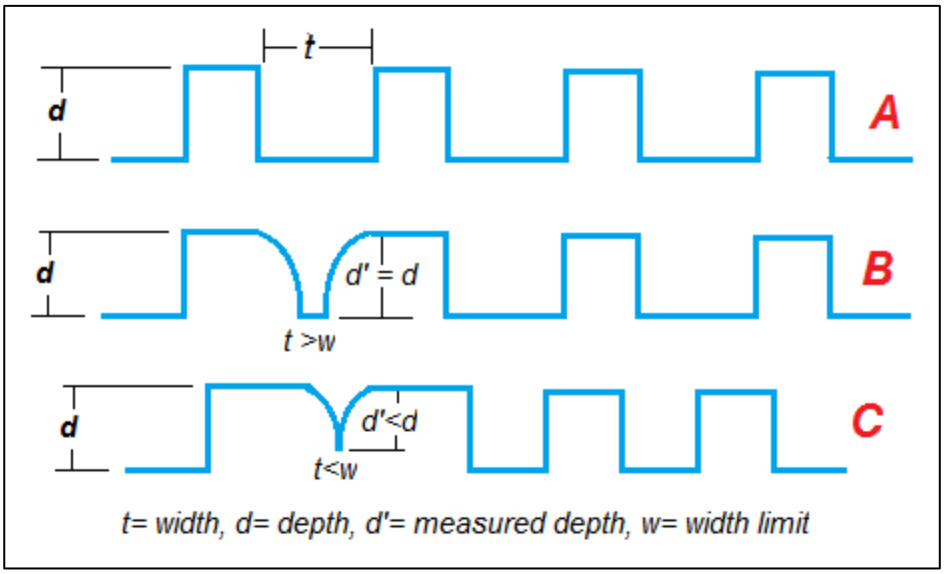

Figure 8: The lateral period limit (LPL).

Material measure

LPL may be determined using different types of artefacts; in their work, Giusca and Leach (2013) stated that a Siemens star artefact could be used to determine LPL. For example, NPL standard artefact of Siemens star. This type of artefact provides continuous spatial wavelengths to measure resolution in different lateral directions, therefore using this type of artefact is useful in determining resolution, if suitable for the measuring instrument. However, the FVM cannot measure this type of artefact, because it has a very smooth surface (Ra < 10 nm). Therefore, a suitable resolution artefact for FVM is required. Leach (2011) demonstrated that the design of resolution artefact is important in generating high quality resolution measurements. Because the artefact design of resolution measurements can affect resolution values, the resolution of other areal surface topography measuring instruments can be determined using a type ASP material measure, following ISO definitions of lateral period limits (Giusca and Leach 2013). The ASP material measure is a 3D version of Siemens star artefact can provide a continuous variation in spatial frequency (Xu, Fang et al. 2012, Giusca and Leach 2013, Leach, Giusca et al. 2015). Giusca and Leach (2013) used star-shaped artefacts of ASP material to determine the lateral resolution of areal surface topography measuring instruments. Different methods can be used to determine the LPL. ISO25178:600 (2012) states that a vertical edge, sphere or a number of gratings, can determine the LPL, e.g. a rectangular grooved surface artefact can be used when combining limits for full height transmission function.

Previous work

Resolution experiments, using optical measuring instruments, were carried out for several optical instruments. The LPL resolution phase shifting interferometry has been reported by Giusca and Leach (2013). In their work, a star pattern comprising ASP material was measured using a 50x objective lens, along with the analysis method used to calculate the LPL. Results from (Giusca and Leach 2013) were confirmed by measuring step height artefacts, however, FVM resolution has not yet been determined. As mentioned previously, the Siemens artefact, used for resolution determination is not suitable for FVM. Measurement of the Siemens star artefact using FVM is shown (Figure 9). Here, the Siemens star artefact is measured on FVM using 20x and 50x objective lenses. The surface features of the artefact failed to be reconstructed by FVM, therefore, LPL quantification cannot be calculated from this artefact.

In addition, profile measurements of both objectives lens do not provide reliable artefact results. When the surface cannot be reconstructed, resolution determination cannot be performed. Figure 10 shows FVM profile measurements of 20x and 50x objective lenses, therefore, FVM requires a suitable artefact with a rough, measurable surface. Alternatively, a random surface artefact is suggested. This thesis therefore proposes a novel method for FVM resolution determination with random surface artefacts.

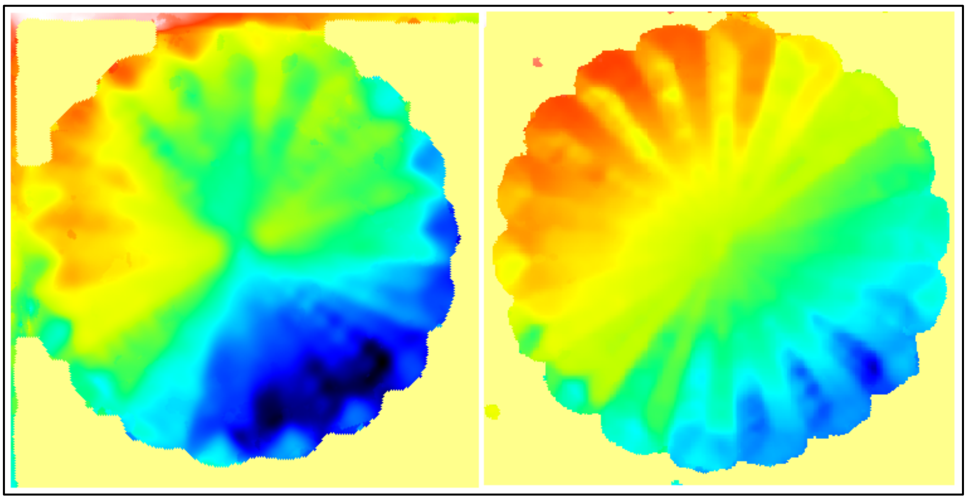

Figure 9: A Siemens star artefact, measured with FVM using 20x (left) and 50x (right) objective lenses. FVM failed to reconstruct the surface of the artefact.

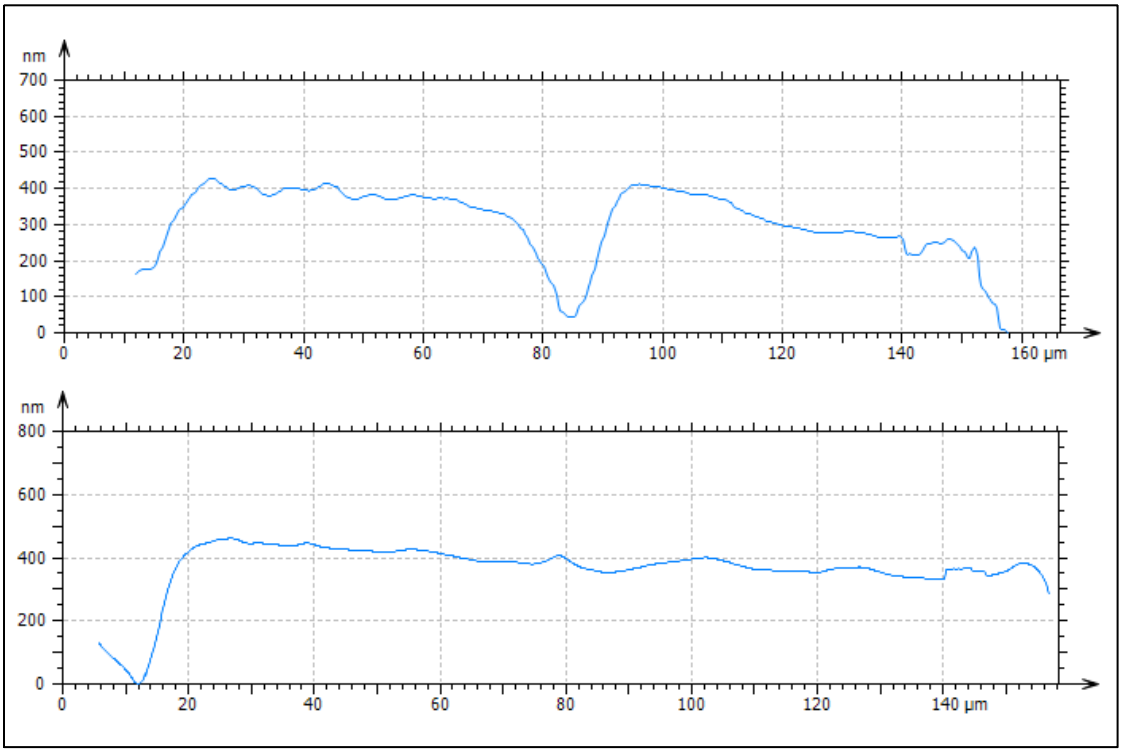

Figure 10: Profiles extracted through the petal of the Siemens star artefact, using FVM 20x (top) and 50x (bottom) objective lenses

2.6 Focus variation microscopy

There are several standard methods available to measure surface texture, one of which is focus variation microscopy (FVM). FVM is a software technology used for operating optical instruments for surface texture measurements. FVM can provide multi-measurements of surface texture in both 2- and 3D. Danzl, Helmli et al. (2009) and Alicona (2015) stated that FVM can measure the roughness, wear, form and welding spots inspection. This makes FVM a reliable measuring tool that can be used in both industry for quality of products and in the laboratory for research and development. FVM has been defined in (ISO25178-6 2010, ISO25178-606 2015) as a '*surface topography measurement method whereby the sharpness of the surface image (or another property of the reflected light at optimum focus) in an optical microscope is used to determine the surface height at each position along the surface'*. This definition emphasises that the FVM method only works with optical instruments to measure surface topography and the data is collected from the reflected light of the optical microscope.

The FVM is developed in several stages until the launch of the final version in the mid to late 1980s (Grossmann 1987, Pentland 1987, Helmli, Hiersemenzel et al. 2012, Hiersemenzel, Singh et al. 2013). The term 'focus variation' was based on a method called 'shape from focus' (SFF) (Hiersemenzel, Singh et al. 2012) – the predecessor of the FVM. The final technique was then commercially deployed as an instrument with hardware and software for surface topography measurements. Hiersemenzel, Singh et al. (2013) mentioned that that FVM was initially developed from 'depth of field', with the final development an accepted improvement of the technology capable of capturing 3D data (with colour) using a specific algorithm at the vertical axis.

2.6.1 FVM working principle

The optical instruments for areal surface topography measurements are similar in their components, but different in working methods. For example, optical instruments have light and different magnifications to measure surfaces. Different sources provide explanations on how the FVM functions (Danzl, Helmli et al. 2009, Danzl, Helmli et al. 2011, Leach 2011, Hiersemenzel, Singh et al. 2013, Tian, Weckenmann et al. 2013, ISO25178-606 2015, Moroni, Syam et al. 2015). A full FVM measurement can be completed when the 3D information of measuring surface is presented.

FVM working principle starts from a white light source passing to the splitting mirror through an optical tube. Then, the splitting mirror guides the white light towards the objective lens that measures the sample's surface. When focused on the sample surface, the white light is reflected by the surface in different directions. Some of the reflected light from the measured sample is captured by the objective and back again through the optical tube to the image sensor after passing a tube lens. It is important to note that the behaviour of reflective light from the sample's surfaces depends on the type of surface. For example, a diffuse surface type causes all light to be strongly reflected in different directions, whereas a specular surface reflects light in one direction. A charge-coupled device (CCD) sensor, which is located behind the tube lens, then gathers and sense the reflected light. The focus variation value then can be calculated for the formed image. Figure 11 shows the working principle of FVM. The ring light can also be used with FVM to allow measurement of slope surfaces that exceed 80°. This option is an advantage for FVM over other optical measuring instruments. A slope angle of more than 80° will prevent the reflected light from coming back to the lens opening (lens aperture) so that there is no light coming to the image sensor, for example, the numerical aperture of 20× objective lens. Other interferometer-based instruments cannot use ring-light because the ring light does not pass through a reference lens as happens in the axial light system. In an interferometer-based instrument, a reference light is required to create interference fringe from where a surface height can be inferred.

3D surface reconstruction is performed during a measurement by capturing a stack of images continually along the vertical movement of the precision optics head. Changing the focus can affect the contrast on the CCD sensor. The contrast analysis evaluates the variation of focus for each pixel in each image using an algorithm. The sample can be measured when the focus position become in focus (see Figure 12). Repeating this process in each lateral position allows one to measure the sample topography in the range of the objective field of view. This process converts 2D information into 3D, including colour imaging and depth information. Figure 12 shows the 3D surface reconstruction process from a stack of images of FVM.

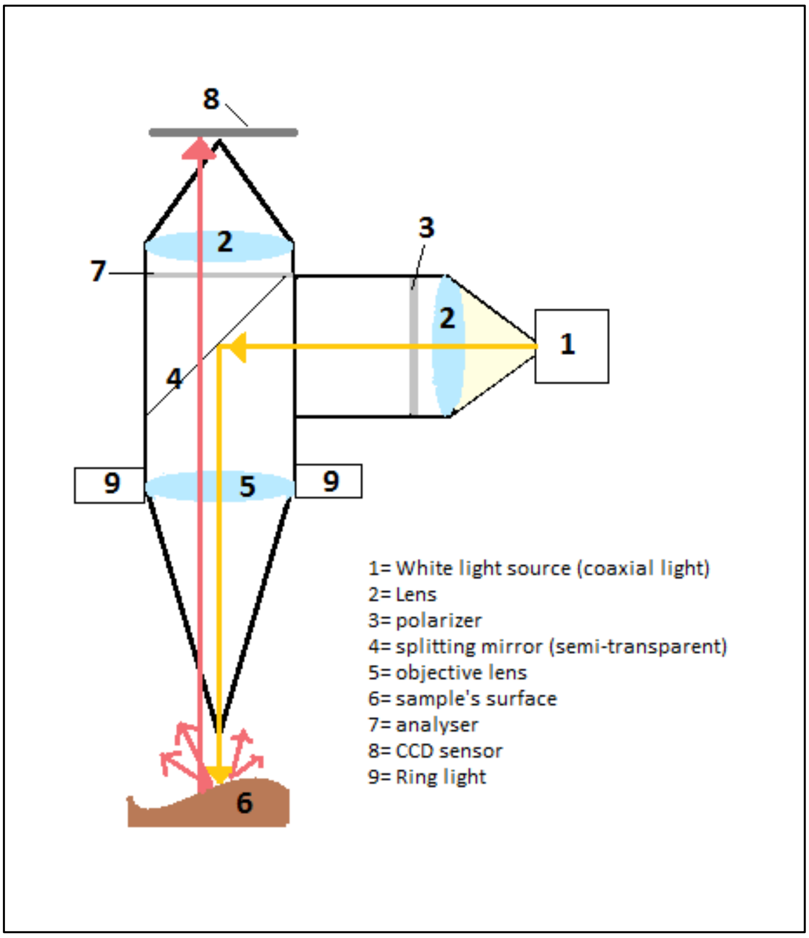

Figure 11: FVM schematic diagram

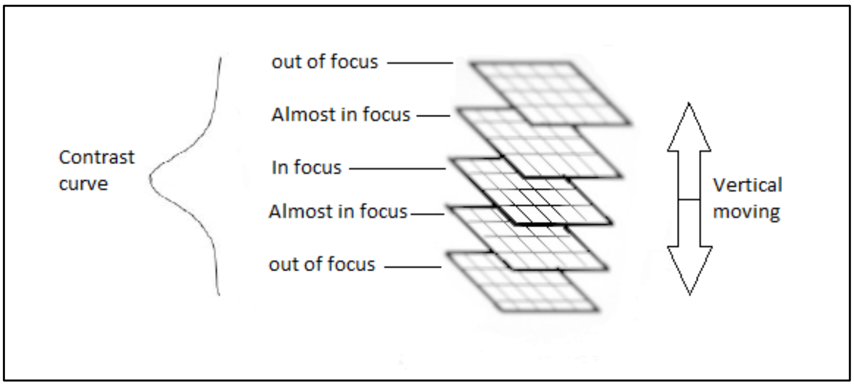

Figure 12: Evaluation process

2.6.2 FVM components

Optical system

According to Vernhes, Bloch et al. (2008), the optical system is the main component of the FVM that confers its precision and includes different lens systems. It is located in the main head of the FVM and can move vertically to elicit the measurement process. In addition, the lens systems require different objectives to allow for measurements of different resolutions (Vernhes, Bloch et al. 2008, Danzl, Helmli et al. 2009, Danzl, Helmli et al. 2011, ISO25178-606 2015). These objectives differ depending on the measuring field of view and required resolution.

Charge-coupled device (CCD) sensor

The CCD is located at the optics system of the FVM (number 8 in figure 6). The CCD collects the reflected light from the measured surface to analyse the data and the sensor must have two characteristics – high spatial resolution and high radiometric resolution – to distinguish between in- and out-of-focus (Leach 2011). The high spatial resolution minimises the calculation region of the focus and the radiometric resolution improves calculation of the focus of low contrast samples. Without these characteristics, the capability of FVM to reconstruct a 3D surface is limited.

Light source

The measurement process begins from the emitted light source, located in the optical system of FVM – as previously mentioned. Leach (2011) stated that the light source confers quality of the FVM measurement. The light source has been defined in ISO25178-606 (2015) as a '*source of light containing a continuum of wavelengths in a predefined spectral and spatial range'*. The FVM can use different light sources, with the illumination type including coaxial light emitted through the optical train and/or from the side called ring light (Danzl, Helmli et al. 2011, Hiersemenzel, Claverly et al. 2013, ISO25178-606 2015). In addition, the light can be external to the measuring instrument (ISO25178-606 2015). The choice of illumination depends on the measuring surface; the ring light can provide more information from the surface by increasing the capability of measuring high slope surfaces so as to exceed 80**°** and overcome the limitation (Danzl, Helmli et al. 2009, Leach 2010, Danzl, Helmli et al. 2011, Hiersemenzel, Claverly et al. 2013, Helmli, Danzl et al. 2014, Leach 2014).

It should be noted that using different illumination types results in different forms of light projection – needed to measure different sample types and to achieve a high contrast image by the CCD (Leach 2011, Macdonald 2014). The different forms of light projection, for general optical instrument, include coaxial illumination, ring light, diffuse light, dark field light or point illumination (Figure 13). Using these different forms of light projection overcomes measurement limitations associated with surfaces with different reflection properties (Leach 2011).

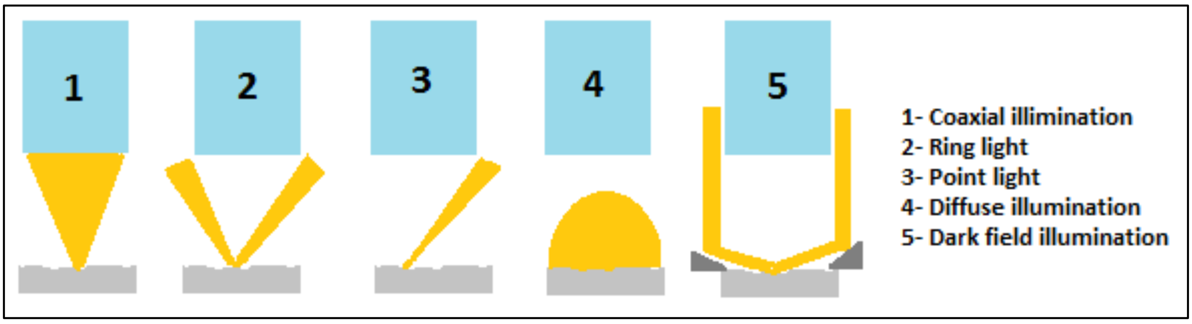

Figure 13: Different types of illumination

Light-emitting diodes (LEDs) are used in the FVM; LED light allows the CCD to detect colour and has the benefit of stability and a long lifetime (Leach 2011). However, halogen bulb light can also be used as light source in the FVM (Hiersemenzel 2013). A polarizer (no. 3 in figure 11) generates the polarized light required for illumination and the analyser (no. 7 in figure 11) filters the reflected light from the sample (Leach 2011). The polarizer is located in the instrument before the light reach the sample, whereas the analyser is reached after the light is reflected to CCD sensor. Polarization helps to reduce the specular components that affect the CCD sensor (SYAM 2014); this is useful when measuring a highly reflective surface. ISO25178-606 (2015) defines polarization as a '*method which allows one to filter out light waves in certain polarization states by using special optical elements called polarizers'*.

Objectives

The objectives are connected to lenses in the optical system and used to capture the reflected light from the sample and magnify a measuring area. The FVM uses different magnification lenses to make measurements, ranging from 2.5×, 5×, 10×, 20×, 50× and 100×. Each magnification has a different resolution, objective's numerical aperture, depth of field, working distance and field of view (Vernhes, Bloch et al. 2008, Danzl, Helmli et al. 2009, Hiersemenzel 2013, Macdonald 2014). Table 4 shows the FVM objective ranges with their measuring field of view and numerical aperture. When the magnification is high, the measurement field of view is reduced and good vertical resolution is achieved (Leach 2011, SYAM 2014). The numerical aperture is different for each magnification. The numerical aperture can determine a large slope angle on a measured surface. The depth of field can be decreased when using a low magnification lens. It is, therefore, important to choose the correct magnification lens for a particular measurement to efficiently obtaining high quality data. For example, using a high vertical resolution increases the scan time.

Table 4: The FVM objective's field of view

Objective's range	Measuring field of view /mm	Numerical aperture of objectives
2.5×	5.63 x 5.63	0.075
5×	2.82 x 2.82	0.15
10×	1.62 x 1.62	0.3
20×	0.81 x 0.81	0.4
50×	0.32 x 0.32	0.6
100×	0.16 x 0.16	0.8

Driving unit

The driving unit of the FVM (sometimes called the control unit) is responsible for the vertical and lateral movements (X, Y and Z axes) and is vital for measurement accuracy and reliability of data. The vertical direction of movement of the optical system is carried out automatically and accurately (Hiersemenzel 2013). Moreover, the driving unit is responsible to vertically scan a surface and also to move a sample in lateral (*x-y*) direction. The movement required depends on the measured sample and the objective. For example, the vertical direction should remain constant when the measured table moves in the lateral direction during the measurement. Although the range of movement in the X, Y and Z planes in the FVM is limited (100 × 100 × 100) mm (Danzl, Helmli et al. 2009, Sun and Claverley 2015, Scherer 2016), it allows measurements to be taken at different positions and in different directions. However, vertical and lateral movements cannot be performed simultaneously.

2.6.3 Advantages of FVM over other optical measuring instruments (Alicona, 2015):

1. FVM can collect the depth information with true colour registration of the surface.
2. Measuring form, position, roughness and dimensions in one system, the gap between classical surface metrology and measuring technology of 3D coordinates is closed in FVM.
3. Ring light allows FVM to measure high slope surfaces that exceed 80°.

2.6.4 FVM limitations

There are limitations to FVM that can prevent measurements of some types of surface texture. For instance, measurement of smooth (small local roughness) and/or transparent surfaces is impossible with the FVM (Danzl, Helmli et al. 2009, Danzl, Helmli et al. 2011, Giusca, Claverley et al. 2014, SYAM 2014, ISO25178-606 2015). Thus, any surface that does not meet this requirement tends to be difficult to measure. A surfaces of minimum roughness with Ra <10 nm at a wavelength cut-off of λc = 2 μm, for instance, is difficult to measure using the FVM (Danzl, Helmli et al. 2011, SYAM 2014, ISO25178-606 2015). It is, therefore, preferable to use a rough surface when using the FVM so as to avoid this limitation. Moreover, the image contrast of the measured surfaces must be high enough for the CCD sensor to differentiate a pixel with respect to its neighbour pixel. Smooth or highly polished surfaces tend to have a low contrast, as captured during vertical scanning. The FVM calculates the focus curve at each position in the stack of images contain a peak of most focused position (see Figure 14). This peak can be detected by using maximum point, polynomial curve fitting or point spread function curve fitting methods (Leash, 2011). The information about these methods is presented in Table 5. A depth map can be available when all lateral positions of the CDD sensor perform the maximum detection.

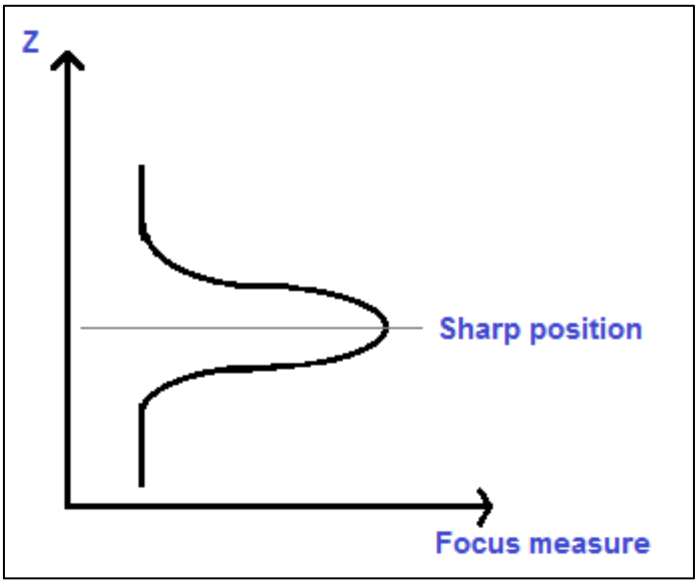

Figure 14: The focus curve

Table 5: Methods of peak detection for focus curve

Methods	Description	Advantage	Disadvantage	Formula
Maximum point	The calculation of the depth value is out of the index of the largest focus	Fastest method	Lowest accuracy	(3) Depth=arg(max F_z) For $Z1 \leq Z \leq Zn$
Polynomial curve fitting	- Using the left and right points that are around the maximum focus point to fit the Polynomial curve by least square technique (4) - The maximum of fitted the polynomial in (5)(6) can be calculated using the coefficients *a* and *b* in (7)	Higher resolution of the depth value	****	(4) $P(z)=az^2+bz+c$ (5) $min_{a,b,c} \sum_{z1 \leq z \leq zn} (F_z - [az^2+bz+c])^2$ (6) $\grave{p}(z) = 2az + b = 0$ (7) $Z_{maximum} = -\frac{b}{2a}$
Point spread function curve fitting	The measured focus values can fit the point spread function to calculate its maximum	Highest accuracy	Slowest method	******

As mentioned, it is impossible to measure transparent surfaces. Bello, Verveniotou et al. (2011) and Leach (2011) argued that a replica coating material allows the FVM to measure transparent surfaces, as it copies these surfaces. In this case, the FVM can easily collect data from these surfaces. However, Macdonald (2014) claim that it is not always possible to use this replica material as some objects are difficult to replicate and modify. The differences in the surfaces are at the nanoscale; thus, the measurement must be sufficient to capture the variations. Using replica materials may therefore not always be a good choice as the accuracy of measurement data may be affected. To conclude, although an alternative to measuring smooth or transparent surfaces, replica materials may not always be applicable for some surfaces.

Chapter three: The measurement artefacts

3. Measurement artefacts

The chapter presents the artefacts used in the research project. Different measuring artefacts have been used in the experiments of determining the MCs for FVM. The details of the artefact used in the project are presented in the following.

3.1 Measurement noise and Residual flatness artefacts

Two artefacts with different roughnesses are measured in different experiments of measurement noise. One artefact is an optical flat with transparent surface and the other has a surface of suitable roughness. The transparent surface cannot be measured by FVM due to the previously mentioned limitation, which is solved by applying a process to replicate the surface and allow measurements to be taken. The replica material is a silicone casting made from polyvinylsiloxane material. The replica can be produced using cartridges that contain a compound of the polymer and curing agent mixture. This compound can be mixed together automatically in a disposal nozzle during the application (Gasparin et al., 2011). The negative-mirror of a surface can be produced. The replica can be applied directly without any requirement for bubble removing. The *Sa* value of the replica material is (0.0138) µm compare to (0.010) µm Sa value of optical flat. The optical flat artefact and its replica are shown in Figure 15. The other standard flat surface artefact is called a Halle flat surface and the artefact is presented in Figure 16. This standard Halle flat artefact has been used in the experiment of measurement noise and residual flatness determination. The standard Halle flat artefact (Line of products: KNT 4080/03) is made of stainless steel material with dimension of (40 × 20 × 11.3) mm. The measuring area contains six grooves of different depths.

Figure 15: The optical flat artefact (left) and its replica (right)

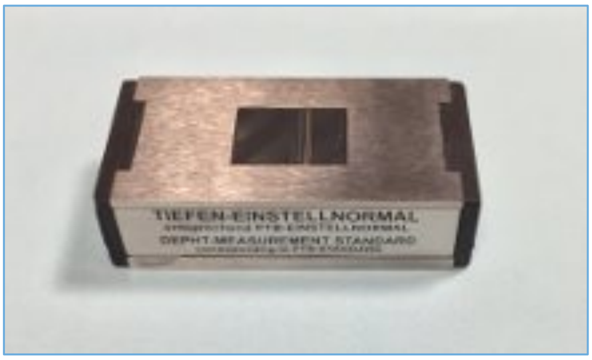

Figure 16: The Halle flat artefact

3.2 Amplification, linearity and perpendicularity artefacts

3.2.1 cross grating artefact for multi-image field measurements

The determination of the lateral amplification, linearity and perpendicularity characteristics requires a calibrated material measure in the form of a two-dimensional (2D) cross-grating (ISO25178-6 2010). The cross-grating can be used to establish the scales of the x- and y-axes. FVM cannot measure commonly available cross-gratings that are smooth (Ra<10nm). Therefore, a new cross-grating artefact that can be measured with FVM needs to be designed and manufactured to calibrate the lateral performance.

The proposed cross-grating artefact has hemispherical groove features (called "calottes" from now onwards) produced by a Kern Evo high-precision micro-milling machine from a block of stainless steel (grade 303). The artefact design is a square block of size of 28 mm with 5 mm thickness, and contains thirty-six calottes with nominal diameters of 0.5 mm. The nominal distance between two calottes is 4 mm. The artefact is designed to capture the scale error of the xy-stage for measurements both with and without stitching, and is presented in Figure 17, which shows the nominal length and thickness of the artefact.

Firstly, a face milling process, using a 6 mm diameter carbide end mill, was applied to flatten the top surface of the block (see Figure 18). The spindle speed and the feedrate of the face milling process were 5000 rpm and 300 mm per minute, respectively. Secondly, the calotte features are machined by a 0.5 mm diameter carbide ball nose mill with the same spindle speed and a federate (see Figure 19). The final surface texture for the top face of the artefact is achieved with a lapping process using a Kemet LM15 lapping machine. Figure 20 shows the Kern milling machine used to make measuring artefact. The artefact is made of stainless steel to create a surface with texture that complies with the FVM requirement. Figure 21 shows the manufactured cross-grating artefact. The *Sa* of the manufactured artefact for the measured surface is (0.357±0.004) μm using nesting indices of S-filter = 2.5 μm and L-filter = 250 μm.

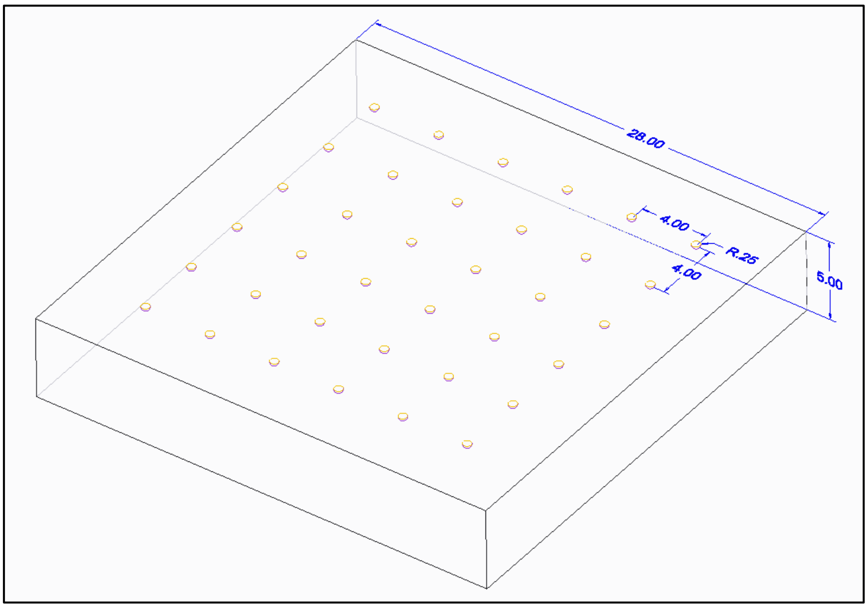

Figure 17: The artefact design.

Figure 18: carbide end mill tool used to flatten the top surface of the artefact.

Figure 19: Ballnose tool used to produce the callotes.

Figure 20: Kern milling machine.

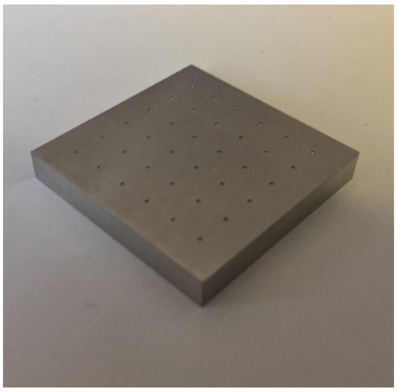

Figure 21:The manufactured artefact.

3.2.2 cross grating artefact for single image field measurements

Another cross grating artefact has been designed and manufactured to determine the amplification coefficient, linearity deviation and perpendicularity characteristics for single image field measurement. This cross grating artefact is stainless steel block containing thirty six hemispheres. Each hemisphere has 0.5 mm diameter and 0.75 mm for the distance between two centre hemispheres. The dimensions and manufactured of this cross grating artefact are shown in Figure 22 and Figure 23, respectively. Same manufacturing process of making first cross grating artefact for multi image field measurement has applied on this artefact. The differences between both artefacts are only in the measurement dimensions. The dimensions of this cross grating artefact are smaller than the previous cross grating artefact for multi image field measurement.

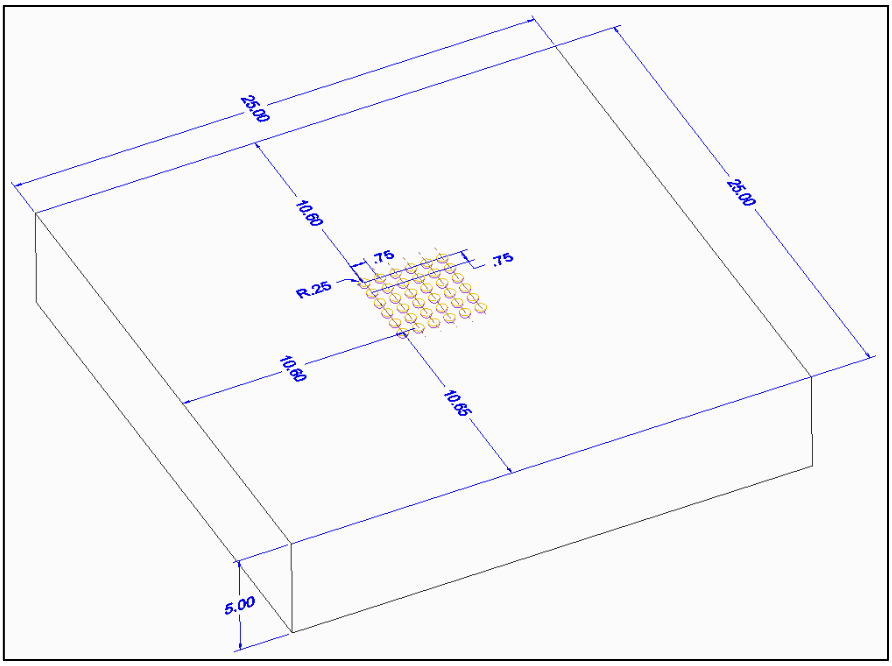

Figure 22: The design of the second cross grating artefact

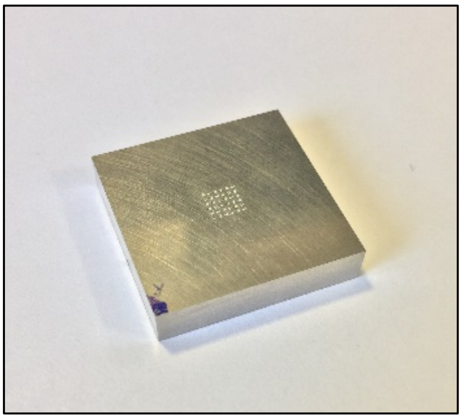
Figure 23: The manufacturing second cross grating artefact

3.2.3 Step height artefact for Vertical scale measurement

The step height artefact is used in this experiment for the error of *Z* axis of amplification coefficient and linearity deviation characteristics. The step height artefact has made from stainless steel containing five slots with different distance. The depth of each slot is different starting from 0.10 mm and increase 0.10 mm until the last slot. The distance between each slot is 0.70 mm. The kern machine that has made the cross grating artefact is also used to make the step height artefact. Figure 24 and Figure 25 show the design of step height with the dimensions and the manufactured artefact.

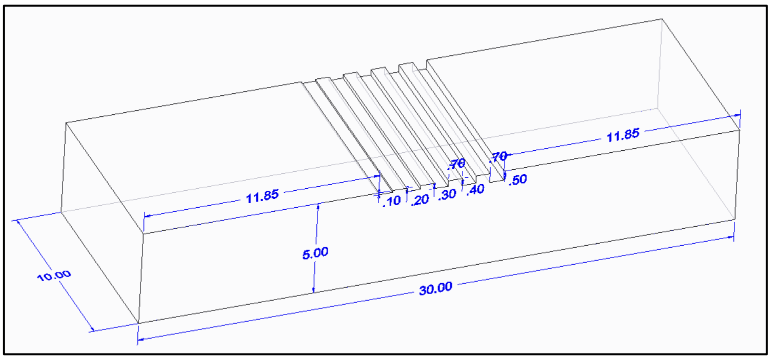

Figure 24: The design of step height artefact

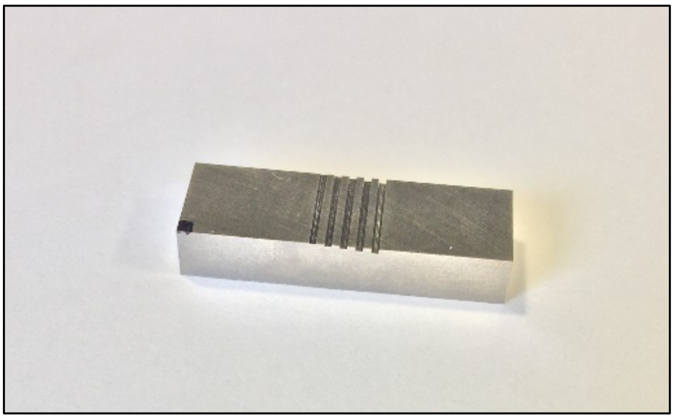

Figure 25: The manufactured step height artefact

3.2.4 Single image field artefact

The artefact is a square block of size of 15 mm with 5 mm thickness. Six slots in each *X* and *Y* directions contain thirty-six intersections with nominal diameters of 0.02 mm. The nominal distance between two intersections is 0.07 mm. Figure 26 and Figure 27 show the designed and manufactured artefact. The stainless steel artefact (grade 303) is manufactured using Kern Evo high-precision micro-milling machine. Figure 20 presents Kern milling machine used for making artefact. The top surface of the block is flatten using 6 mm diameter carbide end mill. A sharp scraping tool carbide material is used to full depth of slot at feed rate of 40 mm/min. Figure 28 shows a scraping tool used to make full depth of slots. The thirty-six slot intersections have been measured to determine the error of *X* and *Y* directions. A 2D height map of measured slot intersections with FVM is shown in Figure 29. The artefact features in Figure 29 are not deterministic. Therefore, the difficulties of manufacturing small features may due to tool wear during scraping or material sticking on the tool.

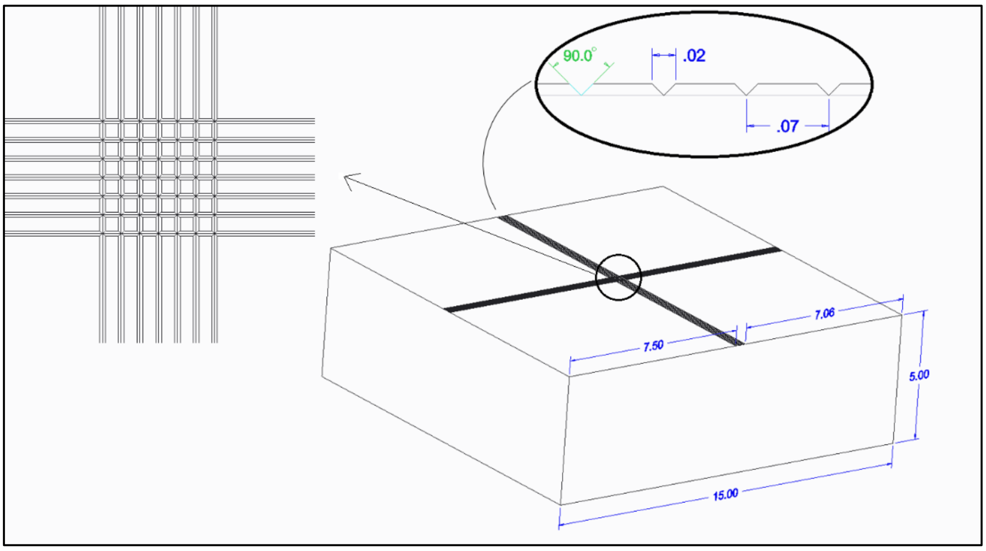

Figure 26: The design of 3rd artefact

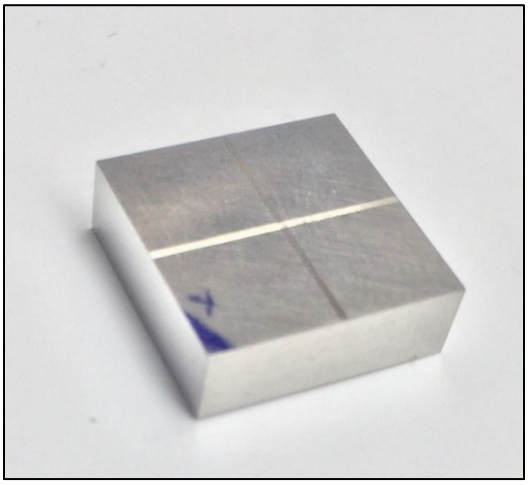

Figure 27: The manufactured artefact

Figure 28: A scraping tool

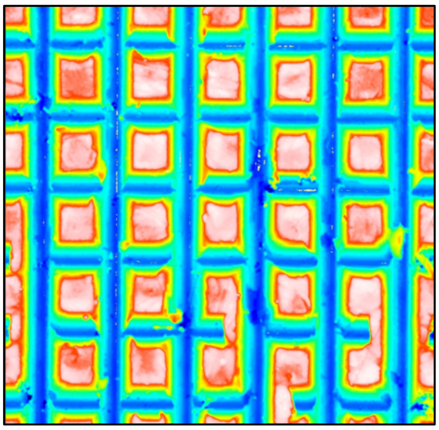

Figure 29: 2D map of slot intersections.

3.3 Topographic spatial resolution artefact

The experiment determines the LPL of topographic spatial resolution using random rough surface artefacts that can be measured by FVM. The artefact used here is a block of stainless steel (grade 303), with six rectangular grooves of the same size on the top. The dimensions are 40 × 20 mm, 5 mm thick and 30 mm for the groove size. The average Sa value on the groove surface is 0.162 µm (Gaussian filter with S nesting index of 2 µm and L nesting index of 0.088 mm). The artefact is made by an electrochemical jet machine (EJM), that removes the surface material using an electrolyte jet, instead of conventional tools (Mitchell-Smith and Clare 2016). When an electrical potential is applied between the electrolyte nozzle and work surface, an anodic dissolution occurs, thereby removing the surface material. Figure 30 shows the EJM used to manufacture the artefact.

Figure 30: Electromechanical jet machine

A tape mark was placed on the block top to measure the same areas of each groove for both the Zygo CSI and FVM instruments. Figure 31 shows the artefact used in the experiment.

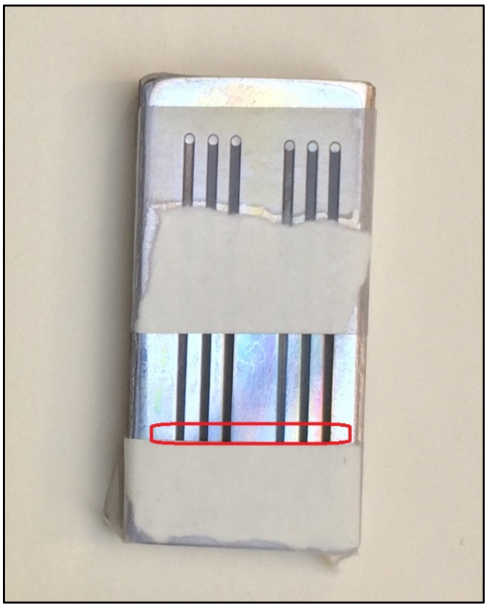

Figure 31: The resolution artefact. The red rectangle shows the groove measuring areas

Chapter four: Measurement noise experiments

The thesis aims to investigate the traceability framework by determining the metrological characteristics (MCs) for a focus variation microscopy (FVM) instrument, as an optical areal surface texture measuring instrument.

The MCs of measurement noise and measurement repeatability can be determined by doing four experiments. The research aim is addressed by determining the measurement noise of FVM using the measurement of a replica of an optical flat, the determination having different measurement parameters, that are illumination, contrast and brightness parameters and finding non-linearity of a vertical scale.

The experiment on a replica of an optical flat measurement addresses all the three questions. In this experiment, the MC can be determined through the measurement noise and measurement repeatability. The replica of an optical flat can be measured in the determination of measurement noise for FVM. Good practical procedures to determine the MC with the replica of an optical flat are presented in the experimental methodology. In this stage of performing the experiment, it can be predicted that the noise is stable between different vertical heights and objective lenses. The variable of vertical height can be kept constant as contrast and exposure time vary.

Regarding the determination of measurement noise with different measurement parameters (illumination, contrast and exposure time parameters), these experiments also address all three research questions. A Halle flat surface artefact can be measured to determine the measurement noise for FVM. Good practical procedures to determine the MC with different parameters using the Halle flat surface artefact have been followed throughout. In this stage, it can be predicted that changing the parameters of illumination, contrast and exposure time does not affect the noise. In these experiments, the variables of the parameters of illumination, contrast and exposure time were kept constant and the vertical height varied.

The finding of non-linearity vertical scale for measurement noise determination addresses all three research questions. The measurement noise was determined for different vertical heights and objective lenses. The Halle flat surface artefact can be measured for measurement noise determination and good practical procedures were followed throughout the experiment. The noise can be predicted in this stage as constant for different vertical height scales. The variable of different vertical height is constant in this experiment and the variable of the contrast and exposure time of different objective lens varies. By doing these experiments of determining the measurement noise, the research aims can be achieved, and the questions answered.

4. The experiments

The measurement of noise in the FVM calibration is important to study instrument's performance in terms of its measuring accuracy. The measurement noise data are obtained using a FVM G5 instrument. The noise measurement experiments have been implemented in different ways to study the effect of different material measures and different measurement parameters to the calculated measurement noises. The experiments of measurement noise are performed using different experiment designs, such as measuring the replica of an optically flat artefact, measuring the flat surface artefact, investigating the effect of contrast and brightness (exposure time) and the effect of different illumination types. The hypothesis for the replica of an optically flat artefact is: 'the noise is stable for different vertical heights and with both objectives because any flatness errors are from the vertical stage error'. The experiment will determine the noise between two objective lenses for different vertical heights. The objective lenses of 50× and 100× and the vertical heights of 5, 35, 40, 55, 70and 85 mm will be used in the experiment.

The hypothesis of investigating the effect of contrast and brightness (exposure time) is: 'changing the contrast and brightness does not affect the noise in both objectives'. The experiment will determine the noise between two objective lenses for different vertical heights between two different parameters of contrast and brightness (exposure time). The hypothesis of investigating the effect of different illumination types is: 'changing the illumination types does not affect the noise'. The experiment will determine the noise between two different illumination types, coaxial light and polariser for different vertical heights. The hypothesis of measuring the Halle flat surface artefact is: 'the noise is stable for different vertical heights'. The experiment will determine the noise between two objective lenses of 50× and 100× at different vertical heights.

Three analytical methods are used to analyse the experiment results, namely subtraction, averaging and measurement repeatability. The values of measurement noise (Sq_{noise}) are calculated three times to better estimate the noise because averaging will reduce random variations in the calculated results. Some measurement noise experiments are conducted at different vertical heights that are from 1 mm to 100 mm. Figure 32 shows the vertical height scale of the FVM instrument. The schematic diagram in Figure 33 shows the vertical height and its relation to sample and stage position. From Figure 33, it can be seen that the height can be adjusted vertically and the stage for the sample is positioned at a suitable distance to allow the objective lens to capture the data. For example, the sample's stage position for 0 mm vertical height is different from the sample's stage position for 50 mm vertical height.

Figure 32: The vertical height scale of the instrument

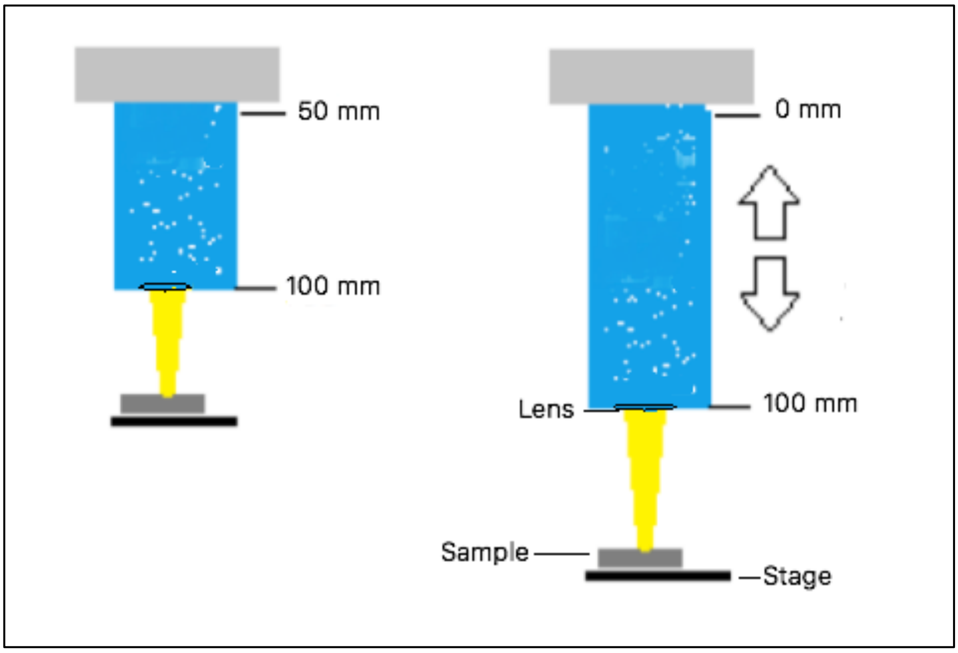

Figure 33: Schematic diagram of the vertical height of FVM related to sample and stage position.

The data analytic process is implemented using MountainsMap surface metrology software (Surf). In the subtraction method, the data of two measuring surfaces are subtracted. The levelling process is applied on the subtracted surface to obtain the Sq value. The Sq_{noise} value was calculated by using the obtained Sq value in formula one (see analytical background section on page 23).

$$(Sq_{noise} = \frac{Sq}{\sqrt{2}}) \qquad (1)$$

The calculation was repeated three times with different measuring data of Sq to obtain the best estimation and reduce the error. Figure 34 shows the subtraction process of the replica of the optical flat surface artefact using Mountainsmap. For averaging purposes, the data of 2, 4, 6, 8 and 10 measured surfaces are averaged. The averaged surfaces are levelled, and the threshold set to remove the spikes from the averaged surface (Figure 35 shows the averaged process from Mountainsmap). Then, the Sq value can be obtained after the thresholding process and used in the following formula. The Sq_{noise} results from the average method were calculated using formula number two (see analytical background section on page 23).

$$Sq_{noise} = \sqrt{\frac{Sq^2 - Sq_{mean}^2}{1 - \frac{1}{n}}} \qquad (2)$$

The *Sq* value is non-averaged data and the Sq_{mean}^2 is the value of a number of averaged *Sq* data, which represented by *n.*

This calculation is repeated three times using different Sq data to obtain the best estimation and reduce the error. For measurement repeatability, the Sq value is obtained from Mountainsmap by levelling and setting the threshold for the measured surface. Figure 36 represents the process of obtaining the Sq value from the measured surface. The SD result is obtained from calculating ten Sq data. The calculation is repeated three times to obtain the best estimation and reduce the error. All the calculations of subtraction, averaging methods and measurement repeatability are presented in figures using minitab software. It is important to mention that the analysis procedures using Mountainsmap are applied on all the following experiments of measurement noise. Details of the design for each experiment to measure noise with their results and discussions are provided below. The measurement processes are applied under normal conditions of temperature and humidity that are 20°C ±1°C and 50% ±5%, respectively.

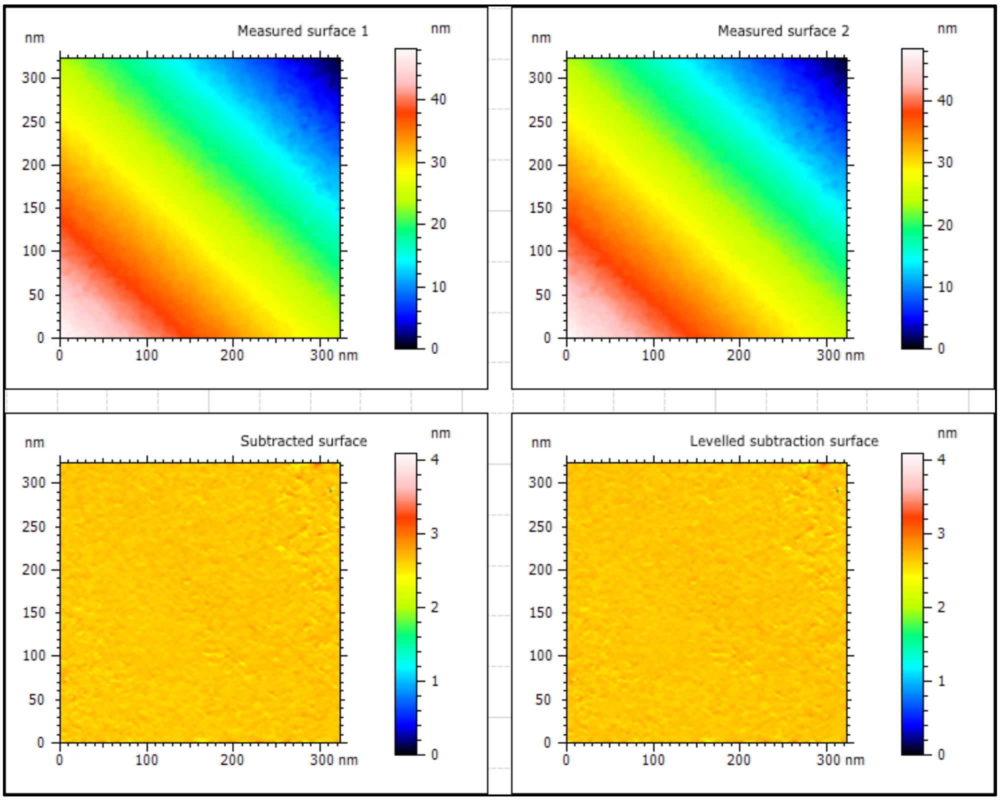

Figure 34: Subtraction measuring surface process using Mountainsmap

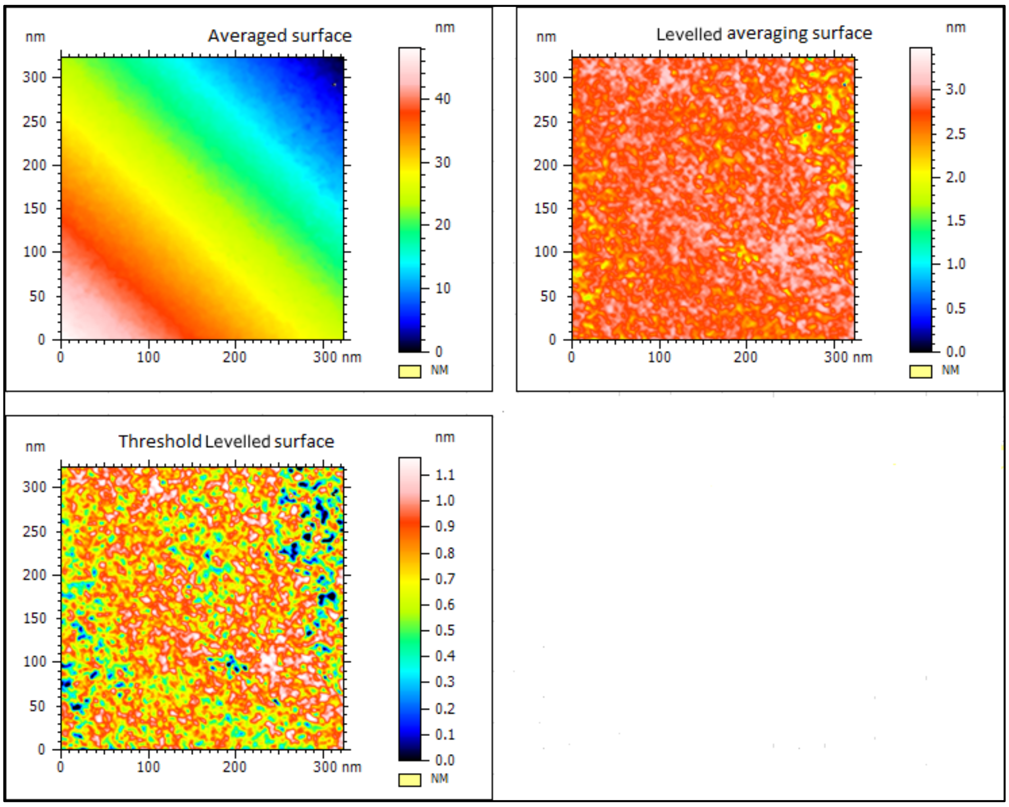

Figure 35: Average process using Mountainsmap

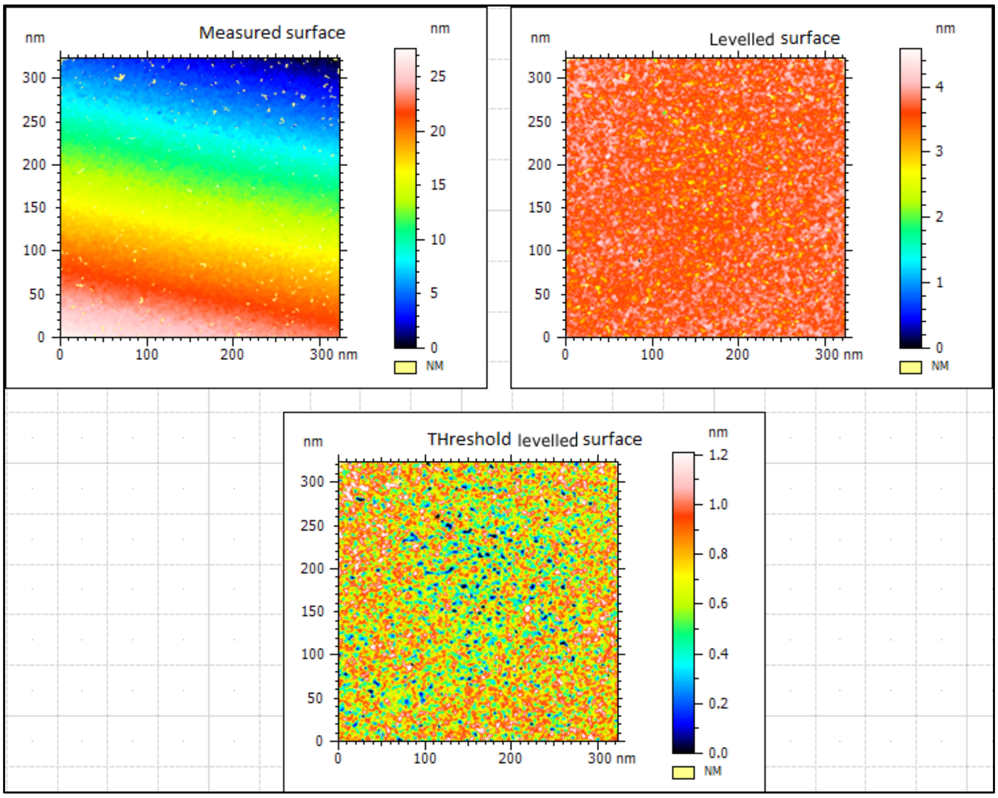

Figure 36: Measurement repeatability using Mountainsmap

4.1 The replica of flat surface artefact

Method

This experiment is designed to find the measurement noise for different objectives and vertical heights by measuring the replica of the optical flat surface. The hypothesis is 'the noise is stable for different vertical heights and with both objectives'. Two different magnification lenses of FVM, 50× and 100×, are used to collect the data. Twenty measurements are collected sequentially in the same area of the surface at different levels (5 mm, 35 mm, 40 mm, 55 mm, 70 mm and 85 mm) of the vertical height range of the FVM instrument. All measuring data for different vertical scale are collected in one session measuring time. The settings for the experiment are presented in Table 6. From Table 6, the contrast and exposure time are chosen to assist in gaining the image data from both objectives. The contrast and exposure time are different. The contrast in this experiment is chosen to make the measuring sample visible and the exposure time is set to make the image bright when measuring. When the contrast value becomes higher, it leads to a long measuring time. Therefore, the contrast and exposure time are chosen to collect good measurement data within short time.

Table 6: Settings for the experiment process

Lens	Height range /mm	Number of measured surface	Image Contrast	Exposure time /μs	Artefact
50× 100×	5, 35, 40, 55, 70, and 85 /every lens	20 / every height	1	500	Replica of optical flat

The procedure of analysing the subtraction method, averaging method and measurement repeatability using Mountainsmap software are explained in the general methodology information (see section 4 The experiments). The average of (2, 4, 6, 8 and 10) surfaces is calculated by using the average method. This process is conducted to find out the differences between the noise results of the averaging surface. The repeatability measurement is applied under the same measuring conditions, but with different height levels, namely 10 mm, 40 mm, 60 mm and 80 mm. The standard deviation (SD) of the *Sq* of the measured surface is calculated for the measurement repeatability.

Results

The subtraction method of the replica artefact has shown some interesting findings. There are statistically significant differences in the noise for different vertical heights. In terms of the 50× magnification lens (see Figure 37), the noise varies between the different vertical heights. The 40 mm level of vertical height has the highest noise, while the 5 mm level has the lowest noise. Figure 38 shows the noise of different vertical heights using the 100× magnification lens. The highest noise appears at the 55 mm level of vertical height, while the 85 mm level shows the lowest noise. The interval results in Figure 37 and Figure 38 are one sigma calculation of standard deviation divided by square root of three i.e. (number of measuring data).

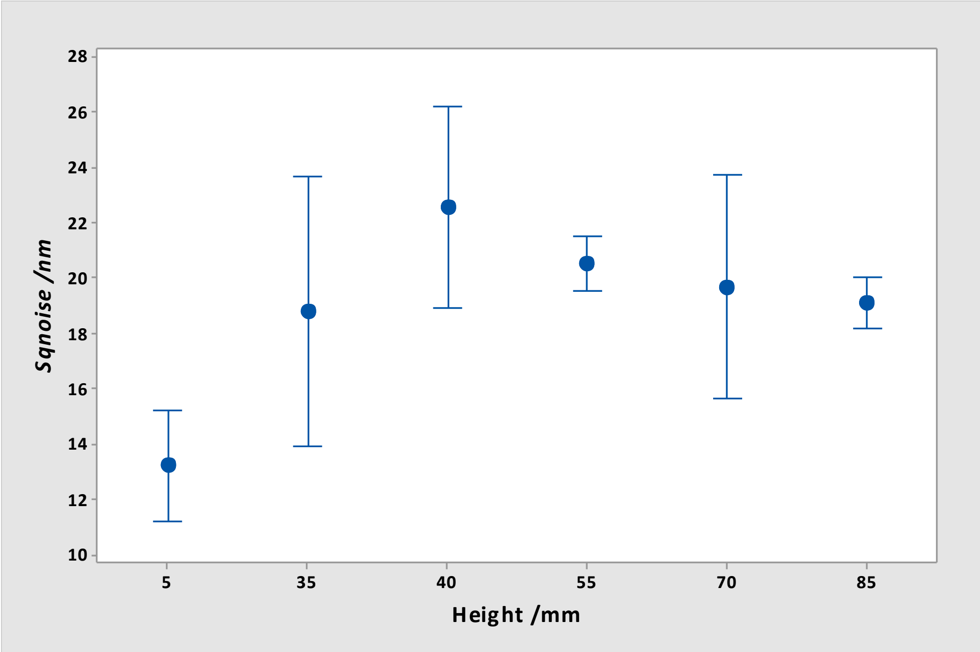

Figure 37: Results of subtraction method for 50× objective lens

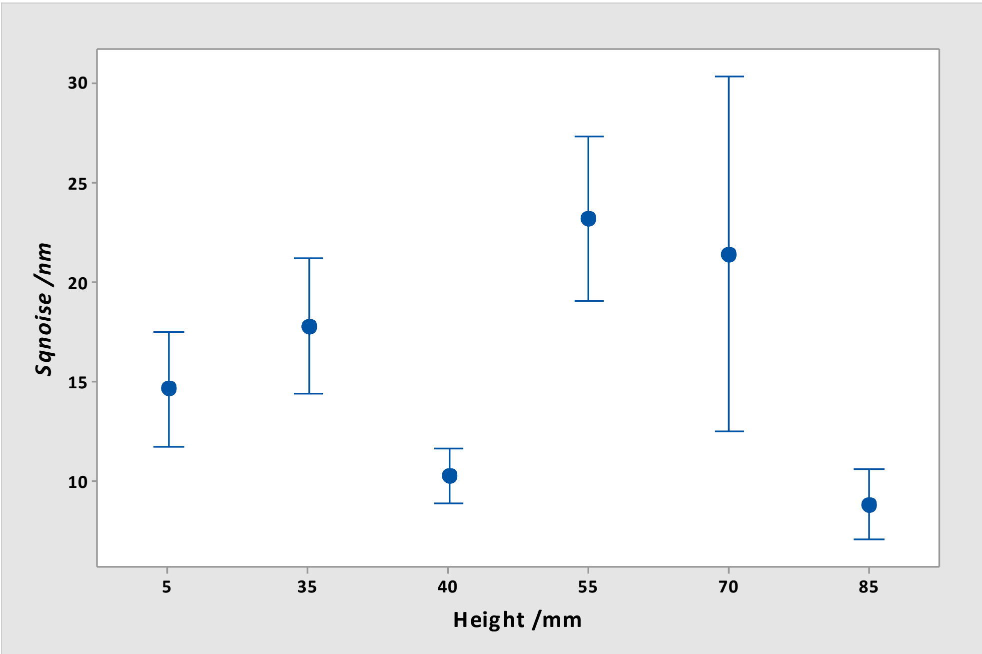

Figure 38: Results of subtraction method for 100× objective lens

The results of the average method are similar to the subtraction method for instrument behaviour. The noise varies between the vertical heights in both objectives. In the 50× and 100× objective lenses, the noise is reduced in each vertical height when the number of averaged surfaces increases. However, at level 55 mm in both objectives, there is an assignable different behaviour that could be related to the vertical stage non-linearity. Figure 39 shows the noise for the average method for the 50× objective lens. The noise for the average method for 100× is shown in Figure 40. The interval results in Figure 39 and Figure 40 are one sigma calculation of standard deviation divided by square root of measured surface i.e. (number of measuring data).

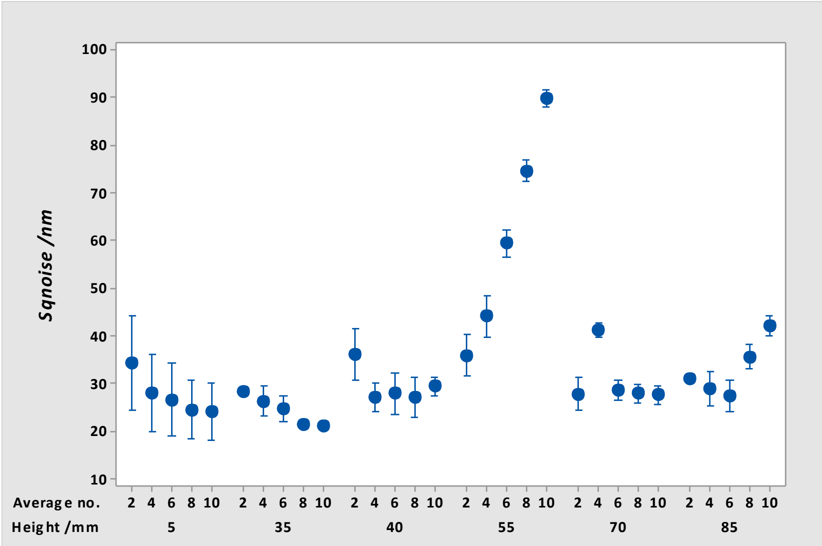

Figure 39: Results of average method for 50× objective lens

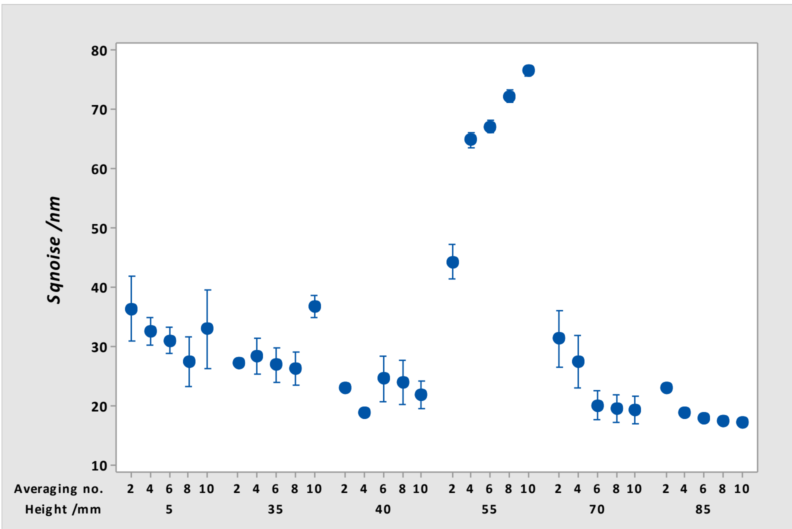

Figure 40: Results of average method for 100× objective lens

The measurement repeatability results agree with the subtraction and averaging methods. The results of different vertical heights are the standard deviation of 10 single measured surfaces. The highest noise of the 50× objective lens at 40 mm vertical height, and the 60 mm level shows the lowest noise. Figure 41 presents the results of Standard Deviation for the 50× objective lens. In the 100× objective lens, the highest noise is at 60% level of vertical height and the lowest noise is at 40 mm level. Figure 42 illustrates the results of Standard Deviation for the 100× objective lens. The interval results of Figure 41 and Figure 42 are one sigma calculation of standard deviation divided by square root of ten surface measured data.

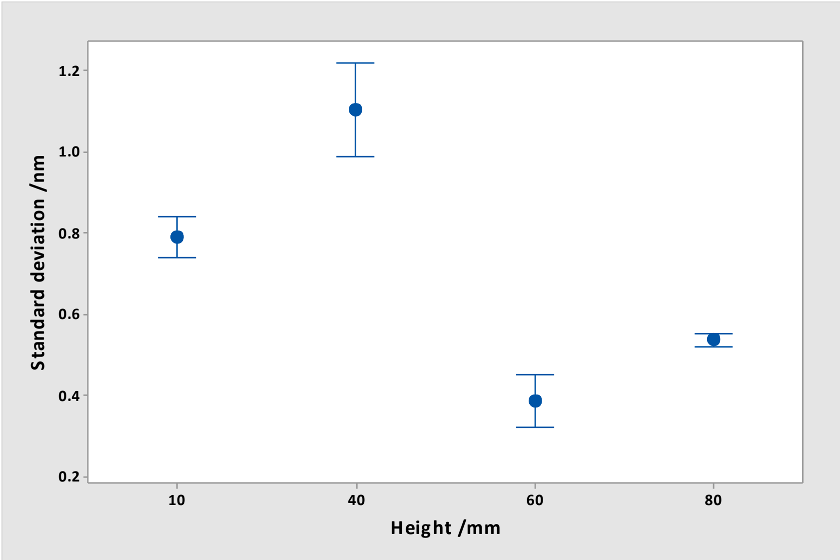

Figure 41: Results of measurement repeatability for 50× objective lens

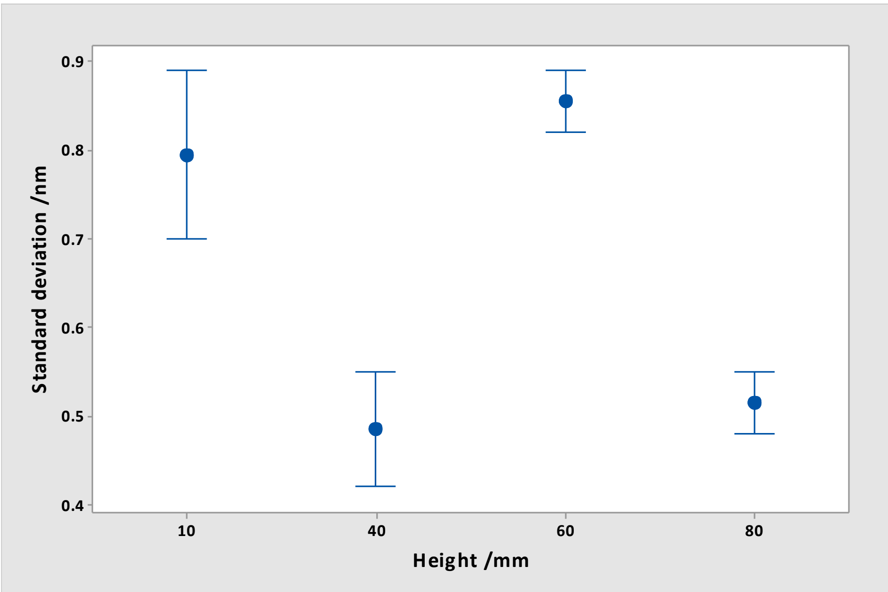

Figure 42: Results of measurement repeatability for 100× objective lens

4.2 The effects of different measuring parameters

4.2.2 Contrast and brightness parameters

Method

Experiments have been carried out focusing on the noise between two different settings of the contrast and brightness parameters. The hypothesis is 'changing the contrast and brightness does not affect the noise in both objectives'. Two objective lenses of 50× and 100× are used to measure the Halle flat artefact. In addition, 20 data are collected for each different setting of contrast and brightness. The vertical range is fixed at 10 mm height. The same vertical and lateral resolutions have been used in both objectives. The details of the experiment are presented in Table 7. From Table 7, the contrast and exposure time are chosen to assist in gaining the image data from both objectives. The contrast and exposure time are discussed in the first measurement noise experiment.

Table 7: Information for the experiment

Lens	Image Contrast	Exposure time (Brightness) / μs	Height range	Number of measured surface	Vertical resolution	Lateral resolution
50×	1.10	130	10 mm	20	10 nm	1.34 μm
	1.70	90				
100×	1.10	130				
	1.70	90				

The procedure of analysing the measured data for subtraction, averaging and measurement repeatability using Mountainsmap software is presented in section 4 of this chapter. For the average method, different average surfaces (2, 4, 6 and 8) are calculated in both settings of contrast and brightness. A standard deviation of each objective at different parameters is obtained for the measurement repeatability calculation.

Results

The subtraction method in both objectives has statistically significant difference for noise results. This means that different parameters of contrast and brightness affect the noise of the FVM instrument. The subtraction method results for different contrast and brightness for 50× and 100× objectives are shown in Figure 43 and Figure 44, respectively. The results of the second (2) contrast and brightness settings are higher than for the first (1) contrast and brightness settings in both objective lenses. The interval results in Figure 43 and Figure 44 are one sigma calculation of standard deviation divided by square root of three i.e. (number of measuring data).

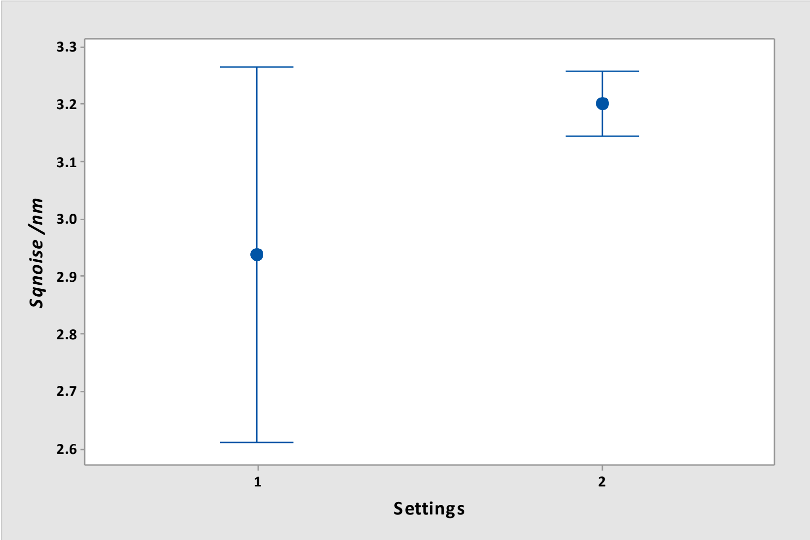

Figure 43: Results of subtraction method for 50× objective lens (1: first contrast and exposure time setting, 2: second contrast and exposure time setting).

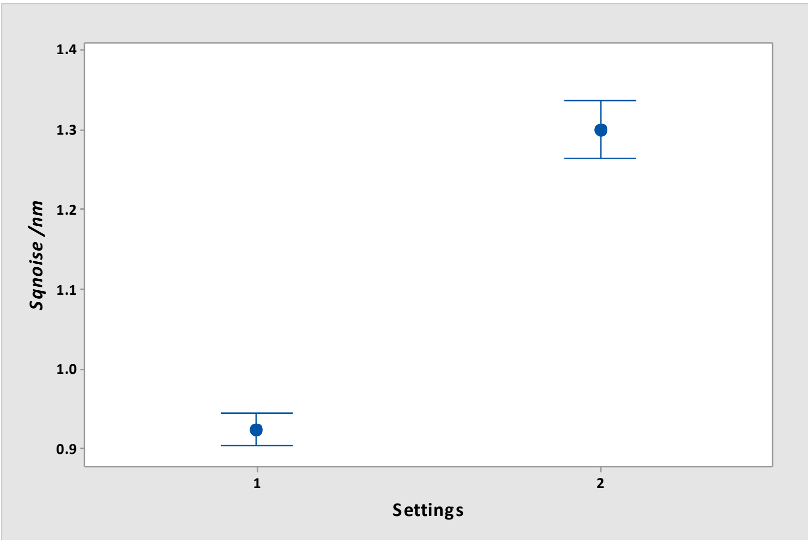

Figure 44: Results of subtraction method for 100× objective lens (1: first contrast and exposure time setting, 2: second contrast and exposure time setting).

The average method results are limited in this situation and cannot capture the significant difference between two measurement parameters. The noise results are decreased when the number of the averaged surfaces is increased in both settings and objectives. Figure 45 and Figure 46 show the average results of 50× and 100× objective lenses. The interval results in Figure 45 and Figure 46 are one sigma calculation of standard deviation divided by square root of measured surface i.e. (number of measuring data).

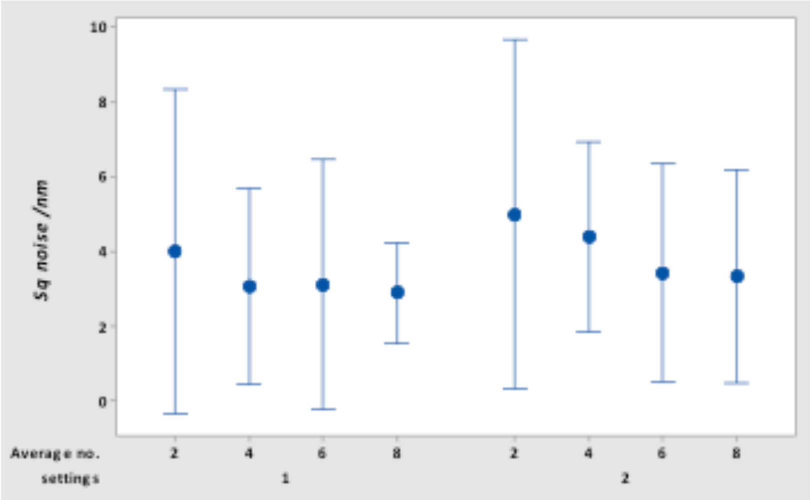

Figure 45: Results of average method for 50× objective lens (1: first contrast and exposure time setting, 2: second contrast and exposure time setting).

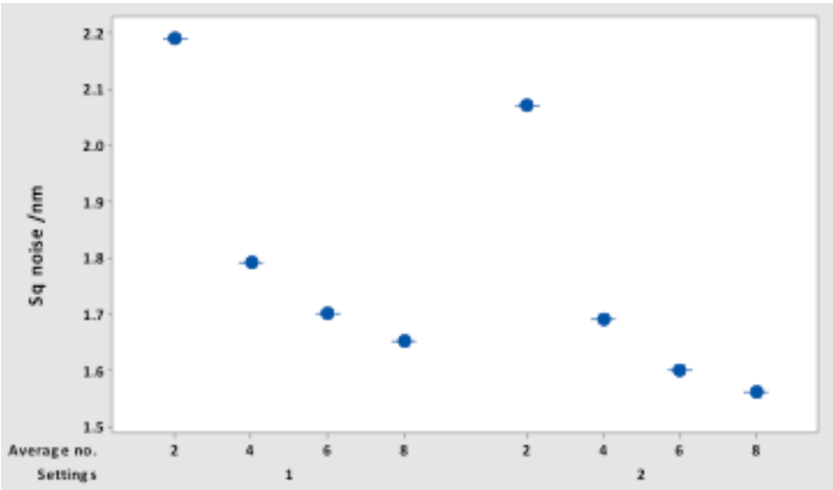

Figure 46: Results of average method for 100× objective lens (1: first contrast and exposure time setting, 2: second contrast and exposure time setting).

Similar to the results of the subtraction and average methods, the measurement repeatability of the 50× and 100× objective lenses are statistically different between the settings of contrast and brightness. Figure 47 and Figure 48 show the measurement repeatability of the 50× and 100× objective lenses, respectively. From Figure 47 and Figure 48, the interval results are one sigma calculation of standard deviation divided by square root of ten surface measured data.

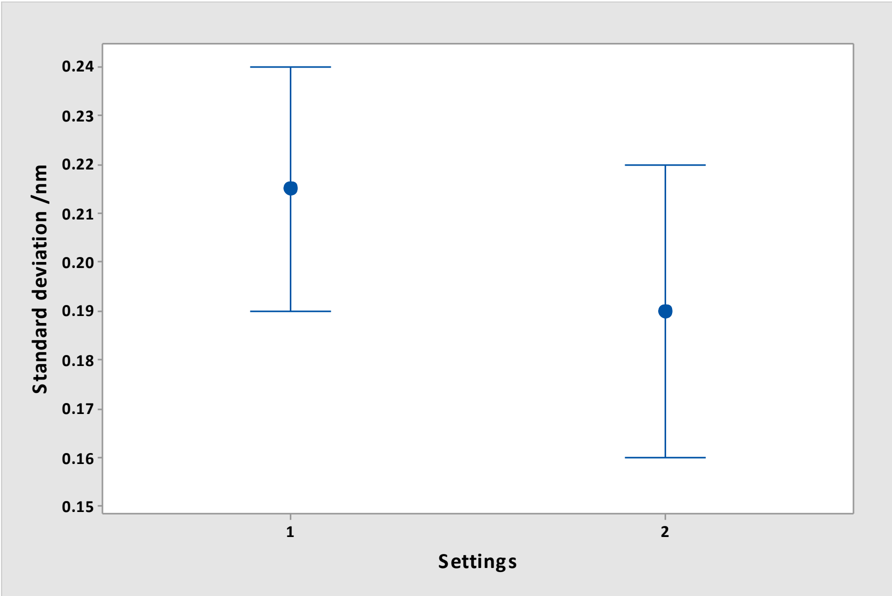

Figure 47: Results of measurement repeatability for 50× objective lens (1: first contrast and exposure time setting, 2: second contrast and exposure time setting).

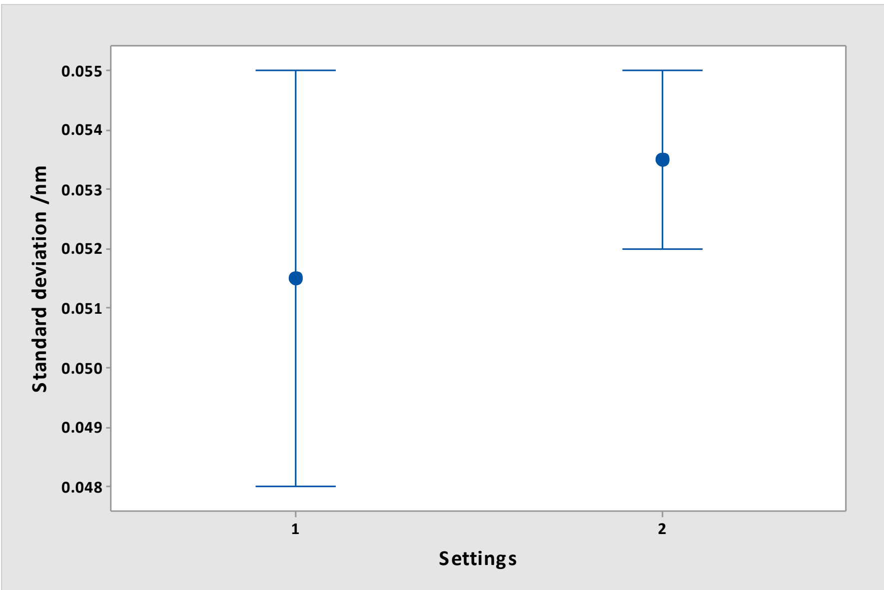

Figure 48: Results of measurement repeatability for 100× objective lens (1: first contrast and exposure time setting, 2: second contrast and exposure time setting).

4.2.2 The illumination parameters

Method

This experiment is designed to find the effect on the noise that could result from using the polariser. The measurements in this experiment are collected twice with different illumination settings. The first measurement is applied on coaxial light as a normal situation, while the second measurement is performed by using the polariser. These different illumination types apply the same parameters of contrast, exposure time and vertical and lateral resolution. Two objective lenses of 50× and 100× magnifications are used to measure the Halle flat surface artefact. The measurements are conducted at different vertical heights (20 mm, 40 mm, 60 mm and 80 mm). Table 8 shows the information of the experimental design. The contrast and exposure time can be changed separately. The contrast and exposure time are chosen to assist in gaining the image data from both objectives. The contrast and exposure time are discussed in the first measurement noise experiment.

Table 8: Details of the experiment

Lens	Height range /mm	Number of measured surface	Illumination	Parameters			
				Image Contrast	Exposure time (Brightness) /µs	Vertical resolution	Lateral resolution
50× 100×	20, 40, 60 and 80	25 data for each height	- Coaxial light - Polariser	1	500 = 50× 80 = 100×	10 nm	1.46 µm

The procedure of analysing the measured data for subtraction, averaging and measurement repeatability using Mountainsmap software is presented in section 4 of this chapter. Regarding the average method, the surface average numbers are 2, 4, 6 and 8. The standard deviation of calculating the measurement repeatability is applied in some of the vertical heights, namely (20, 40, 60 and 80) mm.

Results

The results of the subtraction method demonstrate that the noise with the polariser is statistically higher than the noise with the normal light condition in both of the objectives. One reason could be with the polarised light is that the light intensity on the CCD image sensor is lower compared to the measurement without polariser filter. The difference between the noise of polarised and normal light is significant in both objectives. Figure 49 and Figure 50 show the subtraction results of the 50× and 100× objective lenses, respectively. The interval results in Figure 49 and Figure 50 are one sigma calculation of standard deviation divided by square root of three i.e. (number of measuring data).

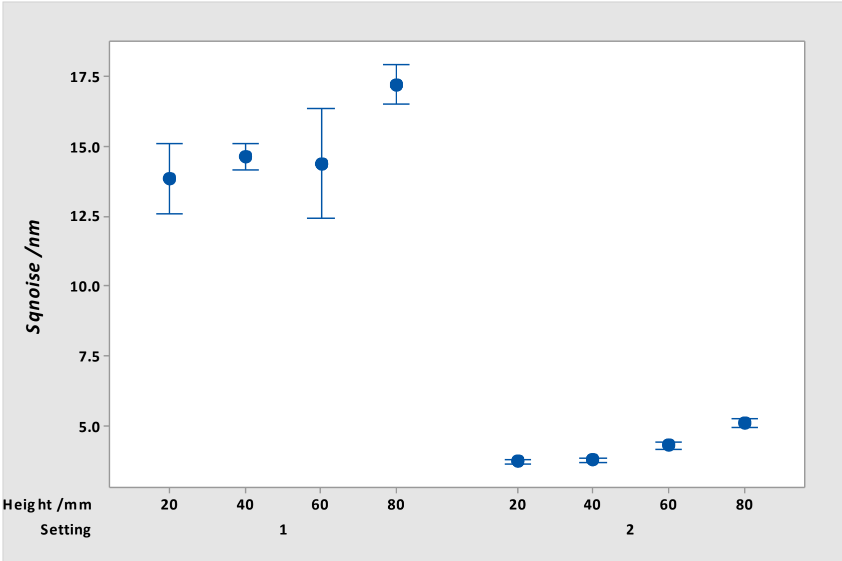

Figure 49: Results of subtraction method for 50× objective lens (1: polarised, 2: normal light)

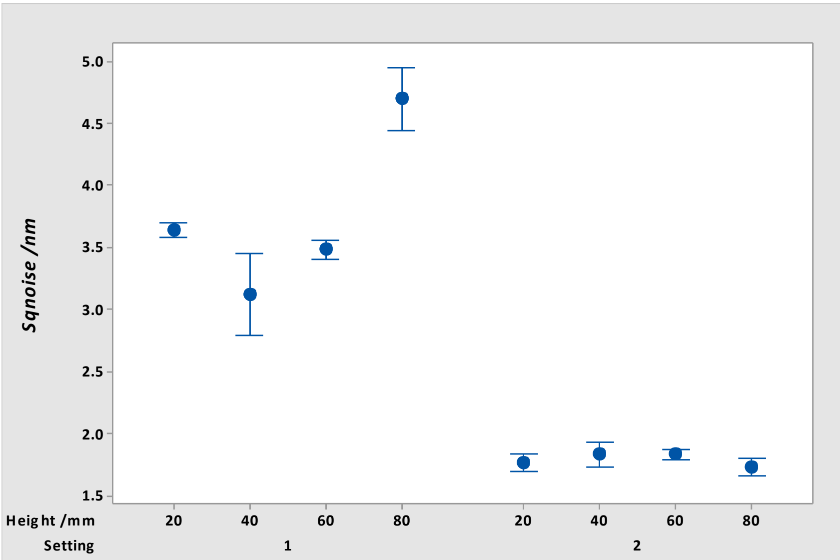

Figure 50: Results of subtraction method for 100× objective lens (1: polarised, 2: normal light)

The findings for an average method for both light settings in two objective lenses seem to be similar to those for the subtraction method. The noise using the polariser is higher than with the normal light. With the normal light setting, the noise decreases when the number of the average surfaces is increased. Figure 51 shows the average method for 50× objective lens for both light settings. The average method results of the 100× objective lens are shown in Figure 52. The interval results in Figure 51 and Figure 52 are one sigma calculation of standard deviation divided by square root of measured surface i.e. (number of measuring data).

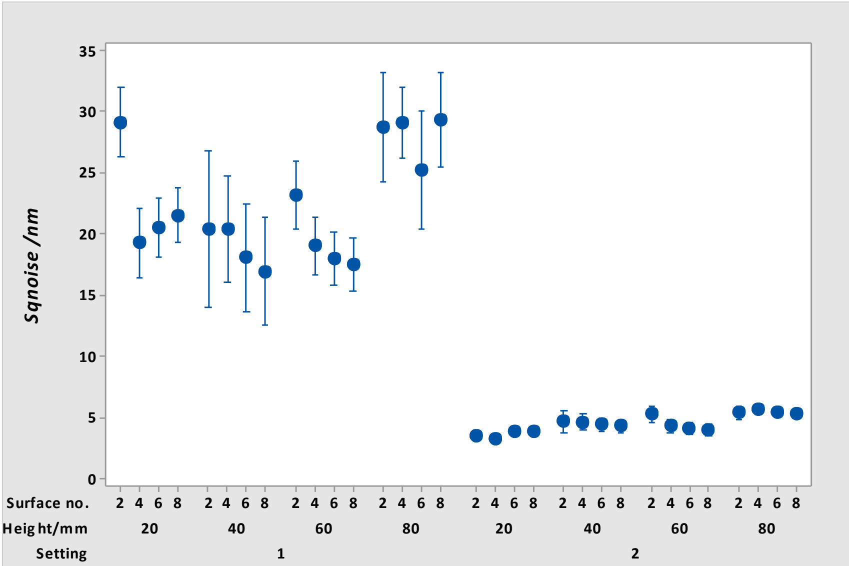

Figure 51: Results of average method for 50× objective lens (1: polarised, 2: normal light)

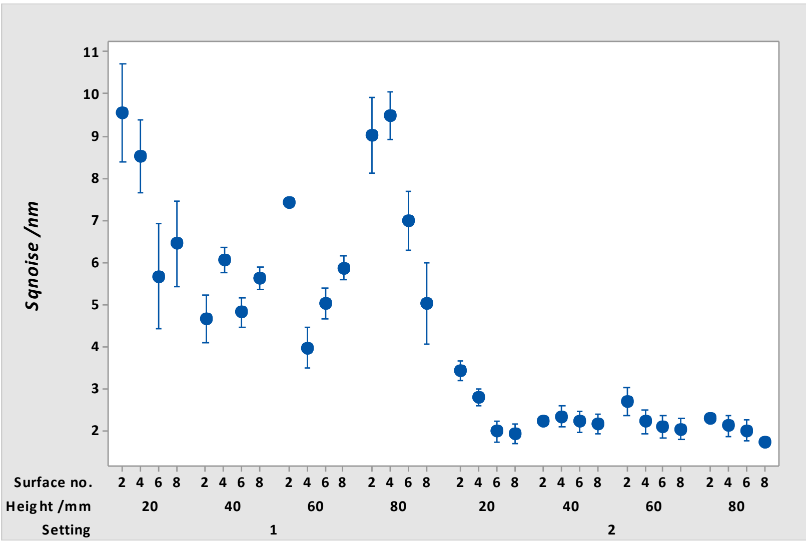

Figure 52: Results of average method for 100× objective lens (1: polarised, 2: normal light)

The measurement repeatability findings are similar (statistically insignificant) to the subtraction and average methods. The polariser data are higher than the normal light data. The results of measurement repeatability for 50× and 100× lenses are shown in Figure 53 and Figure 54, respectively. The interval results in Figure 53 and Figure 54 are one sigma calculation of standard deviation divided by square root of ten surface measured data.

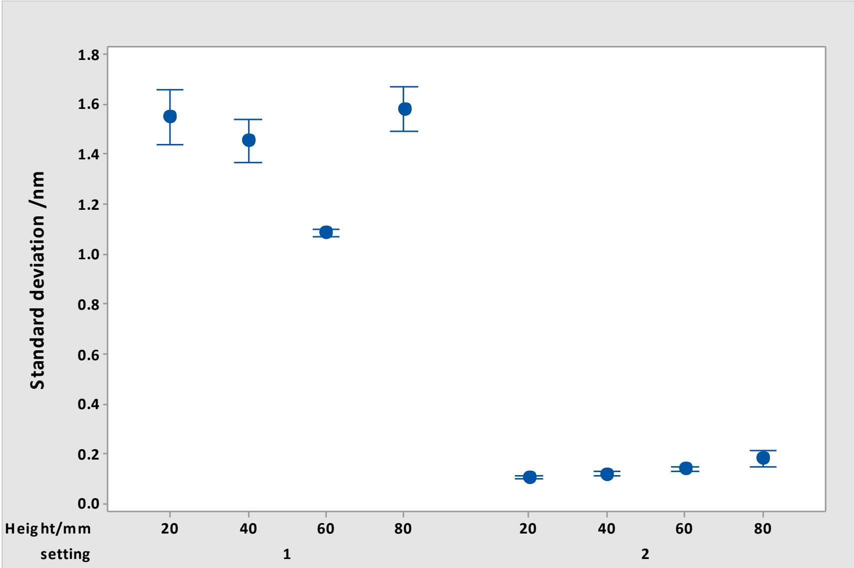

Figure 53: Results of measurement repeatability for 50× objective lens (1: polarised, 2: normal light)

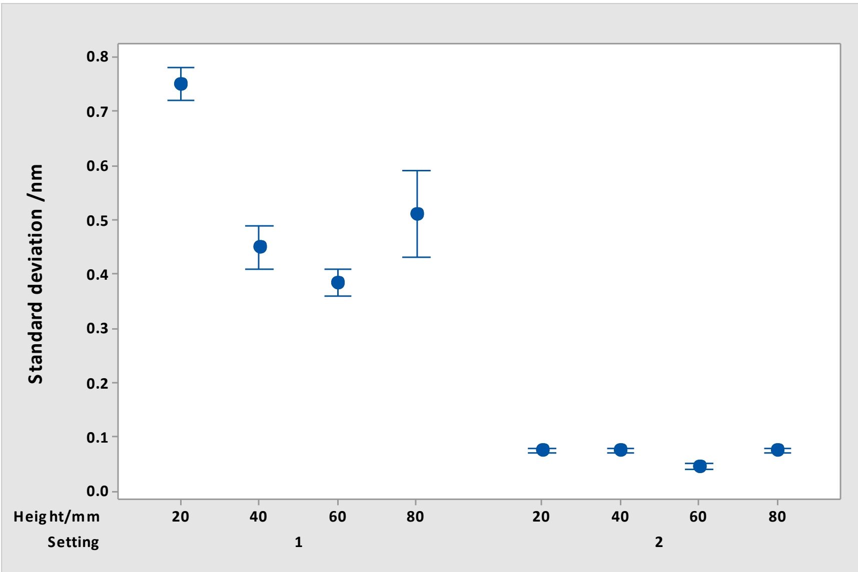

Figure 54: Results of measurement repeatability for 100× objective lens (1: polarised, 2: normal light)

4.3 Discussion

The measurement noise and measurement repeatability are conducted in different experimental designs. The aim of the first experiment is to find the noise between different objective lenses and vertical heights using the replica of an optical flat. The experiment is carried out using two objective lenses, with magnifications of 50× and 100×, to measure the replica of an optical flat surface with equal contrast and brightness parameters. Different height levels (5 mm, 35 mm, 40 mm, 55 mm, 70 mm and 85 mm) of the total vertical scanning range of the instrument are used. The next experiments are conducted between different parameters of the FVM to study the effect of the different parameters on the measurement noise. The aim of the first parameter (contrast and brightness) is to find the effects on the noise of changing the contrast and brightness settings. Two magnifications using 50× and 100× objective lenses have been implemented with the same settings of vertical and lateral resolution. One height range (10 mm) of vertical scanning on the flat surface artefact has been used. Twenty measuring data are collected in each setting for both objectives. In the second parameter (illumination conditions), the purpose is to find the effect of different illumination types on the noise. Coaxial light and a polariser are used. Different height levels (20 mm, 40 mm, 60 mm and 80 mm) of the vertical stage scale have been used in two objective lenses of 50× and 100× magnifications. The results for subtraction and average methods and measurement repeatability have been calculated. At each height level, twenty-five data have been collected in both light settings. The parameters of contrast and vertical and lateral resolution have been fixed for all of the measurements.

The noise is nonlinear between the different vertical heights in both objectives. The finding of nonlinearity of the vertical scale for FVM was not expected when performing the experiment. The nonlinearity of vertical range may be caused by the imperfection of the ball screw of the vertical *Z* drive. The manufacturer of the FVM instrument confirms that the vertical range varies. i.e. the noise is vary in different height. The interpretation of this difference may relate to the way in which the height range adjust is mounted on the guiding rails and the way in which the drive train is guided. The effects of varying the vertical range of FVM seem to be general as confirmed by the FVM manufacturer. The finding of nonlinearity of vertical scale is very significant for FVM users. Therefore, it is important for the FVM users to recognise the nonlinearity of the vertical scale when using FVM; for example, when measuring at the level that provides low noise. In spite of the fact that the FVM instrument can measure the replica of the optical flat artefact to overcome its limitations, using the replica might not always be appropriate to identify the noise. The findings of measurement noise and measurement repeatability are high. Therefore, the replica may not provide valid results of the noise. According to Macdonald (2014), it is not always possible to apply the replica due to the fact that the surface texture of the original surface can be different at the nanoscale level. The surface should have a roughness of more than 10 nm to allow the instrument to collect the data (Leach 2011). Therefore, there is some doubt about the replica of the optical flat artefact. Due to the fact that the optical flat artefact cannot be measured by the FVM, its replica, which overcomes the instrument limitation, may have an issue in the object modification. The measurement can be obtained from the replica, but it could affect the appropriate results. For this reason, the replica of the optical flat artefact seems to become inappropriate for the measurement of noise.

Regarding the noise difference between contrast and brightness parameters, the findings indicate that the effects on the measurement noise of changing the contrast and brightness are significant in both objectives. These findings are similar to a previous measurement noise experiment (Hiersemenzel 2013). In Hiersemenzel's work, changing only the contrast is not affecting the noise, while changing only the brightness can affect the noise. However, the findings of our experiment indicate that changing the contrast and brightness together can affect the noise significantly. The noise between two settings does not exceed 0.5 nm in both objectives. The changing in the noise may be occurring because of the brightness effect. The contrast and brightness can be related to whether polarised or normal light is being used to obtain the data. Leach (2011) explains that the contrast and brightness settings can assist in gaining the image data. It is clear that changing the settings of contrast and brightness can allow the instrument to collect sufficient data from the surface in the measuring operation. The drawbacks of applying this experiment are related to choosing the appropriate settings to allow the measurements to be collected. Some settings of contrast and brightness create difficulties in measuring the surface in both objectives. In addition, some settings of contrast and brightness can result in a long measuring time.

In the findings of different illumination parameters, using the polariser in the measurement with specific settings of contrast leads to increase the noise. The polarised light can assist in collecting the measurement. Leach (2011) and Nikolaev, Petzing et al. (2016) confirmed that the polarisation can reduce the specular light components that cause a problem for the CCD sensor to collect the data. However, the polarised light will reduce the light intensity to the CCD image sensor and can increase the noise. From the practical point of view, the polariser setting can be used when activated to reduce the specular light from the measuring surface. However, when the polariser setting is changed to a different light setting, it may cause some issues in the measurement. Therefore, the noise can be increased when using the polariser when the measurements in both light situations have used the same measuring conditions. The polariser settings can be made suitable for its work. Using the polariser with a different setting leads to some problems in the measurement. High measurement noise can be an example of the measurement problems.

To sum up, the noise results from the previous measurement noise experiments can be improved when averaging the collected measurement over time due to random noise reduction. This measurement collection strategy may help in obtaining better measurement noise results. Also, De Groot and DiSciacca (2018) mention that averaging the measurement over time can assist in getting low measurement noise.

Regarding the question of the determination of MCs for FVM, the determination of measurement noise is provided in three measurement noise experimental designs. A flat surface artefact and replica of an optical flat surface artefact are suitable artefacts in this determination. The replica of the optical flat surface is measured due to the FVM limitations of not being able to measure smooth and transparent surfaces. The calibration procedures for FVM through measurement noise determination are explained in the experimental methodologies.

4.4 Detection of stage non-linearity with measurement repeatability

The experiment is focused on detecting a non-linearity signature of the FVM vertical stage using measurement noise and measurement repeatability. Two objective lenses with magnifications of 50× and 100× have been used. The Halle flat artefact was measured at different vertical heights, namely 5 mm, 40 mm, 55 mm, 70 mm and 85 mm. Twenty data were collected for each height in each lens. The contrast and brightness parameters were set constant between the different lenses. Table 9 shows the information for the measurement. The contrast and exposure time are chosen to assist in gaining the image data from both objectives. The contrast and exposure time are discussed in the first measurement noise experiment (see page 60).

Table 9: Information for the experiment design

Lens	Height range for every lens /mm	Number of measured surface	Contrast	Exposure time Brightness / µs	Artefact
50× 100×	5, 40, 55, 70 and 85	20 data for every height	1	142	Halle flat artefact

All the calculation methods of measurement noise, namely subtraction, averaging and measurement repeatability. The procedure of analysing the measured data for subtraction, averaging and measurement repeatability is presented in section 4 of this chapter. Regarding the average method, different average surfaces were calculated, namely 2, 4, 6, 8 and 10 surfaces. In the measurement repeatability, the standard deviation was calculated for some of the vertical heights, namely 5 mm, 40 mm, 55 mm and 85 mm.

Result

The results of the Halle flat artefact for the subtraction method present a significant difference between 50× and 100× objective lenses. In the 50× objective lens, the 5 mm level of vertical height has the highest noise and the 35 mm level of vertical height has the lowest noise. The results of the subtraction method for the 50× magnification lens are shown in Figure 55. In the 100× objective lens, the 35 mm level of vertical height has the highest noise and the 5 mm level of vertical height has the lowest noise. Figure56 demonstrates the subtraction method results for the 100× objective lens. The interval results in Figure 55 and Figure 56 are one sigma calculation of standard deviation divided by square root of three i.e. (number of measuring data).

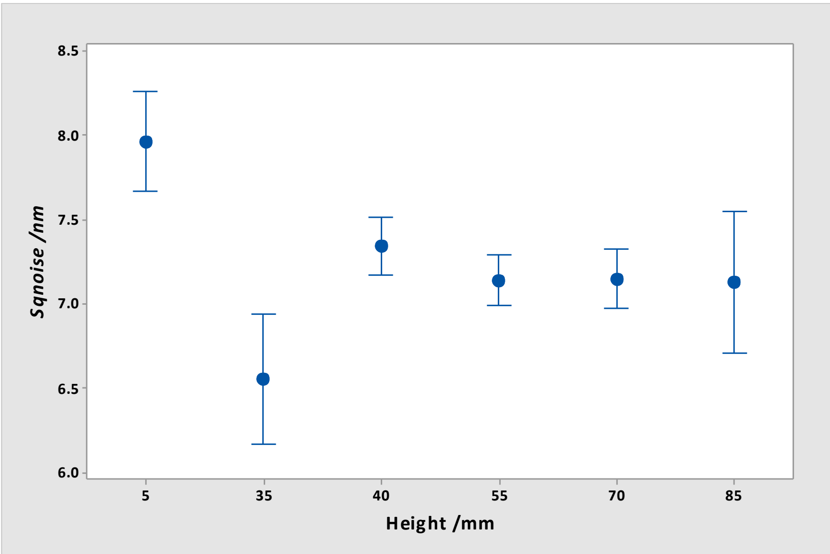

Figure 55: Results of subtraction method for 50× objective lens

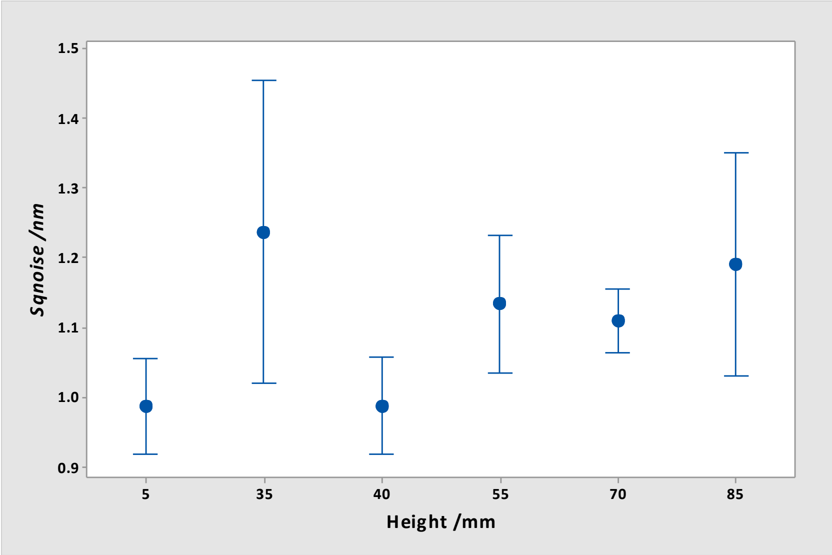

Figure 56: Results of subtraction method for 100× objective lens

The average method findings of the Halle flat artefact show similar results to the subtraction method. For the 50× magnification lens, the noise is higher at 5 mm height, while the values for the other heights seem to be similar. The findings of the average method for 50× are shown in Figure 57. In the 100× magnification lens, the highest noise was at 70 mm level of vertical height and the lowest noise is at 40 mm level of vertical height. The average results of the noise for 100× are presented in Figure 58. By increasing the number of averaging surfaces, the noise can be reduced with a condition that the surface data has a statistically stationary condition. The interval results in Figure 57 and Figure 58 are one sigma calculation of standard deviation divided by square root of measured surface i.e. (number of measuring data).

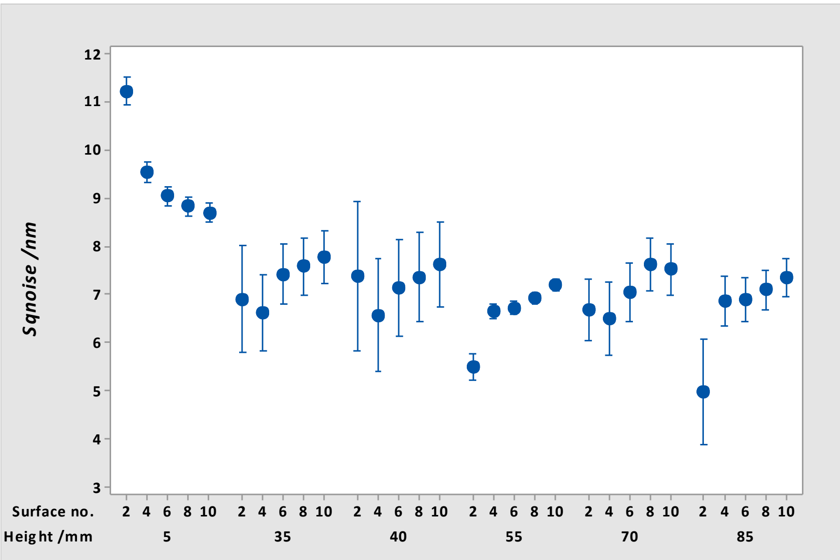

Figure 57: Results of average method for 50× objective lens

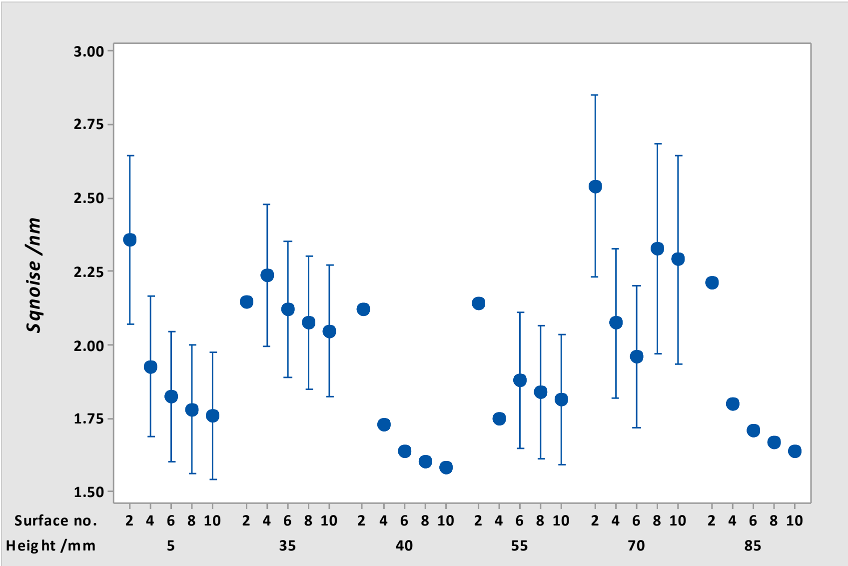

Figure 58: Results of average method for 100× objective lens

The measurement repeatability results are similar to the results of subtraction and averaging methods. Both 50× and 100× objective lenses are non-linear between the vertical heights. A perfect stage should have a constant noise in all of the vertical heights. Figure 59 shows the standard deviation calculation of the 50× objective lens. In comparison, the noise of the 100× objective lens increases when the vertical height increases. The SD calculation of the 100× objective lens is shown in Figure 60. The results obtained in Figure 59 and Figure 60 are the results of standard deviation divided by square root of ten surface measured data.

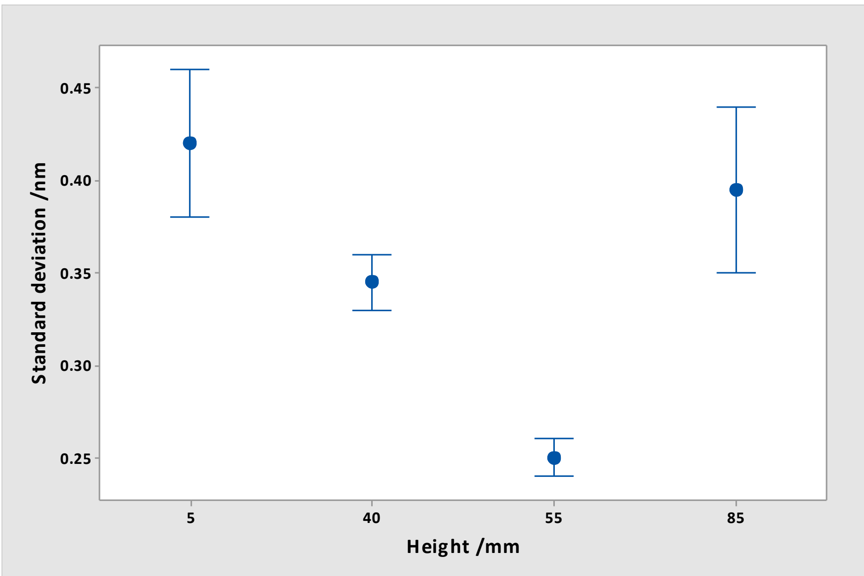

Figure 59: Results of measurement repeatability for 50× objective lens

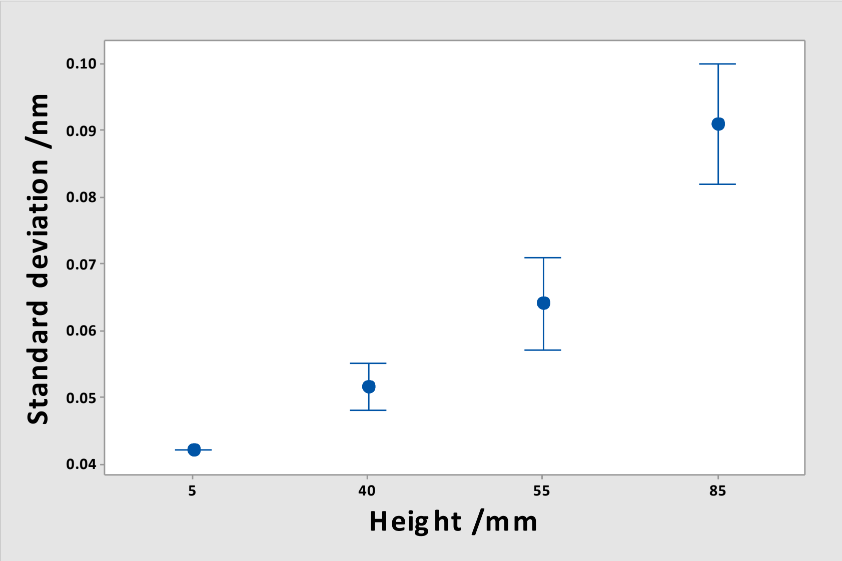

Figure 60: Results of measurement repeatability for 100× objective lens

Summary

This experiment detects the non-linearity signatures of the vertical height for the FVM. Two objectives lenses with magnifications of 50× and 100× have been applied to measure the Halle flat surface artefact with equal contrast and brightness parameters. Subtraction and average as well as the surface topography repeatability methods have been used in the calculation. Different height levels (5 mm, 35 mm, 40 mm, 55 mm, 70 mm and 85 mm) of the total vertical scanning range of the instrument are used.

The noise results show that the vertical stage tends to be non-linear. It is recognised that the nonlinearity of the vertical scale is more significant for FVM users when, for example, measuring at the level that has less linearity. In the 100× objective lens, the noise seems to increase for both the noise and the measurement repeatability. The noise between the different vertical heights is statistically significant. The manufacturer of the FVM instrument agrees with these findings and confirmed that the change between the different levels of vertical height is significant, and the results of this experiment present a similar idea to that presented by the FVM manufacturer (Alicona 2016). Although these differences are quite small, they can add to the increase of the measurement noise of the FVM instrument. The non-linearity could be caused by the way in which the drive train is guided and how the *Z*-axis is mounted on the guiding rails. This interpretation seems to be the reason behind the differences in the linearity of vertical height levels. As the FVM manufacturer obtained similar results, it can be confirmed that the effects seem to be general for FVM.

In this experiment, the metrological characteristic can be determined through the measurement noise and measurement repeatability. A Halle flat reference surface artefact is a suitable artefact that can be measured in the determination of measurement noise for FVM. The good practical procedures to determine the MC with the suitable artefact are presented in the experimental methodology.

Chapter five: Residual flatness experiment

The thesis aims to investigate the traceability framework by determining the metrological characteristics (MCs) for a focus variation microscopy (FVM) instrument, as an optical areal surface texture measuring instrument.

The research aim is addressed by determining the residual flatness of FVM by applying two different filters using the measurement of the Halle flat surface artefact (the ISO filter standard and proposed method). One of the MC of FVM can be determined through the residual flatness. Good practical procedures to determine the MC are used throughout the experiment. Applying the filter can be predicted as an important process in the determination of residual flatness. The variables of different filter and objective lenses were kept constant, and contrast and exposure time for different objective lenses were varied in the experiment. The research aims and questions can be achieved by doing the experiment of determining the residual flatness.

5 The experiment

5.1 Method

The experiment is performed to calculate the residual flatness characteristic using different filtering processes. One process follows the ISO instruction and the other is proposed method. The ISO instructions of the filtering process are to use a low pass Gaussian filter as stated in the ISO standard to generate an *SF*-surface with a cut–off value that is equal to one-tenth of the field of view. Another filtering process (the proposed method) is to multiply the sample distance of the field of view of each objective by ten. The ISO standard requires measurements with a determined specification for sample length and area. This ISO sampling requirement in many cases cannot be satisfied. Therefore, the proposed filter method can be used as an alternative when the sample length or the size of a measured surface area cannot follow the ISO requirements. Two objective lenses with magnifications of 50× and 100× have been used in this experiment. Instrument parameters are fixed to find the differences that may occur between the objectives. The fixed parameters are contrast, brightness, and vertical and lateral resolutions. Only one vertical height range (55mm) has been used. This experiment focuses on the error of the *Z*-scale. The measuring surface should be flat (Ra>10nm) to achieve the measuring requirements of determining the residual flatness for FVM. Therefore, a Halle standard flat surface (with Sa value is 85.4 nm) is chosen to measure in the experiment (see Figure 16, chapter 3). Total of 96 data are collected from four different locations for each lens. Using Alicona’s script (see appendix

1), three sets of data are collected in the first location before moving to the next location and up to a total of four different locations, returning to the first. The goal of this process is to reduce the effect of local variations of the measured surface. The variations mean any variation from an ideal plane of measuring surface. The measuring process is presented in Figure 61. The details of the parameters are shown in

Table 10. From Table 10, the parameters of contrast, brightness/exposure time, vertical and lateral resolution were chosen to assist in gaining the image data from both objectives. The experiment is applied at the normal measuring temperature and humidity. For the purpose of data analysis, the MountainsMap software program is used for data analyses. With the Mountainsmap software program, a number of measurement data can be averaged together. The levelling process was performed for the averaged surface of the 96 sets of measuring data. Threshold, by removing points that have distances more than three standard deviations from the average point heights, was processed on the levelled surface. Two filter settings of the ISO standard and the proposed method were applied on the data of threshold surface. The threshold value was material ratio 0.5% to 99.5%. The ISO filter was a low pass Gaussian filter applied as stated in the ISO standard to generate an *SF*-surface with a cut–off value that is equal to one-tenth of the field of view. The proposed filter method was to multiply the sample distance of the field of view of each objective by ten. The value of Sz was calculated after the filtration process. Figure 62 represents the analysis process of obtaining Sz value using Mountainsmap. From Figure 62, the averaged surface refers to the result of the 96 averaging surfaces.

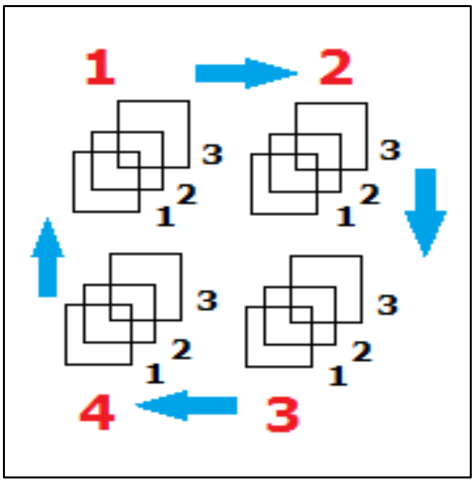

Figure 61: Measuring process

Table 10: The experimental parameters

Parameter	Data	Lens
Image Contrast	1	50× / 100×
Brightness/ exposure time	300 µs	50× / 100×
Vertical resolution	0.01 µm	50× / 100×
Lateral resolution	1.34 µm	50× / 100×

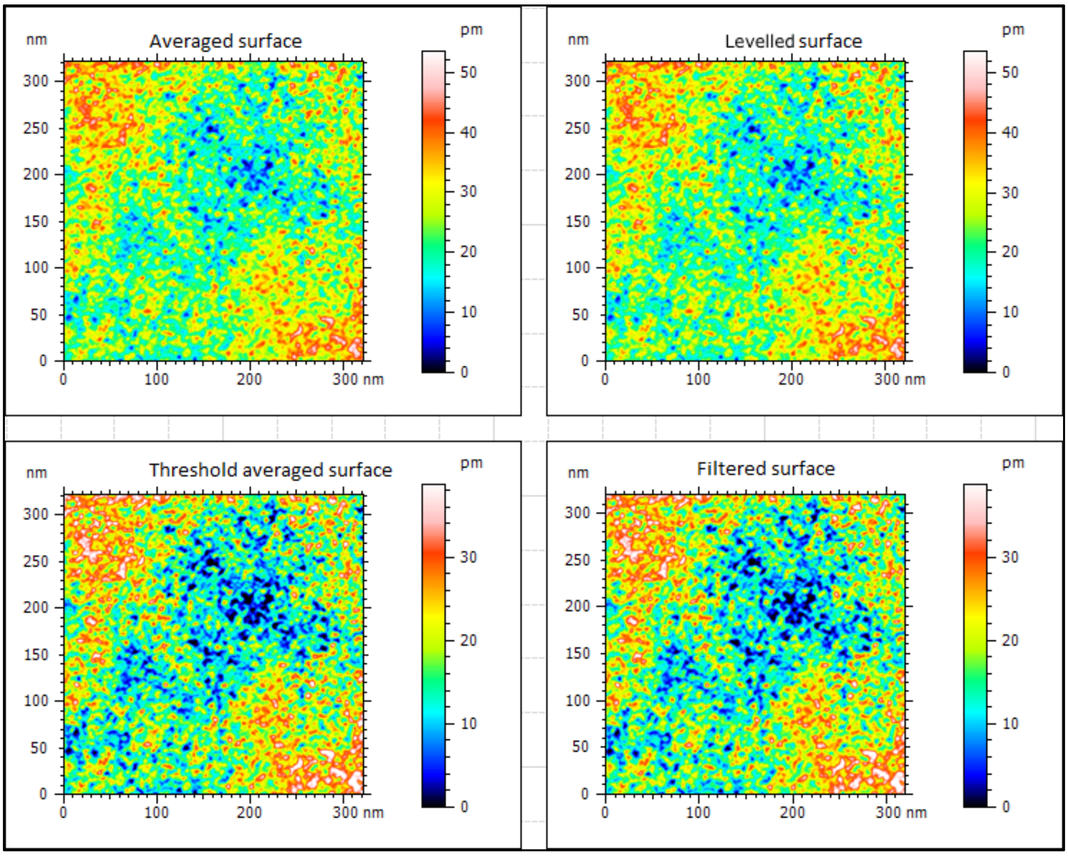

Figure 62: Residual flatness analysis process

5.2 Results

The results have been obtained by averaging from number of surfaces. The levelling process is applied on the averaged surface. To remove the spikes from the levelled surface, the threshold operation is performed. Before calculating the *Sz* values of the residual flatness, two different filter processes are followed, namely the ISO instructions of the filtering process and another filtering process (proposed method). A low pass Gaussian filter is applied as stated in the ISO standard to generate an *SF*-surface with a cut–off value that is equal to one tenth of the field of view. The cut-off of the 50× objective lens was 32 µm and for the 100× was 16 µm. The filter using other process is selected by multiplying the sample distance of the field of view of each objective by ten. The sampling distances of the 50× and 100× lenses are 0.176 µm and 0.088 µm, respectively; hence, the other filtering process uses a filter with sampling distances of 1.76 µm and 0.88 µm. A flow chart of the process is shown in Figure 63. The *Sz* values of the filter process following the ISO standard (setting 1) are 22.9 nm and 26.1 nm for 50× and 100× objective lenses, respectively. The *Sz* results of the filter procedure following the other process (setting 2) are 37.8 nm and 38.7 nm for 50× and 100× objective lenses, respectively. The Sz values of unfiltered data are 53.6 nm and 42.3 nm for 50× and 100× objective lenses, respectively. Although the difference between the two objectives is not significant, using different filter processes is statistically significant different for the residual flatness results. Figure 64 shows the *Sz* findings of the residual flatness.

Figure 63: The flow chart of the analytical process

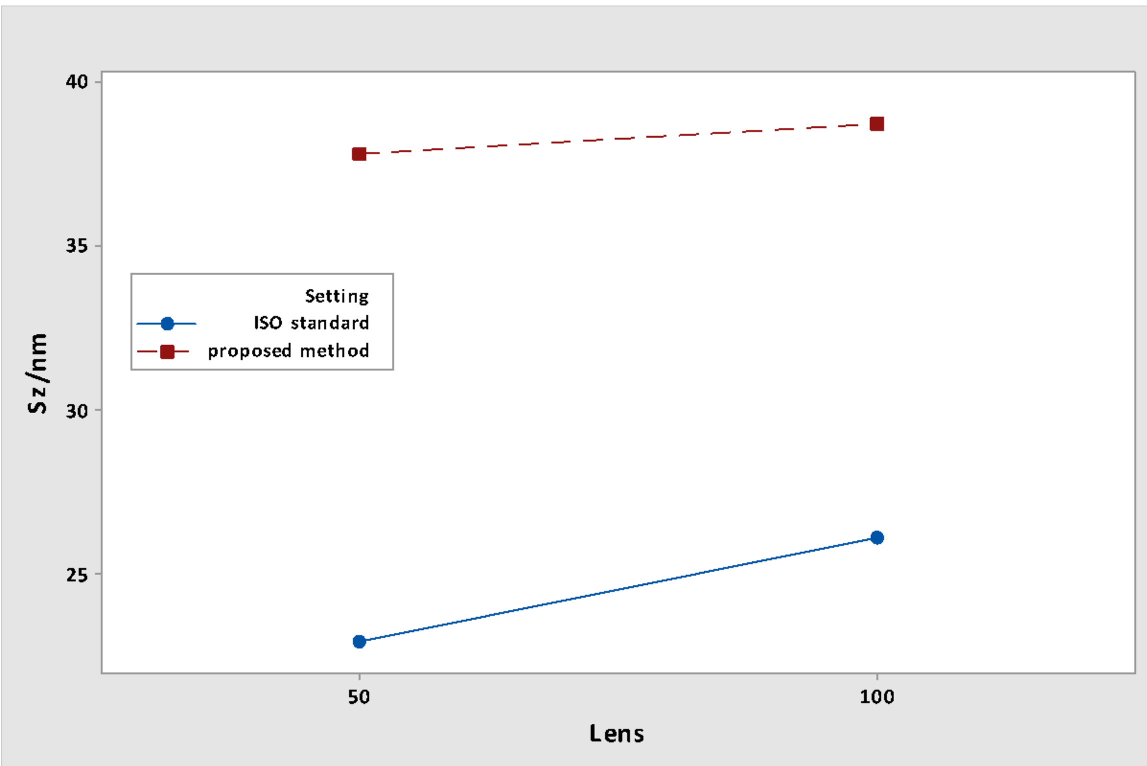

Figure 64: Results of residual flatness for both objective lenses and filter methods

5.3 Discussion

The residual flatness experiment has been conducted on the FVM instrument using two objective lenses with 50× and 100× magnifications. Constant parameters of contrast and brightness and vertical and lateral resolutions have been used in the experiment. A total of 96 surface data has been collected for each objective. The artefact has been measured in different locations to take into account the surface variations. The value of residual flatness has been obtained after applying a mathematically levelling process, threshold and filtering the averaged surfaces. The ISO filtering rule and the other filtering method have been applied.

The difference in values of *Sz* between different objectives lenses is quite small. The result of *Sz* is not significant when the objective lenses are changed. This finding suggests that *Sz* is more related to vertical scale error of the stage rather than the sensor and optical system performances. Therefore, changing the objective will not significantly affect the value of *Sz*. The value can be affected by scratching or/and dirt on the objectives and the measured surfaces (Leach 2011, Leach and Giusca 2012, Leach and Giusca 2013, Giusca, Claverley et al. 2014). Furthermore, the measuring method of the artefact surface has led to reduce the *Sz* value. Measuring the artefact surface in different locations can assist in minimising the value of *Sz* (vdi/vde2617 2004, Leach 2011, Leach and Giusca 2012, Leach and Giusca 2013, Giusca, Claverley et al. 2014, ISO25178:700.3 2016, ISO25178:700.3 2018). Each location on the measured surface has a different topography due to local variations of the measured surface. In addition, applying the *S*-filter on the surfaces in this experiment has led to reduce the effects of high spatial frequency components, which can be caused by the instrument electrical noise, for the residual flatness values. According to ISO25178:700.3 (2016) and (2018), the *S*-filter can assist in obtaining the effective *Sz* value. Using the filter can eliminate the high-frequency noise components from the surface data so that the *Sz* value is reduced after applying the filter process. The Sz values of unfiltered data are 53.6 nm and 42.3 nm for 50× and 100× objective lenses, respectively. Therefore, the results show that filtering process is very influential in determining the residual flatness. Subsequently, a filter value for assessing residual flatness should be carefully and appropriately selected following ISO standard to measure certain length, otherwise, the proposed method can be used instead for determining the residual flatness for FVM.

The MC of residual flatness is determined by applying either the ISO filter process or the proposed method. A suitable artefact to determine the residual flatness for FVM is a standard flat surface artefact (a Halle flat surface artefact was measured in the experiment). The experiment of residual flatness has addressed the question on what is a good practical procedure to determine the MC with suitable reference artefact.

Chapter six: Amplification, linearity and perpendicularity experiments

The thesis aims to investigate the traceability framework by determining the metrological characteristics (MCs) for a focus variation microscopy (FVM) instrument, as an optical areal surface texture measuring instrument. Therefore, this chapter investigates the determination of amplification, linearity and perpendicularity characteristics for FVM

The research aim is addressed by determining the amplification, linearity and perpendicularity characteristics of FVM by applying three novel experiments using novel and low-cost reference artefacts. The experiments are the lateral scale with multiple-image field measurements, vertical scale, and measuring the lateral scale with single image field measurement. Each experiment proposes new low-cost artefacts and procedures for vertical and lateral scale calibration. Cross grating artefacts will be measured in the lateral scale calibration experiment, with multiple image fields, with both stitching and non-stitching measuring strategies. The measurements of reference artefacts for lateral calibration of single image field and step height artefacts for vertical scale are presented.

The MC of FVM can be determined through the amplification, linearity and perpendicularity characteristics. Cross grating and step height artefacts are measured in the determination. Good practical procedures to determine the MC are followed throughout the experiments. Thus, the research aim and questions can be achieved by doing the experiments of determining the amplification, linearity and perpendicularity characteristics.

6 The experiments

6.1 Lateral scale calibration

Calibration of the material measures

In order to calibrate the distances between the centres of the calottes of the cross-grating, a Zeiss O-Inspect non-contact coordinate measuring machine (CMM) is used with a maximum permissible error specification of $E_{L,MPE} = \pm(1.6 + L/300)\ \mu\text{m}$, where L is in millimetres. This CMM is periodically performance verified to assure that it operates within its specification $E_{L,MPE}$. According to the specification, the CMM has one-magnitude higher accuracy for its x- and y-stages compared to that of the FVM, so that the distances between the centre of the calottes measured by the CMM can be used as the length reference, that is traceable via a gauge block measurement, for the distances measured by FVM. The calottes' centre measurements are carried out in four different positions with different orientations at each position. The orientation is changed by rotating the artefact by 90° clock-wise for each position. Measurements are repeated five times for each calotte at each position. With this strategy (ISO/DTS15530-2 2007), the volumetric error of the CMM is taken into account as a contributor for the combined standard uncertainty estimation of the artefact's measurement results. Figure 65 shows the artefact calibration with the CMM, where one of the four artefact calibration positions is shown. The artefact position is not parallel to the CMM's *x*- and *y*-axes (skewed position) so that the CMM will move both the *x*- and *y*-axes to reach each calotte. By moving both axes, the errors from both axes are taken into account as influence factors in the uncertainty estimation of the calottes' centre measurements. The callotes' centre measurements are carried out by the CMM optical-head with a 2D vision system. For the traceability, the measurement of a calibrated gauge block is carried out by using the tactile sensor of the CMM.

The location of the centre of each calotte is measured and the centre distances between pairs of calottes were calculated. The centre locations are obtained by an image processing algorithm that extracts the points of the detected circle of callotes and associates a circle geometry to the extracted points to obtain the centre location of the callotes. Table 11 shows details of the uncertainty estimation for the centre distance and maximum combined uncertainty of a distance between two calottes on the artefact. In Table 11, all influence factors are detailed (The calculation process of Table 11 is in appendix 4). The factors consider the CMM repeatability, CMM geometric error, temperature variation and uncertainty for the length measurement of a Grade 1 gauge block. The measurement uncertainty of the length (the centre distance between two calottes) is estimated according to ISO/DTS 15530-2 for calibration with a CMM (ISO/DTS15530-2 2007). Traceability of the calibration results is established with a substitution measurement of the gauge block, with the tactile sensor of the CMM, with nominal length 4 mm (equal to the nominal length being calibrated).

Table 11: All influence factors of the calibration process. The calculation for the largest uncertainty among all the centre distances is shown.

Sources	Value /μm	Description
u_{rep}	0.817	Influence factor considering the CMM repeatability, part property (form, texture), sampling strategy, contamination of the surface, etc. (Type A).
u_{geo}	0.316	Influence factor considering CMM geometric error, stylus error, tip error, fixturing error and alignment error (Type A).
u_{corr}	0.052	Influence factor considering the length error correction applied to the length measurement (only applied for distance/length and size measurement) (Type B).
u_{temp}	0.005	Influence factor due to thermal variation and error of coefficient thermal expansion of the measured part (Type B).
$u_{gaugeblock}$	0.045	Influence factor from the measurement of the calibrated gauge block (Grade 1 gauge block) (Type B).
u_{total}	0.88	Combined standard uncertainty

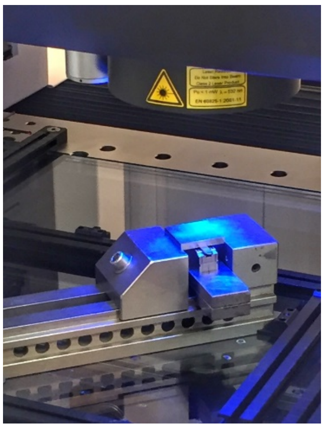

Figure 65: The artefact calibration with the CMM

The second artefact of cross grating has also been measured and calibrated using Zeiss O-inspect CMM to estimate the measurement uncertainty and achieving the traceability (see Figure 65). The measurements have been carried out in four different orientation positions. The measurements have been repeated five times for each hemisphere. The measurement uncertainty of each artefact have been estimated following (ISO/DTS15530-2 2007). Several factors are influence the measurement uncertainty of length errors considering the CMM repeatability, CMM geometric error, temperature variation and uncertainty for the length measurement of reference artefact. The maximum combined standard uncertainty of cross grating artefact is 0.71 μm. Table 12 shows the calibration process of cross grating artefact (The calculation process of Table 12 is in appendix 5.

Table 12: The calibration process of second cross grating artefact. The calculation for the largest uncertainty among all the centre distances is shown

Sources	Value / *µm*	Description
u_{rep}	0.404	Uncertainty source considering the CMM repeatability, part property (form, roughness), sampling strategy, dirt of the surface, etc.
u_{geo}	0.527	Uncertainty source considering CMM geometric error, stylus error, tip error, fixturing error and alignment error
u_{corr}	0.252	Uncertainty source considering the error applied to the length measurement (only applied for distance/length and size measurement)
u_{temp}	0.00095	Uncertainty source due to thermal variation and error of coefficient thermal expansion of the measured part
$u_{gaugeblock}$	0.05	Calibration of gauge block
u_{total}	0.71	

Experimental design

Two objective lenses of 5× and 10× magnifications have been chosen to measure the cross-grating artefact in x- (horizontal), y- (vertical) and diagonal directions. The image fields of the 5× and 10× objectives are $(2.82 \times 2.82)\ \mathrm{mm}$ and $(1.62 \times 1.62)\ \mathrm{mm}$, respectively. The objectives have been chosen to give a relatively large size of image field. The area of measurements is larger than the image field of both the objectives. The measurements are carried out at one height (z −direction) location (at the height of the instrument table where parts are placed) as the calibration is focused on the lateral performance of the FVM. Four measurement types have been determined: measurement in horizontal, vertical and diagonal directions (see Figure 66), and measurements for the whole calottes grid. Each measurement type is replicated three times and averaged to reduce random error. Both stitching and non-stitching measurement methods are applied. The measurements with stitching measure the surfaces in between two callotes and non-stitching measurements only measure the callotes' centre without measuring the surfaces in between two callotes. The purpose of stitching measurements is to study the effect of the stitching algorithm with respect to the lateral stage accuracy. The stitching measurements involve the measurement of multiple image-fields that overlap with each other and the point registration of the overlapped image-fields to reduce the error of the lateral stage. The measurements from the horizontal and vertical directions are used to calculate the perpendicularity error. For amplification and linearity in 2D, all the calottes are measured only with a stitching method, with both 5× and 10× objective lens magnifications, and 2D error maps are presented.

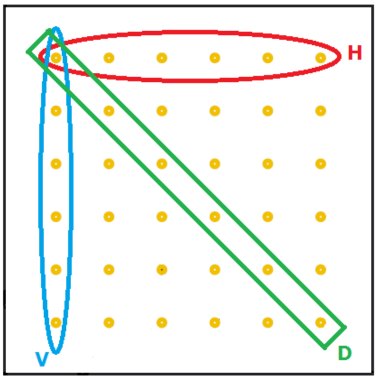

Figure 66: Horizontal (H), vertical (V) and diagonal (D) directions of the measurements.

For the measurements of the second cross grating artefact using FVM, the hemispheres that are in one image field has been measured repeatedly three times for better error estimations. The total hemispheres measurements that are covered by 5x and 10x are sixteen and four, respectively. Due to the number of the measurements using 10x are few in one image field, three different areas were measured. The data of three different measuring directions of horizontal, vertical and diagonal have been calculated for the amplification and linearity characteristics in both objective lenses. Figure 67 and Figure 68 show the covered measuring area and measurement directions for both objectives.

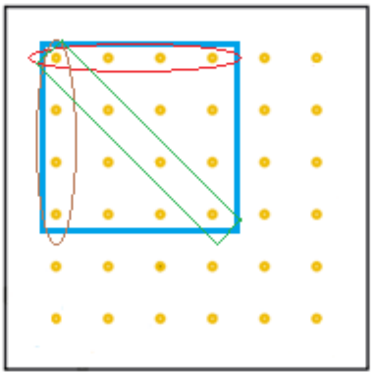

Figure 67: Measuring area using 5x

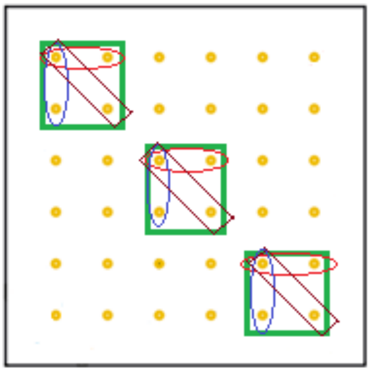

Figure 68: Measuring area using 10×

Amplification and linearity deviation results

The amplification and linearity of the *xy*-stage are determined by calculating the errors between two calottes' centres from measurements in the *x*-, *y*- and diagonal directions. The callote centres are calculated as the centre of a sphere associated to the 3D point cloud of the callottes. An error is defined as the difference between a calibrated length (measured by CMM) and a length measured by FVM. The length is the distance between two calottes' centres. The results show different errors for the measurements carried out in different measuring directions with both the objectives 5× and 10× and with and without stitching. In addition, the results show that the choice of the different objective lenses does not significantly affect the error, but the use of stitching does have a significant effect

Figure 69, Figure 70 and Figure 71 show the errors of the length measurements of 1st artefact with the 5× objective lens for the horizontal, vertical and diagonal directions respectively. From Figure 69 and Figure 70, it can be seen that the average length errors measured of 1st artefact with stitching are reduced by up to 52 % and 25 % for the x- and y-directions respectively, compared to the errors obtained from the measurements without stitching. Similarly, Figure 72, Figure 73 and Figure 74 show the errors of 1st artefact for the measurements with the 10× objective lens for horizontal, vertical and diagonal directions respectively. From Figure 72 and Figure 73, the average length errors can be reduced by up to 62 %, and 10 %, for x- and y-directions respectively, for measurement with stitching compared to without stitching. The length errors in the diagonal direction obtained from both the 5× and 10× objective lenses are similar for both stitching and non-stitching measurement strategies. The results show that the stitching algorithm is only effective for measurement in the single *x*- and *y*-directions, but is not as effective in the diagonal direction. The figure calculations are in appendix 6.

From the non-stitching measurements with both the 5× and 10× objective lenses, the results show that the lateral error of the stage is the largest in the x-direction. Since the non-stitching strategy measures each calotte separately to calculate their centre positions, their errors cannot be numerically compensated. Numerical compensations are applied by stitching overlapping surfaces when the calottes are measured. The measurement results obtained by the 10× objective lens with the stitching method have lower errors than the measurements obtained by the 5× objective lens. Lager numbers of images for stitching are obtained to reconstruct the measured surfaces with the 10× objective lens due to a smaller field of view. Subsequently, with larger numbers of images for stitching, compensation of the stage's error can be improved so that the measurement error is reduced. The higher error of the non-stitching method could be because of no compensation of stage error is available.

The measurement uncertainty of length errors considers several influence factors: the standard error from measurement repetitions, the uncertainty of the length calibration, the error due to the material expansion and the error in the estimation of the coefficient of the material's thermal expansion coefficient. Table 13 shows the influence factors that contribute to the measurement uncertainty. In Table 13, the largest uncertainty estimation corresponding to a 20 mm length measurement is shown. The combined standard uncertainty for the 20 mm length measurement is 1.48μm.

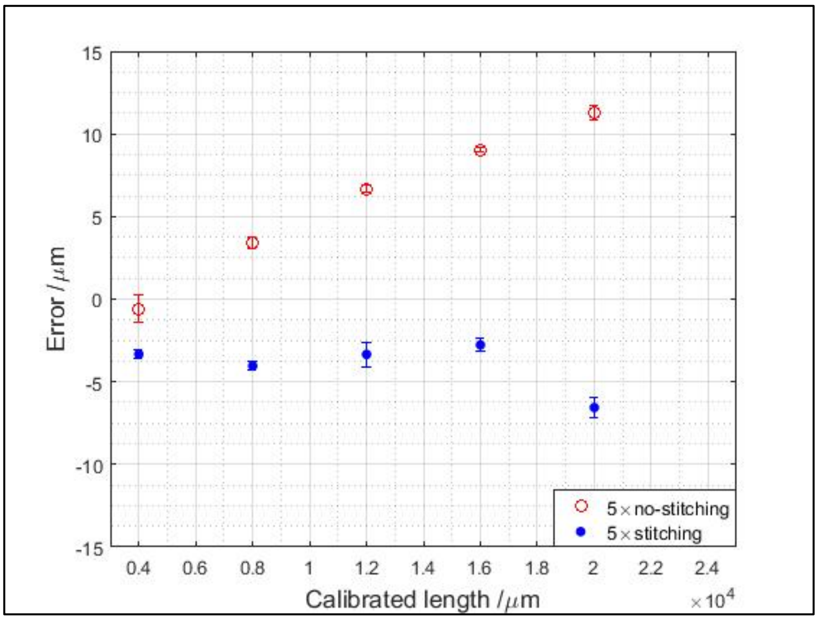

Figure 69: Results of the error calculation of 1st artefact for the 5× objective in the horizontal direction

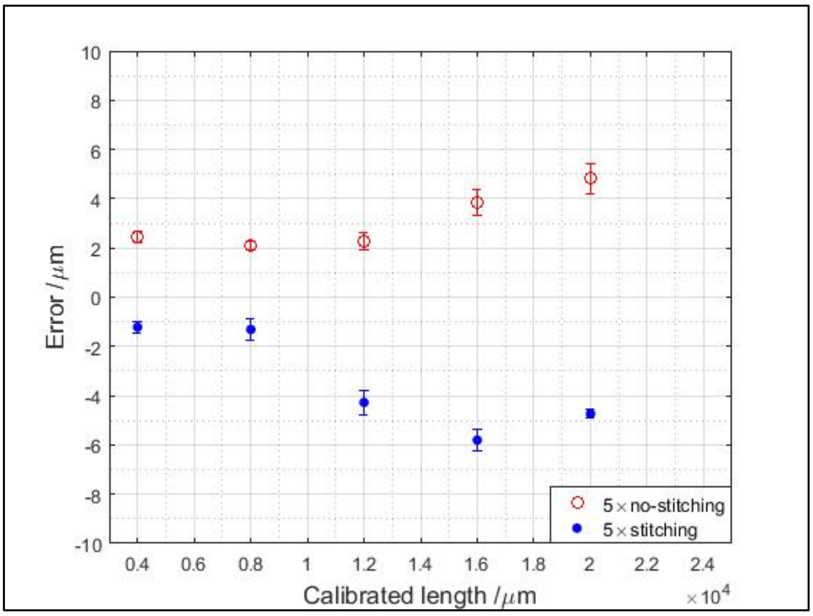

Figure 70: Results of the error calculation of 1st artefact for the 5× objective in the vertical direction.

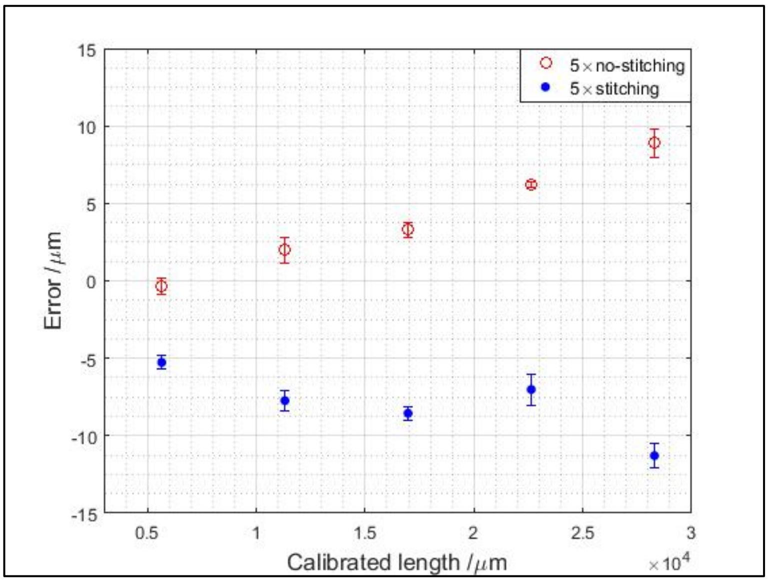

Figure 71: Results of the error calculation of 1st artefact for the 5x objective in the diagonal direction.

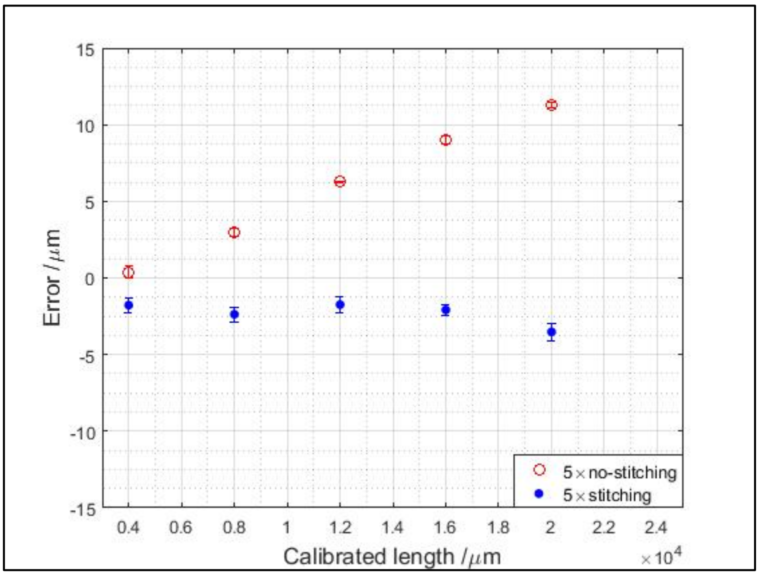

Figure 72: Results of the error calculation of 1st artefact for the10x objective in the horizontal direction.

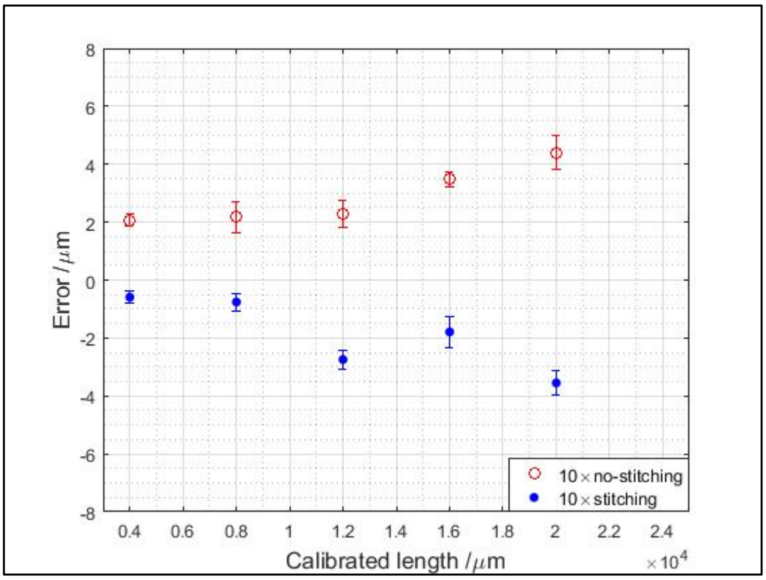

Figure 73: Results of the error calculation of 1st artefact for the 10x objective in the vertical direction.

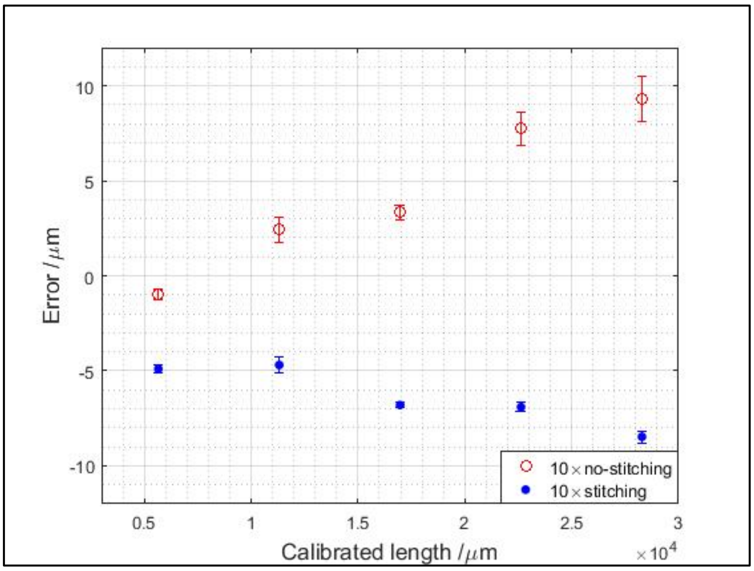

Figure 74: Results of the error calculation of 1st artefact for the 10x objective in the diagonal direction.

Table 13: Measurement uncertainty estimation and its influence factors. The shown estimated combined uncertainty is the largest uncertainty estimation among the errors measured with the 5× and 10× objective lenses corresponding to a 20 mm length measurement.

Uncertainty contributor	Value / µm	Description
u_{rep}	1.17	Standard error from multiple measurements (Type A).
u_{temp}	0.23	Uncertainty due to stainless steel coefficient of thermal expansion (CTE) $11.7 \times 10^{-6}\ \mathrm{K}^{-1}$ and ΔT =1 °C) (Type B).
u_{CTE}	0.023	Uncertainty due to error in the CTE estimation (10 % CTE) (Type B).
u_{trace}	0.88	Uncertainty of calibration of the length (Type B).
u_{total}	1.48	Combined uncertainty

According to the results of an analysis of variance (ANOVA), the length measurement errors obtained with the 5× and 10× objectives are statistically similar for all the measurements in *x*-, *y*- and diagonal-directions. The results show that the errors are mostly contributed by the performance of the *xy*-stage. Therefore, changing the objective may not significantly affect the results of the calibration. Giusca, Leach et al. (2012) also reported that errors of amplification, linearity and perpendicularity of the *xy*-stage of other instruments are not affected by the magnification of the objectives. The results suggest that a low magnification lens can be used to determine the amplification and linearity errors of the *xy*-stage. By using a low magnification lens, a larger field of view can be obtained so that measurement time can be reduced.

In summary, the results of the amplification coefficient (α) and linearity deviation (*l*), following their definition in ISO/DIS 25178 (ISO25178:600 2018), are numerically presented in Table 14. From Table 14, the calculated amplification coefficients show that the measurements with stitching tend to decrease the measured distance and the measurements without stitching tend to increase the measured distance between the centres of two callottes. The amplification coefficients calculated from the measurements with stitching have value less than one unity, meaning the measured distances are shorter than the calibrated distance. In contrast, the coefficients calculated from measurements without stitching have values more than unity, meaning the measured distances are longer than the calibrated distances. From the calculated linearity deviation shown in Table 14, the results show that, even though the measurements with stitching decrease the stage errors, they also increase the non-linearity. It is worth noting that the stage error and linearity deviation are different. The stage errors show the difference between a measured and calibrated distance between two callottes' centres, while linearity deviations show the maximum difference between the measured data and the line from which the amplification coefficient is derived (ISO25178:600 2018).

Table 14: The calculated values of amplification coefficient and linearity deviation.

	5×		10×	
Amplification coefficient (*a*)	stitching	non-stitching	stitching	non-stitching
a_x	0.99987	1.0007	0.99992	1.00069
a_y	0.99971	1.00016	0.99982	1.00015
$a_{diagonal}$	0.9998	1.0004	0.99983	1.00045
Linearity deviation (*l*)	stitching	non-stitching	stitching	non-stitching
l_x/µm	1.24	0.51	0.41	0.21
l_y /µm	0.84	0.60	0.61	0.42
$l_{diagonal}$ /µm	1.47	0.51	0.51	0.73

The error results of the second cross grating artefact of 5× and 10× objective lenses have been collected for horizontal, vertical and diagonal directions. For the 5× objective lens, the horizontal direction has low error comparing to the other directions. The high error, that can caused by dirt, for the vertical direction may be obtained. Figure 75, Figure 76 and Figure 77 show the error results of 2nd artefact with 5× objective lens for horizontal, vertical and diagonal direction, respectively. Due to small area can be measured using 10× objective lens, the error results for all different measuring positions in different directions are presented in Table 15, Table 16 and Table 17. Each measuring position has different results. The error results of position1 in all measuring directions are lower the other measuring positions. The vertical direction has high error result in measuring position 1. The measuring position 2 shows the horizontal direction is higher error than the other directions. In the measuring position 3, the diagonal results are higher than the horizontal and vertical directions. It is important to know that each measuring area position has different error stage, therefore, it is difficult to obtain same error results in different measuring positions. When the measuring area is changed, a new measuring data can be collected. The figure calculations are in appendix 7.

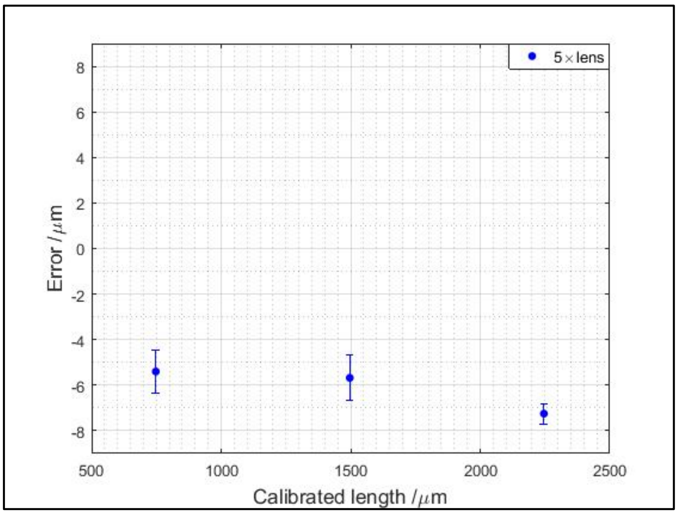

Figure 75: Results of error calculation of 2nd artefact for the 5× objective lens for horizontal direction

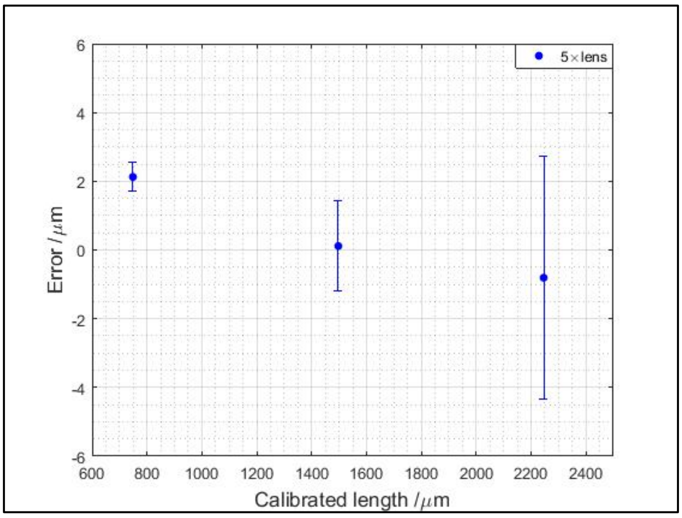

Figure 76: Results of error calculation of 2nd artefact for the 5× objective lens for vertical direction

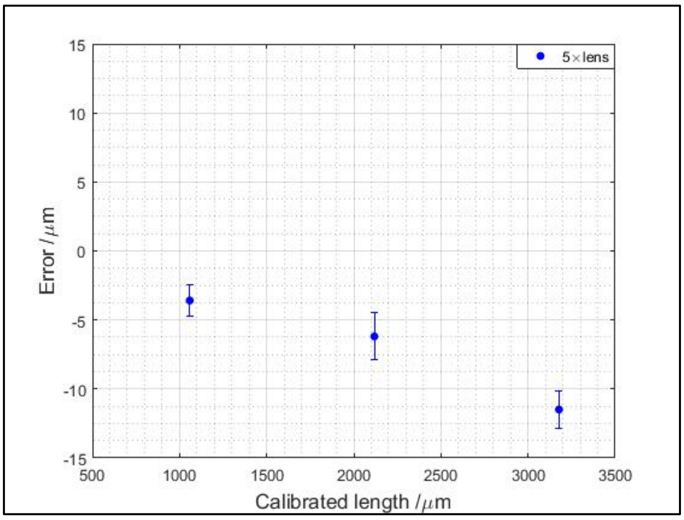

Figure 77: Results of error calculation of 2nd artefact for the 5× objective lens for diagonal direction

Table 15: Error results of 2nd artefact for 10× objective lens for horizontal direction in different positions

TRIAL	POSITION1 /μm	POSITION2 /μm	POSITION3 /μm
1	-1.95	-1.94	-1.87
2	-2.60	-3.25	-1.98
3	-1.93	-4.03	-3.08

Table 16: Error results of 2nd artefact for 10× objective lens for vertical direction in different positions

TRIAL	POSITION1 /μm	POSITION2 /μm	POSITION3 /μm
1	-0.26	-1.61	-3.07
2	0.22	-1.03	-1.34
3	-1.67	-2.27	-1.36

Table 17: Error results of 2nd artefact for 10× objective lens for diagonal direction in different positions

TRIAL	POSITION1 /μm	POSITION2 /μm	POSITION3 /μm
1	-2.97	-3.63	-2.75
2	-0.97	-3.32	-4.42
3	-2.61	-3.42	-4.37

Perpendicularity deviation result

The perpendicularity deviation is obtained by calculating the differences of the angles between the x- and y-axes from the CMM measured data and from the FVM measured data. For the perpendicularity deviation, the calottes' centre locations are estimated from the measurements in the x- and y-directions, using stitching and non-stitching strategies. Three repeated measurements are carried out for stitching and non-stitching measurements to estimate the calottes' centre locations. From the estimated calottes' centre locations, least-square lines are fitted to the centre locations in both the x- and y-directions. The perpendicularity deviation the 5× and 10× objective lenses are 0.46° and 0.22°for the measurements with stitching, and 0.22° and 0.19° for the measurements without stitching, respectively. Table 18 shows the results of all perpendicularity deviations. From Table 18, the maximum differences for the perpendicularity deviation for both stitching and non-stitching measuring strategies, and both the objective lenses are around ± 0.2°. Giusca, Leach et al. (2012) also found a similar perpendicularity deviation of 0.3° with a coherence scanning interferometer. The differences in 5× and 10× for the second cross grating artefact are 0.002° and -0.023°, respectively. Table 19 shows the perpendicularity calculation of second cross grating artefact.

Table 18: Results of perpendicularity deviation (± standard deviation of the mean).

	5× STITCHING / °	**5× NON-STITCHING / °**	**10× STITCHING / °**	**10× NON-STITCHING / °**
FVM	90.46 ±0.53	89.77 ±0.20	90.22 ±0.07	90.19 ±0.46
CMM	89.99±0.01			
Difference	0.46	0.22	0.22	0.19

Table 19: Results of perpendicularity calculation for the second cross grating artefact

	5x / °	10x / °
FVM	90.003 ± 0.06	89.979 ± 0.05
CMM	90.002	
Difference	0.002	-0.023

Amplification and linearity errors in 2D

The amplification and linearity deviation in xy-directions are presented as 2D error maps. The 2D error maps for measurements with the 5× and 10× objectives lenses are shown in Figure 78 and Figure 79 respectively. For all the measurements, stitching is employed and the measurements cover the whole surface of the artefact. All the calottes' centre locations are calculated from the average of three repeated measurements. The coordinates of the calculated centres are mathematically aligned, by least-squares fitting a line to the callottes' central position, calculating the angle of the fitted line with respect to the *x*-axis of the reference coordinate system and rotating all the central positions based on the calculated angle, to remove errors due to fixturing and placement when setting up the artefact for the measurements. After the alignment, all centre locations from both the measurements of CMM and FVM are registered and overlapped, by translating the coordinate system of all the centre positions (from both the CMM and FVM measurements) to the centroid position of the centre location, based on their centroid locations (Daemi, Ekberg et al. 2017). After all the centre locations have been registered and overlapped, the errors of each centre's location on the grid are calculated as the difference between the centre locations measured with the FVM and centre locations measured with the CMM. The centre locations measured with the CMM are used as reference values. The maximum differences between the CMM and FVM measurements with the 5× and 10× objective lenses are 7.6 µm and 5.2 µm, respectively (The CMM data calculations of the figures are in appendix 8).

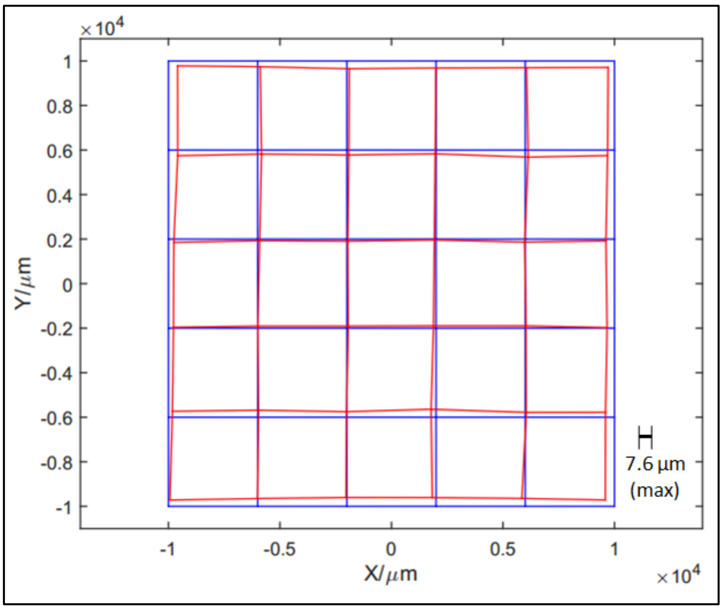

Figure 78: 2D error map for the measurement obtained with the 5× objective lens (the FVM data is red and the CMM is blue).

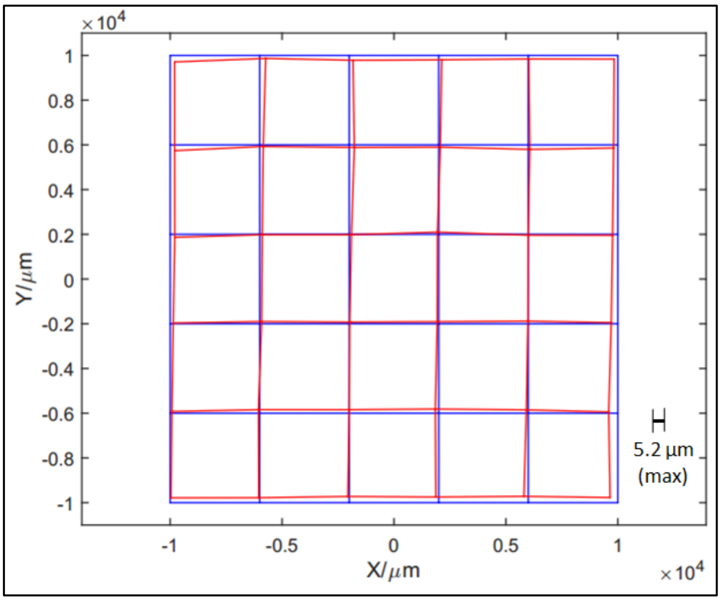

Figure 79: 2D error map for the measurement obtained with the 10× objective lens (the FVM data is red and the CMM is blue).

From the 2D error maps, it can be seen that the measurement errors with stitching, for both the 5× and 10× objectives lenses, are generally 15 % higher than the errors in the single axis measurements with stitching. The increase of the errors can be attributed to the contribution of both the *x*- and *y*-axis errors for the 2D measurements.

6.2 Vertical scale measurement

Prior to measuring the new artefacts using FVM, the artefacts have been measured and calibrated using Zeiss O-inspect CMM to estimate the measurement uncertainty and achieving the traceability. The measurement has been repeated five times for each slot in step height artefact. The measurement uncertainty of each artefact have been estimated following (ISO/DTS15530-2 2007). Several factors are influence the measurement uncertainty of length errors considering the CMM repeatability, CMM geometric error, temperature variation and uncertainty for the length measurement of reference artefact. The maximum combined standard uncertainty of the step height artefact is 0.22 μm. Table 20 shows the calibration process of step height artefact (The calculations of Table 20 are in appendix 9). Each source in table 20 shows the maximum value obtained in appendix 9. For example, the value of $\boldsymbol{u_{rep}}$ indicates its maximum value of the calculation in appendix 9, while the value of $\boldsymbol{u_{\mathrm{total}}}$ is the square root calculation of the sum of each squared source.

Table 20: The calibration process of step height artefact

Sources	Value / μm	Description
u_{rep}	0.097	Uncertainty source considering the CMM repeatability, part property (form, roughness), sampling strategy, dirt of the surface, etc.
u_{geo}	0.101	Uncertainty source considering CMM geometric error, stylus error, tip error, fixturing error and alignment error
u_{corr}	0.158	Uncertainty source considering the error applied to the length measurement (only applied for distance/length and size measurement)
u_{temp}	0.00062	Uncertainty source due to thermal variation and error of coefficient thermal expansion of the measured part
$u_{gaugeblock}$	0.05	Calibration of gauge block
u_{total}	0.22	

The measurements of step height artefact have been carried out at five different vertical heights of 15mm, 35mm, 55mm, 75mm and 90mm. Each slot measurement in each vertical height has been repeated three times. All the measurements have been carried out using 50x objective lens with increasing the vertical resolution to detect the small error. The distance between the top point and bottom point of each slot is calculated. The calculation of step height artefact is applied using MountainsMap software. Figure80 shows the step height slot from the top.

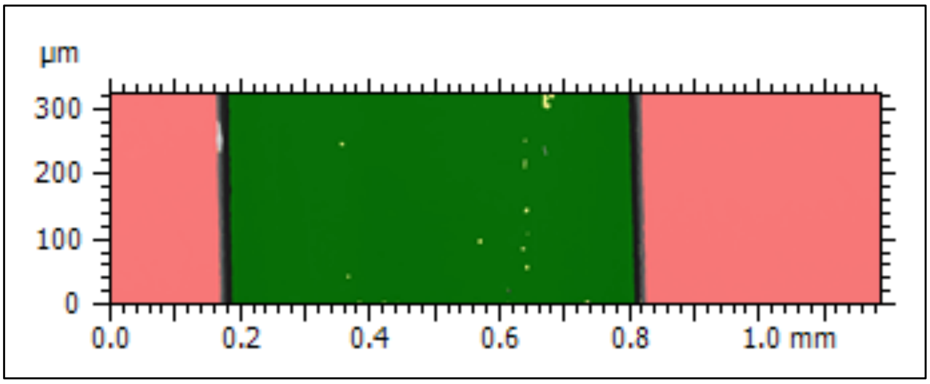

Figure 80: Top view of step height

The results of Step height artefact:

The measurement results of step height artefact are collected at different vertical height levels. The results from FVM are compared with the reference CMM results. Measuring at different height level does not indicate any differences between the levels. As the artefact is measured using one objective lens (50×), Each level can measure the artefact with the same measuring field of view of objective lens and measuring vertical distance. However, the measurement at level 15 mm can be maximum differences between the CMM and FVM. The maximum difference result is 3.14 µm. Figure 81 shows the results of step height measurements.

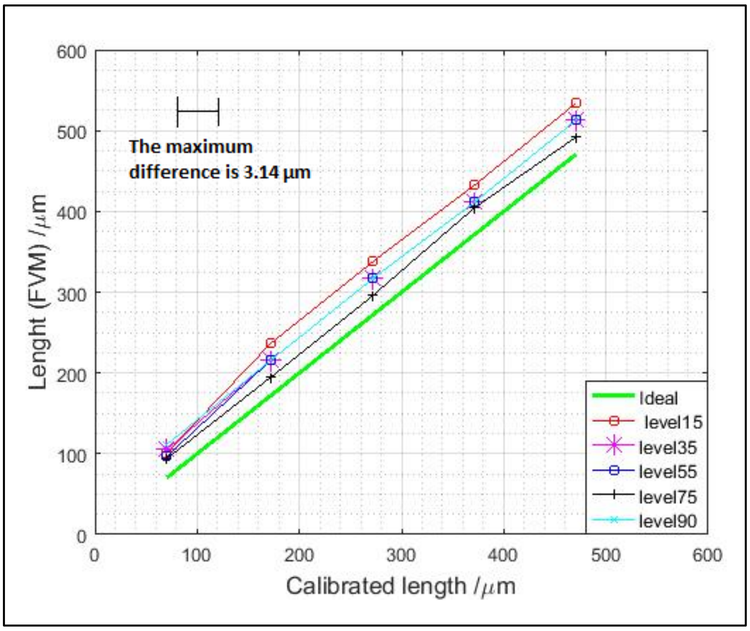

Figure 81: Results of step height measurements

6.3 Single image field calibration

Prior to measure the artefact with FVM, a coherence scanning interferometer (CSI) instrument has been used as reference in the artefact calibration (CSI instrument is traceable). Five repeated measurements in four different positions are carried out using 20× objective lens. Figure 82 presents the artefact measuring with CSI instrument. The FVM measure the artefact using 10× and 20× objective lenses. Three repeated measurements are carried out for each objective. The amplification and linearity are determined by calculating the errors between two intersection's centres from measurements in the *x*-, *y*- and diagonal directions. An error is defined as the difference between a calibrated length (measured by CSI) and a length measured by FVM.

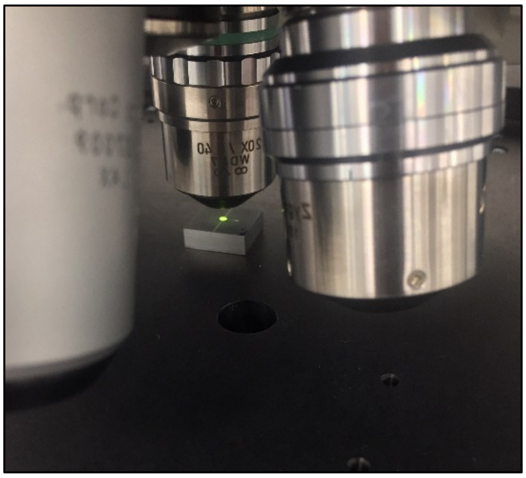

Figure 82: The artefact measurement with CSI

Measurement Uncertainty calculation:

Zygo CSI instrument was used to calibrate the distances between the intersection centres of the artefact. Zygo CSI instrument is used as the length reference due to its higher accuracy compared to the FVM. The measurement uncertainty of the length (the centre distance of between two intersections) was estimated. The artefact is measured in four different positions with different orientations at each position. The orientation is changed by rotating the artefact by 90° clock-wise for each position. Measurements were repeated five repeated measurement were carried out at each position. Several factors influence the measurement uncertainty of length errors considering the Zygo repeatability, Zygo geometric error, temperature variation and uncertainty for the length measurement of reference artefact. Table 21 shows the calibration process of the cross grating artefact. The maximum combined standard uncertainty in Table 21 is 1.7414 µm. From Table 21, it is important to notice that a calibrated reference artefact called areal cross grating is measured by a commercial coherence scanning interferometry (CSI) from Zygo to achieve the traceability. The calculations of Table 21 are in appendix 10. The result of reference artefact is contributed in the total calculation of calibration process. Due to non-deterministic features that were shown in Figure 29, large uncertainty calibration is obtained in Table 21. Each source in Table 21 presents the maximum value obtained from the calculation in appendix 10. For example, the value of u_{rep} indicates its maximum value of the calculation in appendix 10, while the value of u_{total} is the square root calculation of the sum of each squared source.

Table 21: The calibration process of cross gating artefact

Source	Value / µm	Description
u_{rep}	1.5544	Uncertainty source considering the Zygo repeatability, part property (form, roughness), sampling strategy, dirt of the surface, etc.
u_{geo}	0.5605	Uncertainty source considering Zygo geometric error, stylus error, tip error, fixturing error and alignment error
u_{corr}	0.00008816	Uncertainty source considering the error applied to the length measurement (only applied for distance/length and size measurement)
u_{temp}	9.29356E-08	Uncertainty source due to thermal variation and error of coefficient thermal expansion of the measured part
$u_{reference\ artefact}$	0.55	Calibration of reference artefact
u_{total}	1.7414	Combined standard uncertainty

Amplification coefficient and linearity deviation results:

The results show different errors for the measurements carried out in different measuring directions with both the objectives 10× and 20×. The errors of the length measurements with the 10× objective lens are in Figure 83, Figure 84 and Figure 85 for the horizontal, vertical and diagonal directions, respectively. Similar results are obtained from different objective lenses. The errors of diagonal direction are higher than the errors of other directions in both objectives. The instrument algorithm can be more effective when measuring in vertical and horizontal directions. Figure 86, Figure 87 and Figure 88 show the errors of length measurements with the 20× objective lens for the horizontal, vertical and diagonal directions, respectively (The figure calculations are in appendix 11).

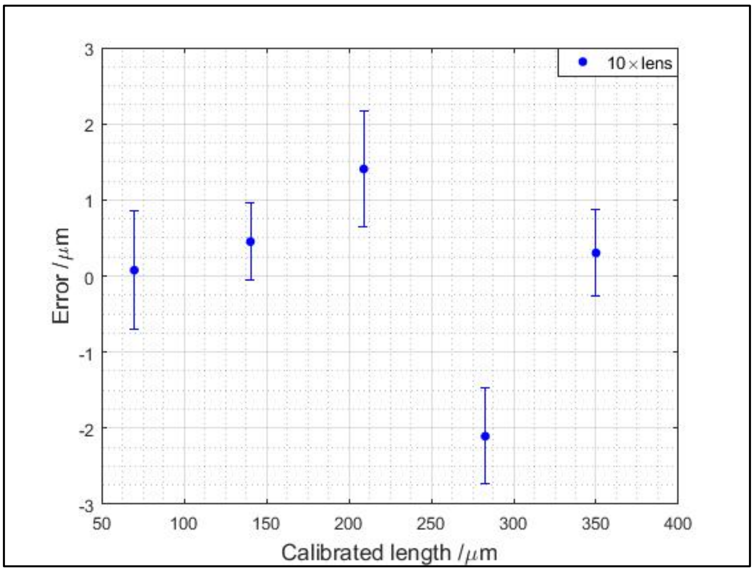

Figure 83: Error results of 10× in horizontal direction

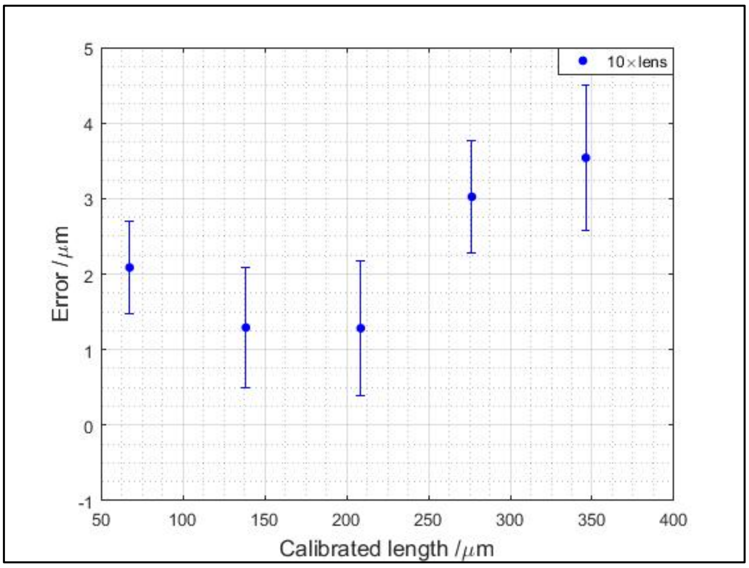

Figure 84: Error results of 10× in vertical direction

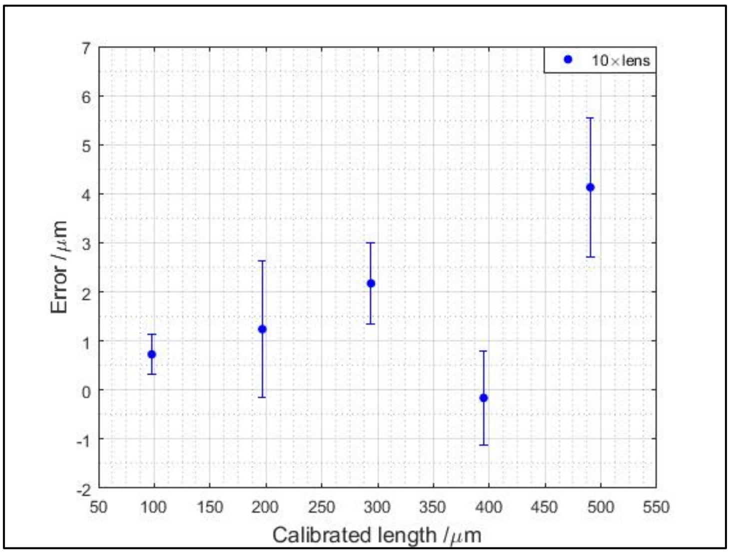

Figure 85: Error results of 10× in diagonal direction

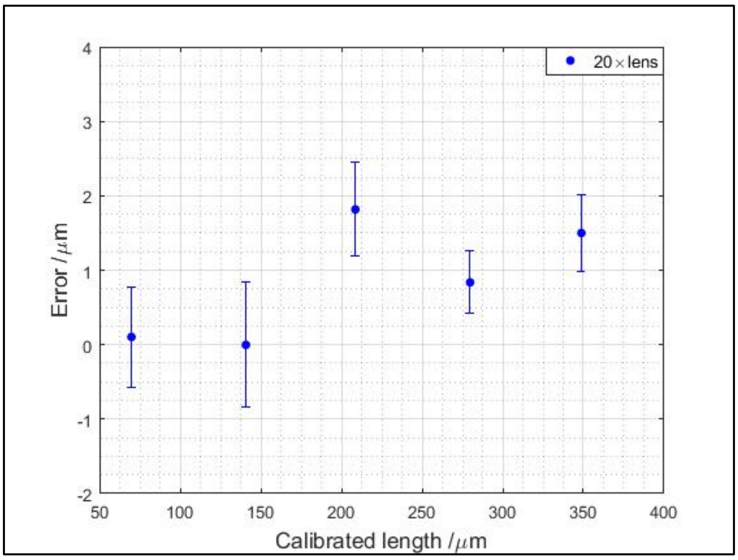

Figure 86: Error results of 20× in horizontal direction

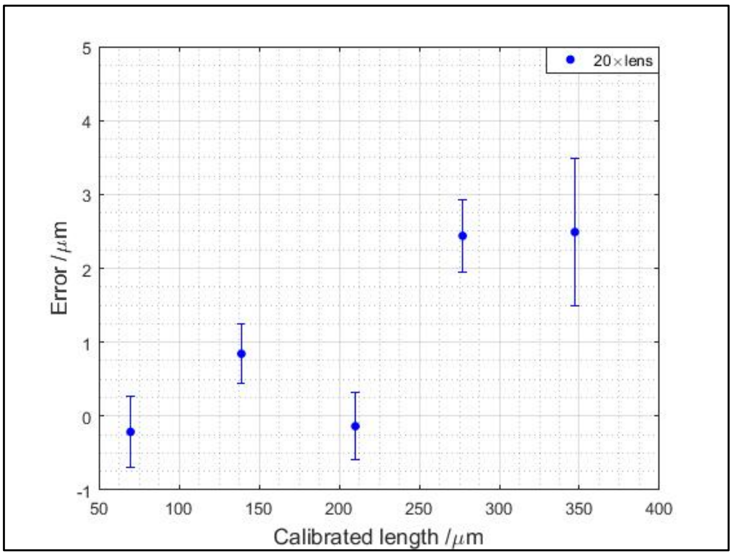

Figure 87: Error results of 20× in vertical direction

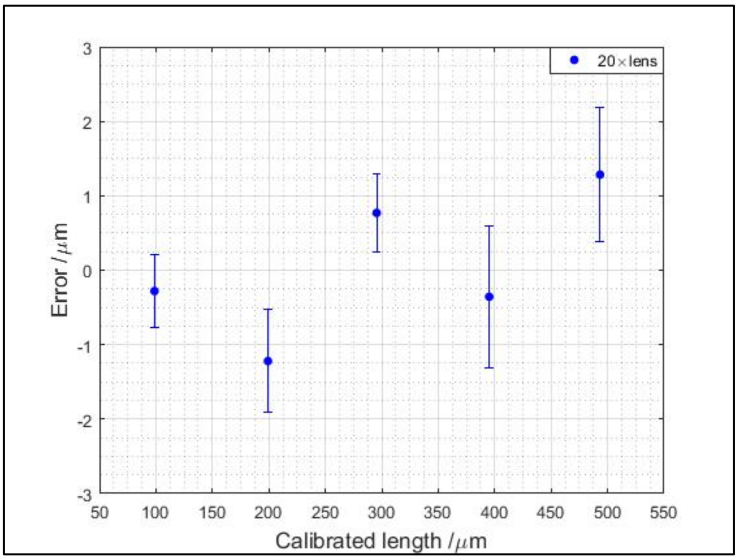

Figure 88: Error results of 20× in diagonal direction

Perpendicularity deviation results:

The perpendicularity deviation is obtained by calculating the differences of the angles between the x- and y-axes from the CSI and FVM measured data. The perpendicularity deviation estimates the measurement of the intersection's centre locations in the x- and y-directions. Three repeated measurements are carried out for the intersection's centre locations in both objectives. A least-square lines are fitted to the centre locations in both the x- and y- directions. The perpendicularity deviation of the 10× and 20× objective lenses are 0.155° and 0.391°, respectively. Table 22 shows the results of all perpendicularity deviations. The maximum differences in Table 22 for the perpendicularity deviation for both the objective lenses are around ± 0.2°.

Table 22: The perpendicularity calculation

	20x	10x
FV	90.175 ± 0.474	89.629 ± 0.579
CMM	90.02 ± 0.109	
Difference /°	0.155	-0.391

Amplification and linearity errors in 2D:

The measurements are applied on the whole artefact surface. The average of three repeated measurements of all the centre intersection locations are calculated. The intersection centres are mathematically aligned by fitting the least-squares line. Then, the angle of the fitted line is calculated with the reference coordinate system. All the central positions are rotated to remove errors based on the calculated angle. The registered centre location from Zygo and FVM are overlapped to the centroid position of the centre location. The error differences of each centre's location between Zygo and FVM are calculated. The centre locations of Zygo value is used as reference. The maximum differences between the Zygo and FVM measurements with the 10× and 20× objective lenses are 3.3 μm and 2.8 μm, respectively. Figure 89 and Figure 90 show the 2D map of error map for the 10× and 20× objective lenses, respectively. (The data calculation of the figures is in appendix 12).

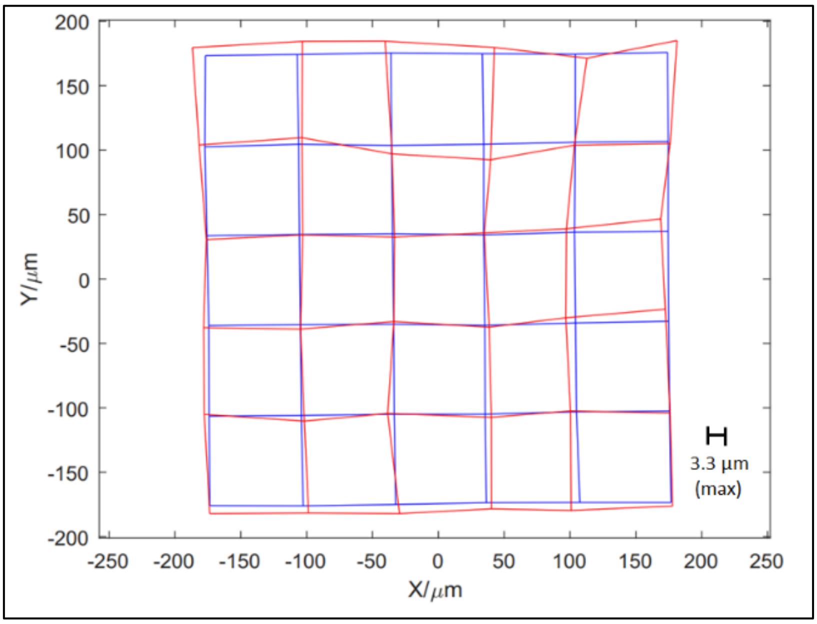

Figure 89: 2D error map for the measurement obtained with the 10× objective lens (the FVM data is red and the Zygo is blue)

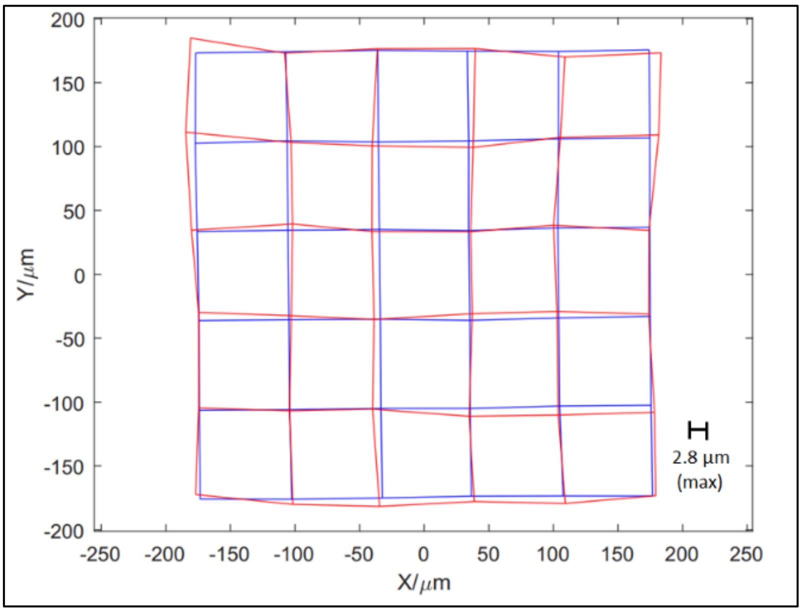

Figure 90: 2D error map for the measurement obtained with the20× objective lens (the FVM data is red and the Zygo is blue)

Conclusion and future work

The calibration of the vertical and lateral scale for FVM is presented by determining its amplification, linearity and perpendicularity characteristics. For lateral scale calibration measurement, a novel and low-cost calibrated cross-grating artefact (£100 for manufacturing cost), consisting of a grid of calottes, and procedures for the determination of linearity, amplification and perpendicularity characteristics have been proposed. As part of this study for determining the characteristics, two objective lenses of 5× and 10× are used to measure the proposed cross-grating artefact with both stitching and non-stitching strategies. Measurements in the horizontal, vertical and diagonal directions, along with measurements of the entire grid of calottes, are carried out. The results from the measurements of the proposed cross-grating artefact indicate that:

1. Measurements with stitching can reduce errors in the x- and y-directions, but not in the diagonal direction.
2. Measurements in 2D direction have 15 % larger errors than measurements in only one direction.
3. Measurements with stitching can significantly reduce lateral stage error, but increase the non-linearity of the error.

For the measurement results of the second cross grating artefact, a high error has been found in the vertical direction of 5× objective lens. Some dust on the measured artefact may be the reason behind the obtained high error. Regarding the measurement using 10× objective lens, different measuring positions are carried out due to small measuring area can be covered. Each measuring position has different measuring error results. Small measuring dimensions should be used to collect a good measuring process for single image field.

In the calibration of single image field experiment, some issues have limited determining the amplification coefficient, linearity deviation and perpendicularly characteristic. The micro features of used artefact have non-deterministic square shapes due to the manufacturing process complexity. In the process, some of the slot intersections of the artefact have inaccurate dimensions due to tool wear during cutting. This issue causes a high uncertainty when calibrating the artefact and make it not reliable. A large uncertainty of artefact calibration reduces the significance of the experiment data. Some post processing for the artefact may be required to get a better shape and to avoid this issue. When the artefact is measured, some good features can be used for single image field, particularly, on the top right corner region (see Figure 29). Alternatively, another type of micro-scale precision machining can be used to get deterministic grid shape with a possibility of more complex processing and higher manufacturing cost. The high manufacturing technology, for example special nano-pulse laser drilling may produce required artefact with precise dimensions. However, it is important considering the cost of making a new artefact using high manufacturing technology such as laser texturing process. The new artefact can be designed and manufactured using high manufacturing technology in the future work.

The MC of amplification, linearity and perpendicularity have been determined in the experiments for lateral and vertical scale measurements. The measurement of lateral scale was applied for single and multiple image fields using low-cost manufactured artefacts of cross grating and the measurement of vertical scale is performed using step height artefact. The process of applying the experiment addressed the question of good practical procedures to determine the MC with the suitable reference artefact.

Chapter seven: Topographic spatial resolution experiment

The thesis aims to investigate the traceability framework by determining the metrological characteristics (MCs) for a focus variation microscopy (FVM) instrument, as an optical areal surface texture measuring instrument. Therefore, this chapter investigates the lateral period limit (LPL) determination for FVM.

The research aim is addressed by determining the LPL of FVM by comparing its resolution with CSI measuring instruments using 20x with FVM and 20x and 50x objective lenses with CSI. The traceability will be achieved by linking the FVM results with CSI results. The CSI instrument is used to measure a calibrated reference start artefact to calibrate the LPL of the CSI. The MC of FVM can be determined through the LPL. Random surface artefact is measured in the determination of LPL for FVM. Good practical procedures to determine the MC are followed throughout the experiment. The resolution of CSI measuring instrument can be predicted as better than the resolution of FVM. The research aims and questions can be achieved by doing the experiment of determining the LPL.

7.1 A methodology to determine LPL from a random surface

This methodology determines the LPL of any kind of surface, using FVM. The methodology involves the comparison of an areal measurement with another optical method that is traceable, for example CSI and confocal microscopy. Applying this methodology will be presented in the next sections. The methodology is as follows:

1. Measure any random surface with an FVM, at a predefined area with a specific field of view.
2. Measure again the predefined area with any other optical areal topography instrument, with a specific field of view that is traceable, for example, CSI or confocal microscopy. In this thesis, a CSI was used. Mathematically align the measured areal from the FVM to the measured areal from the other traceable optical instrument. This process can be applied using specific software called MountainsMap. The software includes colocalisation module that can colocalise images of different measuring instruments and overlay the images on 3D surface topography. The colocalisation is an automatic tool using advanced algorithms of pattern recognition. This algorithm of pattern recognition can detect sorts of basic features to identify matching landmarks on the two image-like datasets. The image overlaying can facilitate the correlation study between the image and topographic features. The overlays can provide 3D

visualisation, such as zooms, translation, axes rotation and adjusting the transparency of overlaid image (Digitalsurf, 2018).

3. Obtain areal measurements from the FVM and the other instrument with the same lateral size (measured data with the same length and width).
4. For each instrument, calculate the average height h_i of each lateral sampling distance d_i:

$$h_i(d_i) = \frac{1}{N}|z_{i1} - z_{i2}| \quad (8)$$

Where z_{i1}, z_{i2} are the heights at pixel location 1 and 2, with lateral distance d_i. N is the total number of height differences for each lateral distance d_i.

5. For each calculated h_i from both measured areas, each with the same d_i, calculate the transmitted height ht_i and build a transmission height curve:

$$ht_i = \left|\frac{h_iFVM - h_iCSI}{h_iCSI}\right| \times 100 \quad (9)$$

Where h_iFVM is the h_i from the FVM and h_iCSI is h_i from the CSI.

6. Determine the lateral resolution by determining the resolution that corresponds to 50 % height transmission on the transmission curve following the LPL definition (see Figure 95 and 97).

7.2 The experiment

Measurements are performed for all six grooves. Five measurements are performed on each groove. The Zygo CSI is used as a measuring reference to compare results with the FVM. A 20x objective lens is used in the FVM, and 20x and 50x objectives lenses are used in the CSI. The CSI resolution, under 20x and 50x objectives lenses, is checked by measuring a calibrated Siemens star artefact, before comparing the data with the FVM resolution, to establish traceability. Then, resolution of the CSI is determined using 20x and 50x objective lenses, according to Giusca and Leach (2013). The results from these CSI measurements are compared to the resolution results from the FVM (using the 20x objective lens). Using Mountainmap software, data are overlapped to assess the same measurement areas from both instruments. Figure 91 and Figure 92 show the surface measuring areas of the FVM and CSI instruments, using the 20x and 50x objective lenses, respectively. From these figures, the surface height coloured map measurement for the 20x objective lens of the FVM and CSI is (600 x 500) µm and (170 x 170) µm for the 50x objective lens of the CSI. This work proposes the use of a random surface artefact to determine the LPL of FVM.

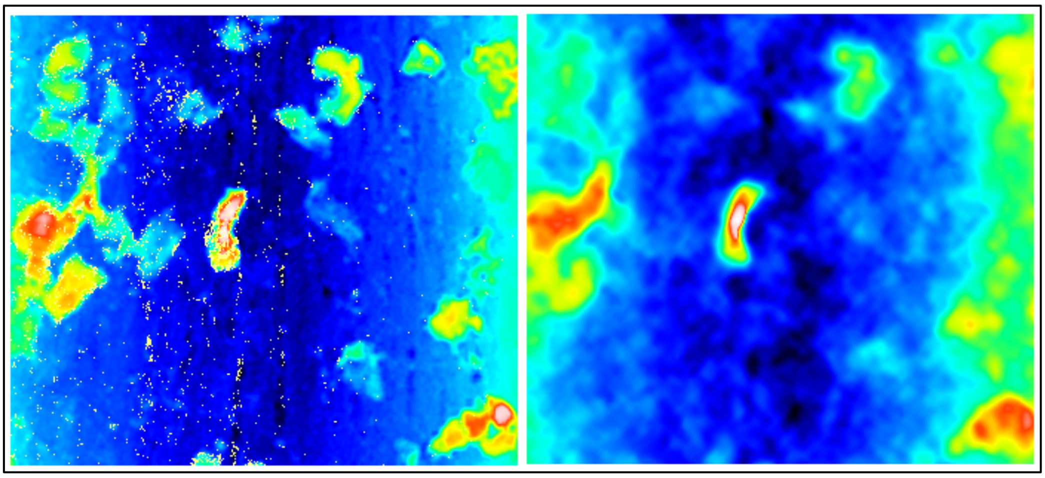

Figure 91: The measuring areas of the 20x objective lens of the Zygo CSI (left) and the 20x objective lens of the FVM (right).

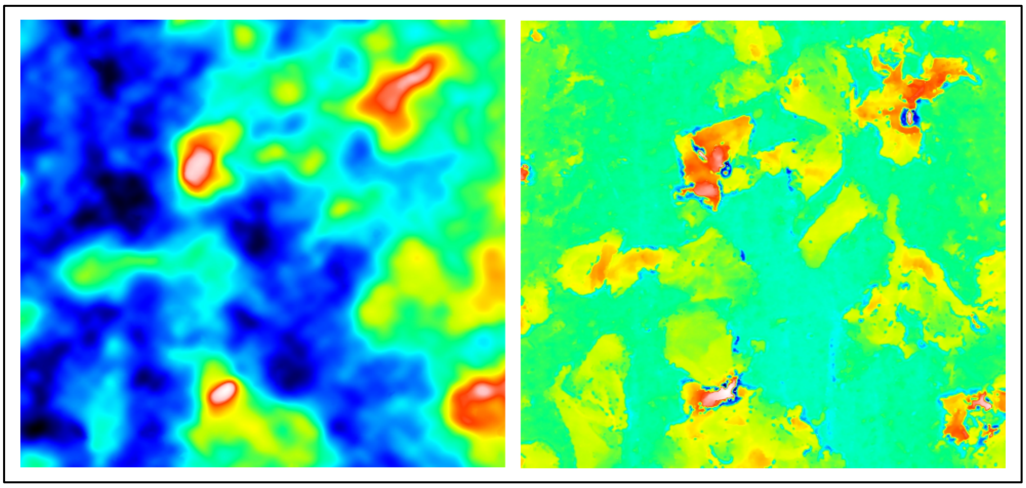

Figure 92: The measuring area of the 20x objective lens of the FVM (left) and the 50x objective lens of the Zygo CSI (right).

7.2.1 CSI 20× and 50× LPL calibration with NPL Siemens star reference artefact

The LPL is function can be used to quantify the topographic spatial resolution characteristic (ISO25178, 2018). The quantification can be performed depending on the measurement method used. The determination of LPL following the ISO definition (described in the literature review chapter) has mentioned the sinusoidal profile of ASP artefact that can be used. According to Giusca and Leach (2013), the star patterns artefact, which is often assessed using circular profiles of different diameters (see figure 93), has similar functionality compare to the use of grids. The circular profile is only limited to a discrete series of spatial frequencies. However, the advantage of the ASP artefact can be obtained by extracting the profile of star patterns along the star radial direction. The ASP artefact that is used to determine the LPL is Siemens star artefact.

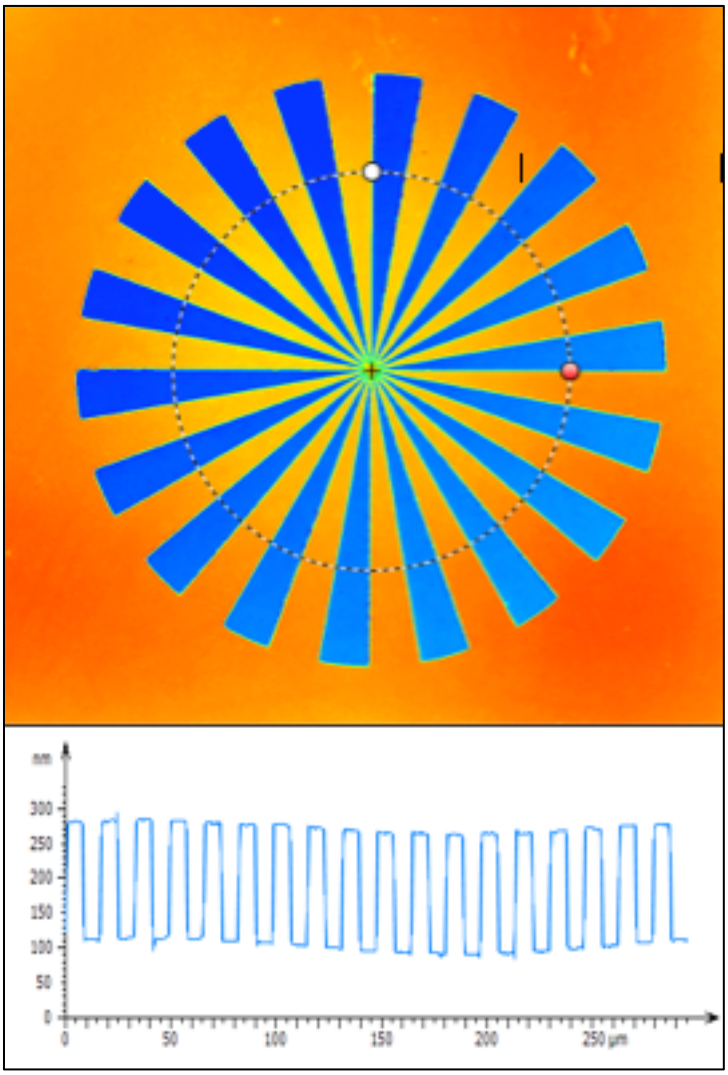

Figure 93: circular profile of ASP artefact

Prior to achieving an unbroken chain of measurement traceability, a Siemens star artefact is measured using 20x and 50x objective lenses on a CSI Zygo. The Siemens star is an NPL reference calibrated artefact, widely used for topographic spatial resolution measurement for optical measuring instruments, such as phase shifting interferometry and CSI. Figure 93 shows the Siemens star artefact used in this experiment.

The Siemens star artefact is calibrated by subtracting two profiles that are extracted through the middle of the petals. One profile is from the upper petal, while the other profile is from the lower petal. Figure 94 shows the two profiles extracted through the petals. The profiles are extracted through the middel of petals 5-23 (lower) and petals 8-26 (upper). The result of subtracting two profiles is called instrument response profile (IRP), which can determine the instrument resolution. The resolution of the instrument is determined following the ISO definition of LPL. From the IRP, the lateral scale should be multiplied by π/n (where n = petal number, 18) and the vertical scale is normalised to the maximum height (Giusca and Leach, 2013). The LPL results can be the point at which the height response of the instrument falls to 50 %. This process is applied in the determination of the LPL following the ISO 25178-6 definition. The LPL of the 20x and 50x objectives lens is (1.34 ± 0.128) µm and (0.783 ± 0.064) µm, respectively. Figure 94, Figure 95 and Figure show the process used to determine the LPL of the Siemens star artefact using CSI for 20x objective lens and Figure 97, Figure 98 and Figure 99 show the 50x objective lens results. From Figure 94 and Figure 97, two profiles are extracted through the middle of the petals; one from the lower petal and the other from the upper petal. These petal profiles are subtracted and are shown in Figure 95 and Figure 98. In Figure 96 and Figure 99, the vertical scale is normalised to the maximum height, and the lateral scale is multiplied by π/18. The LPL is determined at which the height response of the instrument falls to 50 %. These procedures are applied according to Giusca and Leach, 2013. Theoretically, the instrument resolution (optical resolution) of the 20x and 50x objective lenses is calculated using the Rayleigh criterion. The optical resolution of the 20x and 50x objective lenses of the Zygo CSI are 762.5 nm and 554.54 nm, respectively, based on the Rayleigh criterion. As the optical resolution is smaller than the LPL, the surface topography is measured. The Rayleigh criterion is used to calculate the optical resolution as follows (Leach and Haitjema 2010):

$$r=0.61\,\frac{\lambda}{NA}\,, \qquad (10)$$

where λ is the central wavelength (500 nm) of the white light, and NA is the numerical aparture of lenses. The NA of the 20x and 50x CSI objectives lens is 0.40 and 0.55, respectively.

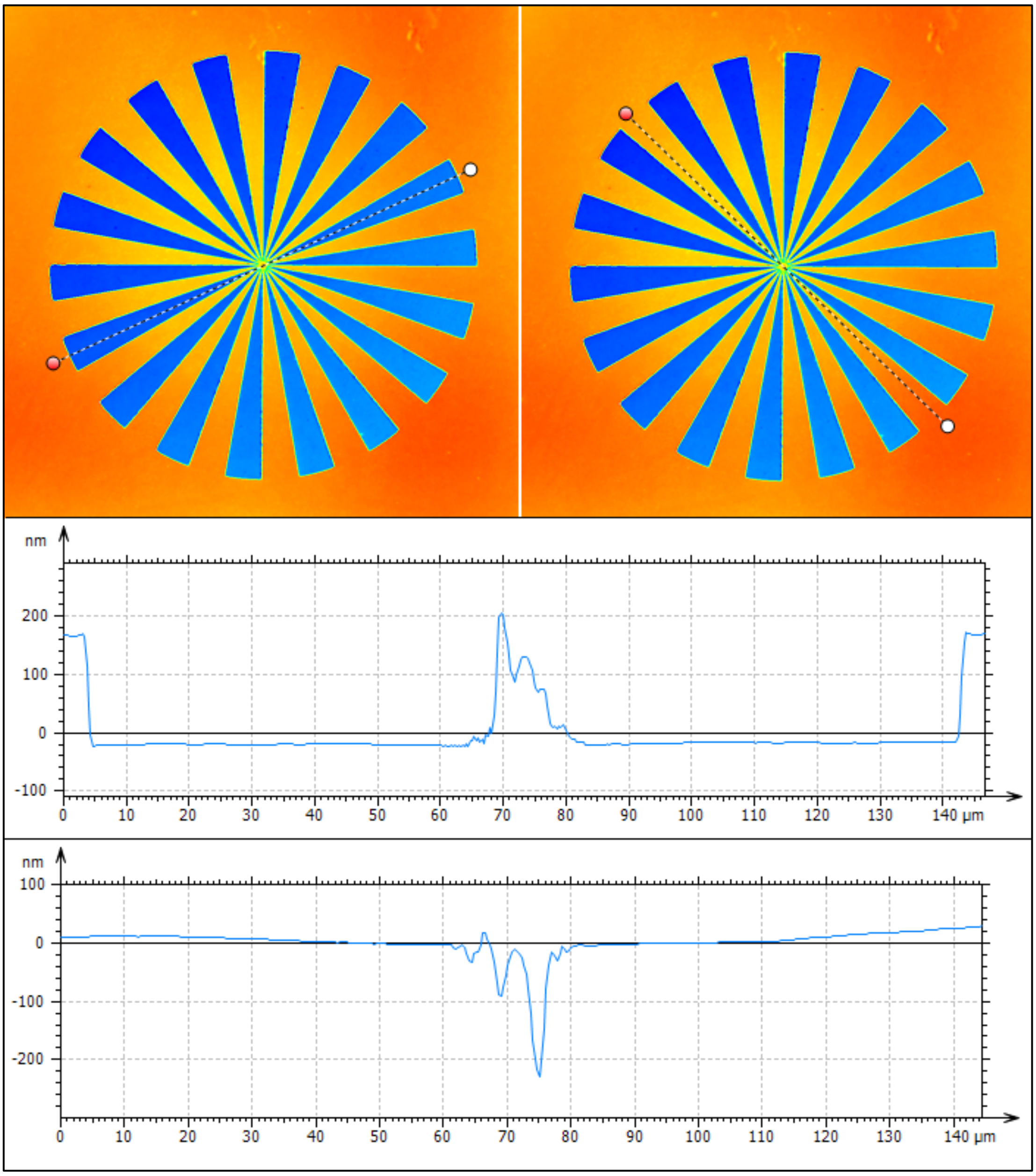

Figure 94: Two profiles extracted through the middle of the lower petal (left) and the upper petal (right) using the 20x CSI objective lens.

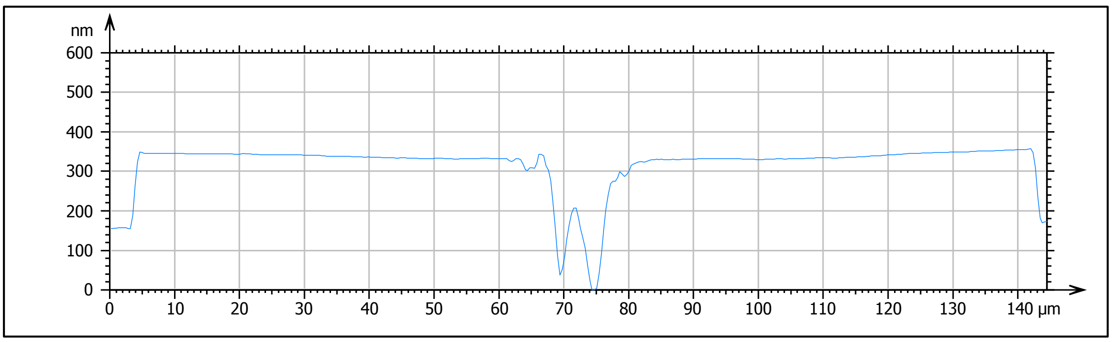

Figure 95: The subtraction result of the two profiles

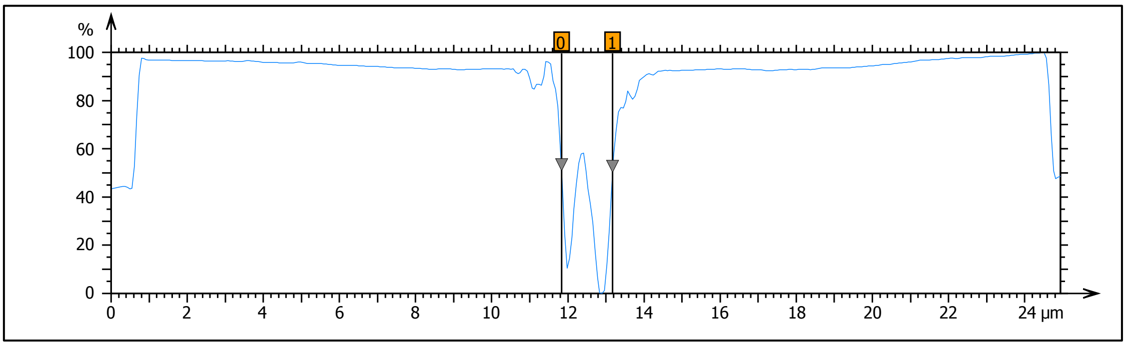

Figure 96: The lateral period limit (LPL) using the 20x CSI objective lens

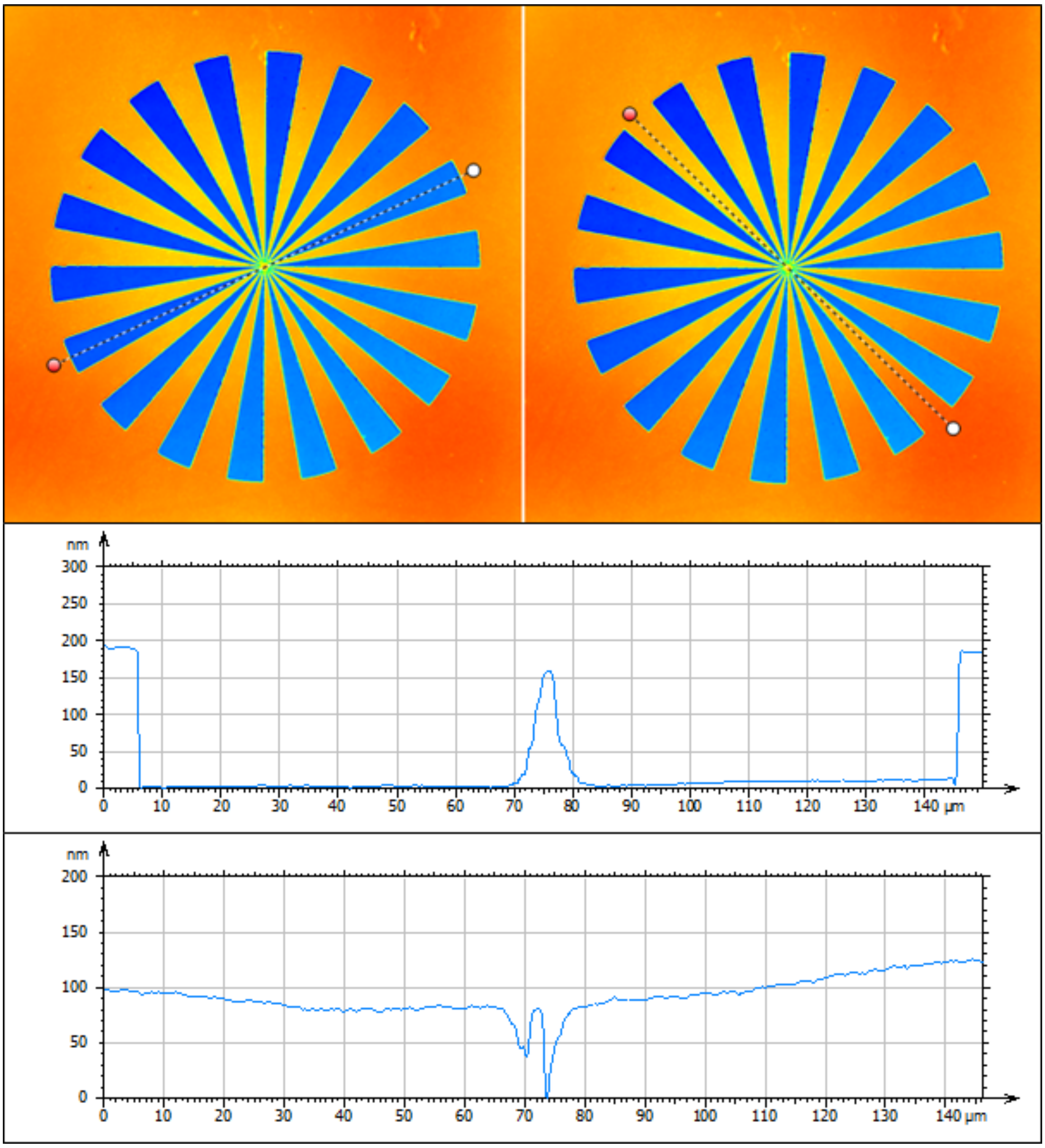

Figure 97: Two profiles extracted through the middle of the lower petal (left) and the upper petal (right) using the 50x CSI objective lens.

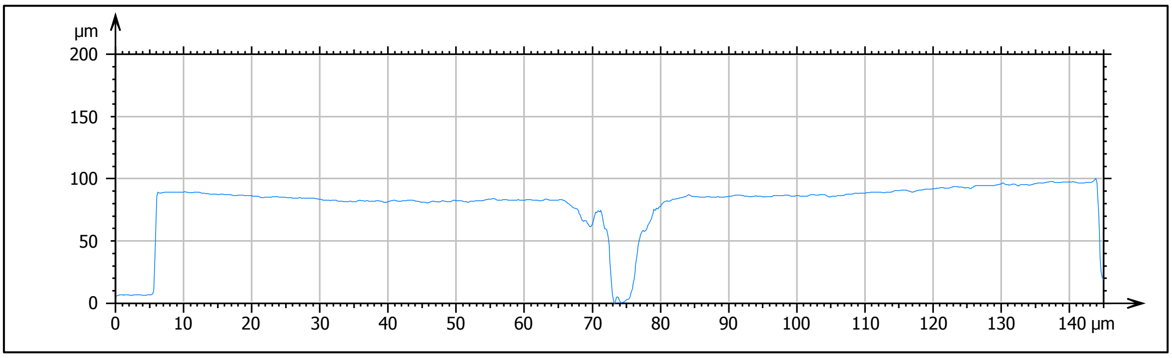

Figure 98: The subtraction result of the two profiles

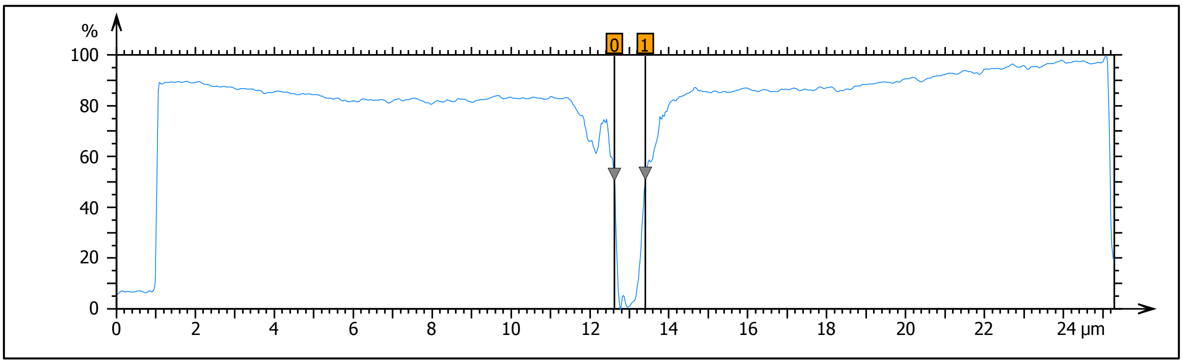

Figure 99: The lateral period limit (LPL) using the 50x CSI objective lens

7.2.2 Results

Part 1: The LPL by comparing with Zygo 20x measurement data

The experiment results of LPL compare the Zygo CSI with FVM of approximately the same measuring area. Using a 20x objective lens, different height measurement results are obtained between the 20x objective lenses of the FVM and CSI, and the 20x objective lens of the FVM with the 50x objective lens of the CSI using random surface artefact. The FVM has lower height than CSI measurements, suggesting that more filtering effects are obtained from FVM measurements. In addition, the more filtering effects suggest that FVM has lower lateral resolution when compared to the CSI instrument. The filter process can remove the effect of high spatial frequency noise. Figure 100 shows profile data comparisons between CSI and FVM. The LPL is calculated using height transmission, by determining the corresponding lateral resolution that corresponds to a 50 % height transmission. The LPL using height transmission is presented in Figure 101. From the fitted curve in Figure 101, 50 % transmission height corresponds to 19 µm, therefore, the estimated LPL for the FVM is determined at 19 µm, and the LPL of the 20x CSI objective lens is 1.34 µm. The optical resolution of the 20x CSI objective lens is 0.7762 µm.

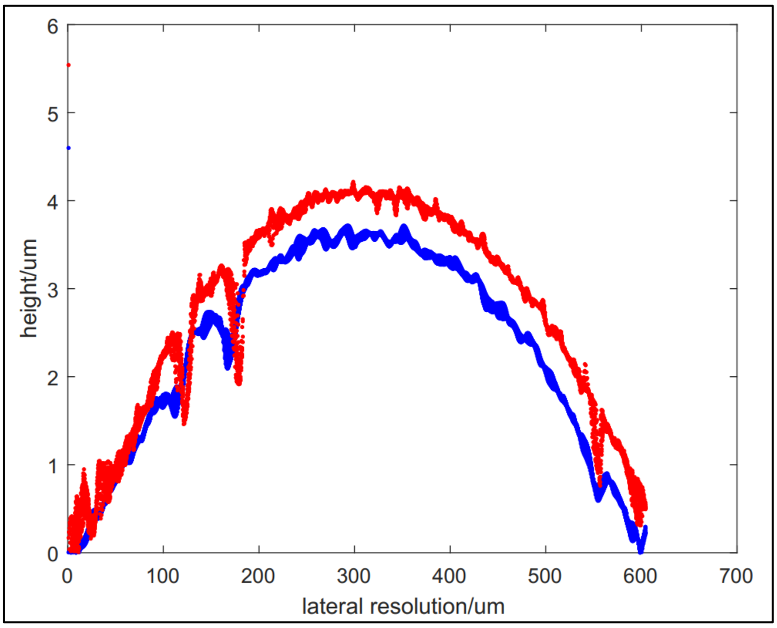

Figure 100: Average height $h_i(d_i)$ data comparisons (blue) FVM 20× and (red) CSI 20x

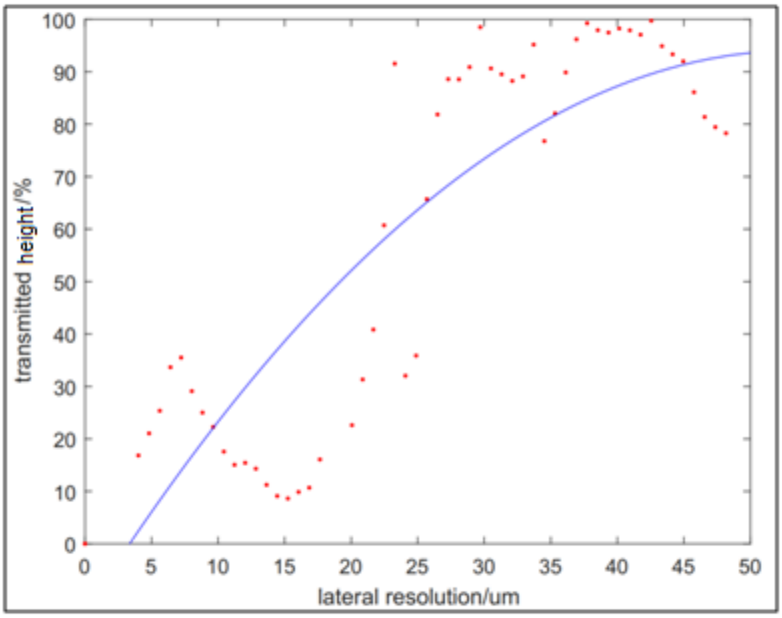

Figure 101: Height transmission ht_i data (red dots) between FVM 20× and CSI 20x lenses. Fitting curve (blue line). The lateral resolution corresponding to the 50 % height transmission is 19 μm and the calculated optical resolution is 0.7762 μm.

Part 2: LPL by comparing with Zygo 50x measurement data

Another experiment compared the same measuring area of Zygo CSI using a 50x objective lens with FVM using a 20x objective lens. In this experiment, the LPL is determined by comparing different objective lenses. Due to different objective sizes between the two instruments, the results of same measuring area seem not appropriate. The graph should present similar results for the same measuring area. Figure 102 compares the profile of the 20x FVM objective lens (blue) with the 50x CSI objective lens (red). Calculation of LPL, using height transmission, is presented in Figure 103. From this figure, 50 % transmission height from the fitted curve corresponds to 4.8 μm, therefore the estimated LPL of the FVM is 4.8 μm and the LPL of the 50x CSI objective lens is 0.783 μm. The optical resolution of the 50x CSI objective lens is 0.554 μm.

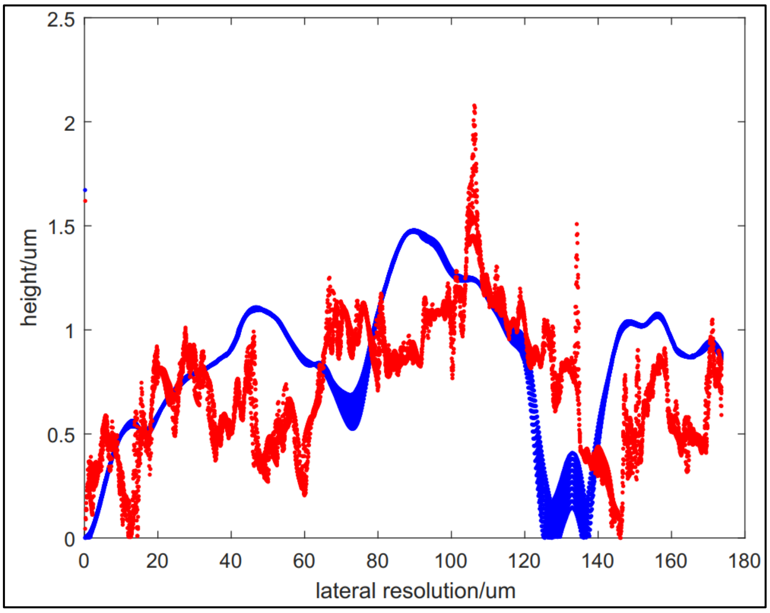

Figure 102: Average height $h_i(d_i)$ data comparisons for FVM 20x lens (blue) and the CSI 50x lens (red).

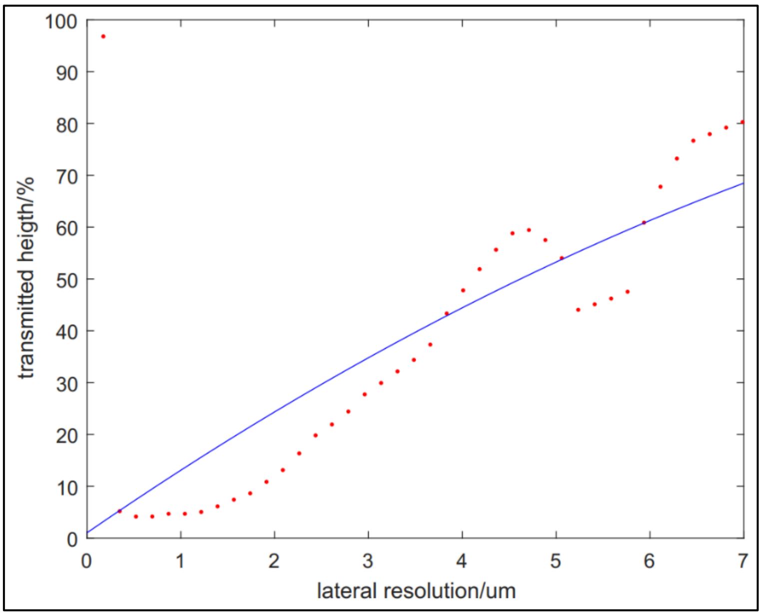

Figure 103: Height transmission ht_i data (red dot) between the FVM 20× and CSI 50x lenses. Fitting curve (blue line). The lateral resolution that corresponded to 50 % of the height transmission is 4.8 µm, and the calculated optical resolution is 0.554 µm.

7.3 Summary

In this experiment, a novel method to determine the LPL of an FVM instrument by measuring a rough random surface has been presented. The FVM is compared with a CSI to generate measurement traceability. Therefore, the reference artefact of the Siemens star is measured with CSI to link the traceability chain. The CSI measured the Siemens star artefact using 20× and 50× objective lenses. Then, the rough random surface artefact is used to compare the measurement results of the FVM and CSI. The results of the 20× objective lens of the FVM are compared with the 20× and 50× objective lenses of the CSI.

The results showe that the CSI resolution, for both 20x and 50x objective lenses, is better than the resolution of the FVM 20x objective lens. The estimated LPL for measurements with the 20x FVM objective lens and the 20x CSI objective lens is 19 µm and 1.34 µm, respectively. The optical resolution of the 20x CSI objective lens is 0.7762 µm. Comparison of the 20x FVM objective lens and the 50x CSI objective lens show that the estimated LPL of the FVM and CSI are 4.8 µm and 0.783 µm, respectively. The optical resolution of the 50x CSI objective lens is 0.554 µm.

Further investigations should be carried out to confirm the efficiency of this novel method. These investigations could incorporate experiments using several random artefacts that could corroborate data from this study. The metrological characteristic of

LPL for FVM is determined using a novel method with measuring random surface artefact. The calibration procedure is presented by comparing the resolution of CSI and FVM. The traceability is achieved by measuring a reference Siemens star artefact.

Chapter eight: Conclusion and future work

8 Conclusion and future work

8.1 Conclusion

This project presents novel calibration infrastructures of FVM for surface texture measurements in the form of novel low-cost artefacts (£100 for each artefact) and practical calibration procedures to determine its MCs. The metrological characteristics of FVM, addressed in this project, include: measurement noise, residual flatness, amplification coefficients, linearity deviations and perpendicularity and topographic spatial resolution. Each MC for FVM was determined separately by measuring a suitable artefact in a separate experiment. Most of the available artefacts cannot be measured with FVM because of its limitation in measuring smooth and transparent surfaces. The new low-cost artefacts were designed and manufactured when the suitable artefact for FVM was not available; for example, the artefacts measured for determining the amplification, linearity and perpendicularity characteristics. The new artefacts were calibrated with more traceable measuring instruments to achieve the traceability. The results of the new artefacts with the more traceable instrument were compared with the FVM and the uncertainty was estimated. Each chapter is summarised as follows:

Chapter Two is a literature review of related work and covers all topics related to surface texture measurements, including application of surface texture measurements, measurement traceability, calibration, measurement uncertainty, material measures and metrological characteristics. In addition, the chapter reviews the FVM as an optical measuring instrument including its working principles, instrument components and limitations. The literature review indicates that most available reference artefacts for calibration of surface texture measuring instrument are not suitable for use with the FVM due to their very smooth surfaces. Hence, from this literature review, new reference artefacts, and the procedure to use them for calibration, are still required and are proposed in this thesis to overcome the lack of artefacts suitable for most of FVM instruments and practical procedures using the proposed artefacts to quantify the metrological characteristic.

Chapter Three: the measurement artefacts used in the determination of metrological characteristics for FVM has been presented. The artefacts for determining the measurement noise characteristic are replica of optical flat surface and flat surface artefacts. For the residual flatness determination, the artefact of Halle flat surface is used in the measurement. Three new artefacts have been designed and manufactured for the determination of amplification, linearity and perpendicularity characteristics. The artefacts have been manufactured by Kern micro milling machine. The determination of topographic spatial resolution uses random surface artefact that is manufactured by EJM.

Chapter Four presents a work on the determination of the metrological characteristic of measurement noise, determined with both subtraction and averaging methods, for FVM. The chapter presents novel various experiments for the measurement of noise and measurement repeatability. These experiments include the determination of measurement noise using replicas of an optical flat having very smooth surface with *Ra* < 10 nm and the determination of measurement noise with different measurement parameters, that are illumination parameters, contrast and brightness parameters. A novel experiment finding uncovers vertical scale non-linearity of the FVM by measuring its measurement noise at different scale location of the vertical motion stage. Another novel experiment is also carried out by using the replica of an optical flat to determine the measurement noise for different objective lenses at different vertical heights. The general results show that the noise determined by measuring the replica is significantly higher than the noise from the other experiments using flat surface artefacts. Instead, the replica measurements can overcome FVM limitations, but may always give higher measurement noise from a real situation. The reason could be due to the fact that the replica may have issues in the replication of surface features, therefore, measurements can be obtained from the replica, but they could affect result reliability. For this reason, the measurement of the replica of the optical flat artefact will give higher measurement noise than the measurement of the optical flat itself. The experiment using different illumination parameters shows statistically a significant effect of illumination on noise. The results also shows that measurements using polariser for determining the noise, with the same contrast setting of normal light, leads to higher noise than the measurements without using the polariser. The contrast and brightness effects on measurement noise are also carried out. Form this experiment, the noise findings indicate that changing the contrast and brightness together significantly affects the noise. The last measurement noise experiment detected the non-linearity of the vertical height for the FVM. The non-linearity of vertical scale of FVM could be caused by the way the drive train is guided, and how the *Z*-axis is mounted on the guiding rails. The measurement results of measurement noise determination can be achieved by using the replica of an optical flat that cannot be measured directly with the FVM due to very smooth surfaces (Ra<10nm). However, by using the replica of an optical flat artefact, high noise results are obtained. This result show that the use of replica will give an overestimate of the true measurement noise of the FVM and users should carefully aware of this result. Another measurement noise result is related to the non-linearity of vertical scale for FVM. This result is the most significant as with the measurement noise quantification; the stage non-linearity behaviour of the FVM can be detected. In this experiment, the MC can be determined through the measurement noise and measurement repeatability. The replica of an optical flat and Halle flat surface artefact were measured in the determination of measurement noise for FVM. The good practical procedure to determine the MC is described in the experimental methodology. The research aims and questions are achieved by doing these experiments to determine the measurement noise.

Chapter Five focuses on determining residual flatness characteristics. The experiment compares the determination of residual flatness by using ISO filtering rule and the proposed filtering method with two objective lenses of 50x and 100x. The proposed filtering method is applied by multiplying the sample distance of the field of view of each objective by ten. For example, the sampling distances of the 50× and 100× lenses are 0.176 μm and 0.088 μm, respectively; hence, the other filtering process uses a filter with values of 1.76 μm and 0.88 μm, respectively. The results from the ISO filtering rule are lower than the proposed filtering method for both objective lenses. The results from the ISO filtering rule are 22.9 nm and 26.1 nm for the 50× and 100× objective lenses, respectively and the results from the proposed filtering methods are 37.8 nm and 38.7 nm for the 50× and 100× objective lenses, respectively. The results show that filtering has a significant effect in determining the residual flatness and has to be chosen appropriately. The measurement results of residual flatness determination are reliable. The proposed filter method can be suggested to be applied by FVM users when the ISO filter cannot be performed. The experiment of residual flatness addressed all the three research questions. The MC of FVM was determined through the residual flatness. The Halle flat surface artefact was measured in the determination of residual flatness for FVM. Good practical procedure to determine the MC was followed throughout the experiment. The research aims and questions have been addressed by doing the experiment to determine the residual flatness.

Chapter Six: the amplification coefficient, linearity deviation and perpendicularity characteristics are determined in three novel experiments, using novel and low-cost reference artefact to determine the amplification coefficient, linearity deviation and perpendicularity characteristics for the lateral scale with multiple-image field measurements; vertical scale; and measuring the lateral scale with single image field measurement. Three new low-cost artefacts (£100 for each) were proposed to determine characteristics in vertical and lateral scale calibration. The lateral scale calibration experiment, with multiple image fields, with both stitching and non-stitching measuring strategies, used cross-grating artefacts. The results show that measurements with stitching reduced lateral errors in the x- and y-directions (due to the inaccuracy of the lateral motion stage), but increase the stage's non-linearity of the error. This significant measurement result of the experiment is reliable. The lateral error was reduced by up to 2 µm for measurements with stitching. The proposed reference artefact for lateral calibration of single image field measurements shows a significant optical lateral error (distortion). From this result, it is recommended that some post-processing, e.g. distortion correction for the artefact may be required to get required accuracy for very smooth surfaces. Alternatively, another type of micro-scale precision machining may be used to manufacture an artefact with deterministic grid shapes, with the possibility of more complex processing and higher manufacturing costs. This process of making the artefact for single image field measurements can be a challenge and will be one of future work. The experiment of the amplification, linearity and perpendicularity characteristics addressed all the three research questions. The MC of FVM is determined through the amplification, linearity and perpendicularity characteristics. Cross grating and step height artefacts were measured in the determination. Good practical procedures to determine the MC have been proposed and implemented throughout the experiments. The research aim and questions have been answered by doing the experiments to determine the amplification, linearity and perpendicularity characteristics.

Chapter Seven: the determination of lateral period limit (LPL) is demonstrated and a novel method to determine LPL is presented. The novel method presents the use of an artefact with random surface to determine the FVM's LPL. Promising results from a methodology to determine LPL from any random surfaces are presented. The experiments compare the measuring results of FVM with CSI. The reliable results show that the resolution of CSI is better than the resolution of FVM. Traceability is achieved by measuring a calibrated artefact by the CSI and then comparing the results of the CSI with the results of the FVM. More investigation is required for the proposed method to determine the LPL using any random surface artefact. The experiment of LPL addressed all the three research questions. The MC of FVM is determined through the LPL. Random surface artefact is measured in the determination of LPL for FVM. Good practical procedures to determine the MC have been followed throughout the experiment.

In summary, the project presents novel calibration infrastructure for FVM by determining the MCs for the FVM, including: measurement noise, residual flatness and amplification coefficient, linearity deviation and perpendicularity characteristics. In general, the proposed practical procedures of calibration are developed for ease of use by the industry. The traceability is established by measuring the novel low-cost material measures by other instruments that have traceable measurement results.

8.2 Future work

The calibration infrastructure for FVM, by providing low-cost material measures (£100 for each) and practical procedures to determining metrological characteristics, was performed in this project. However, further work is required to better manufacture a reference artefact to determine the amplification coefficient, linearity deviation and perpendicularity characteristics for single image field measurements. In addition, the proposed method to determine the lateral period limit with any artefact having random surface requires more investigations, for example by validating the method with more artefact with different surface topography. The list of metrological characteristics, for surface texture measurements, as mentioned in (ISO25178:600 2018), contain topography fidelity characteristics. This project has not determined the topography fidelity for FVM, but this is planned for future work.

List of references

Advanced Instruments I 2015 *What is Calibration* Retrieved 16/12/2015, from http://www.aicompanies.com/index.cfm/ServiceAndSupport/CalibrationExplained/What_is_Calibration.

Alan M 2001 *Measurement and Instrumentation Principles* Oxford, Butterworth-Heinemann.

Alburayt A, Syam W P and Leach R K 2017 Detecting the signature of motion stage non-linearity for focus variation microscopy using measurement noise and surface topography repeatability

Alburayt A, Syam W P and Leach R K 2018 Lateral scale calibration for focus variation microscopy *Meas. Sci. Technol.* **29** 065012

Alicona 2015 *Focus-Variation for surface measurement in research and production* Retrieved 15 May, 2015, from http://www.alicona.co.uk/home/products/infinitefocus/focus-variation.html.

Alicona 2016 Measurement noise at different Z-values

Alting L, Kimura F, Hansen H N and Bissacco G 2003 Micro engineering *CIRP Annals-Manufacturing Technology* **52** 635-657

Barker A, Syam W P and Leach R K 2016 MEASUREMENT NOISE OF A COHERENCE SCANNING INTERFEROMETER IN AN INDUSTRIAL ENVIRONMENT

Bell S 2001 *A beginner's guide to uncertainty of measurement* National Physical Laboratory.

Bello S M, Verveniotou E, Cornish L and Parfitt S A 2011 3-dimensional microscope analysis of bone and tooth surface modifications: comparisons of fossil specimens and replicas *Scanning* **33** 316-324

Bermudez C, Felgner A, Martinez P, Matilla A, Cadevall C and Artigas R 2018 Residual flatness error correction in three-dimensional imaging confocal microscopes *Optical Micro-and Nanometrology VII*, International Society for Optics and Photonics.

BIPM I 2008 Evaluation of measurement data—guide for the expression of uncertainty in measurement *Citado en las*: 167.

Blateyron F 2015 *Surface Metrology Guide* Retrieved June, 2016, from http://www.digitalsurf.fr/en/guidearealfieldparameters.html.

Blunt L and Jiang X 2003 *Advanced techniques for assessment surface topography: development of a basis for 3D surface texture standards* surfstand Elsevier

Bruzzone A, Costa H, Lonardo P and Lucca D 2008 Advances in engineered surfaces for functional performance *CIRP Annals-Manufacturing Technology* **57** 750-769

Bucher J L 2012 *The metrology handbook* ASQ Quality Press

Caja J, Gómez E and Maresca P 2015 Optical measuring equipments. Part II: Measurement traceability and experimental study *Precision Engineering* **40** 305-308

Chand M, Mehta A, Sharma R, Ojha V and Chaudhary K 2011 Roughness measurement using optical profiler with self-reference laser and stylus instrument—A comparative study

Chen A and Chen C 2016 Comparison of GUM and Monte Carlo methods for evaluating measurement uncertainty of perspiration measurement systems *Measurement* **87** 27-37

Concise Oxford Dictionary 2011 *Concise Oxford English Dictionary* Oxford University Press

Cox M G and Harris P M 2006 Measurement uncertainty and traceability *Measurement Science and Technology* **17** 533

Czichos H, Saito T and Smith L E 2011 *Springer handbook of metrology and testing* Springer Science & Business Media

Daemi B, Ekberg P and Mattsson L 2017 Lateral performance evaluation of laser micromachining by high precision optical metrology and image analysis *Precision Engineering* **50** 8-19

Danzl R, Helmli F, Rubert P and Prantl M 2008 *Optical roughness measurements on specially designed roughness standards Optical Fabrication, Testing, and Metrology III* International Society for Optics and Photonics.

Danzl R, Helmli F and Scherer S 2009 Focus variation–a new technology for high resolution optical 3D surface metrology *Proc.10th Int. Conf. of the Slovenian Society for Non-Destructive Testing 'Application of Contemporary Non-Destructive Testing in Engineering' (Ljubljana, Slovenia*, *1–3 September)* pp 481–91

Danzl R, Helmli F and Scherer S 2011 Focus variation–a robust technology for high resolution optical 3D surface metrology *Strojniški vestnik-Journal of mechanical engineering* **57** 245-256

de Groot P 2015 Principles of interference microscopy for the measurement of surface topography *Advances in Optics and Photonics* **7** 1-65

de Groot P and Beverage J 2015 Calibration of the amplification coefficient in interference microscopy by means of a wavelength standard *SPIE Optical Metrology*, International Society for Optics and Photonics

de Groot P and DiSciacca J 2018 Surface-height measurement noise in interference microscopy *Interferometry XIX* International Society for Optics and Photonics 107490Q

de Groot P J 2014 Progress in the specification of optical instruments for the measurement of surface form and texture *SPIE Sensing Technology+ Applications* International Society for Optics and Photonics

de Groot P J 2017 The meaning and measure of vertical resolution in optical surface topography measurement *Applied Sciences* **7** 54

Digitalsurf 2018 *Colocalization Module for MountainsMap* Retrieved July, 2019, from https://www.digitalsurf.com/wp-content/uploads/2018/06/Colocalization-Mountains-7-Optional-Module.pdf

EdmundOptics 2018 *Optical Flats* Retrieved 18/12, 2018, from https://www.edmundoptics.com/resources/application-notes/optics/optical-flats/

Estler W T 2014 Traceability. *CIRP Encyclopedia of Production Engineering* L. Laperrière and G. Reinhart, Springer Berlin Heidelberg**:** 1251-1254.

Etsion I 2005 State of the art in laser surface texturing *Journal of Tribology* **127** 248-253

Evans C 2010 Clash of cultures: uncertainty vs. accuracy *Optical Fabrication and Testing* Optical Society of America

Evans C J and Bryan J B 1999 Structured, textured or engineered surfaces *CIRP Annals-Manufacturing Technology* **48** 541-556

Fleming A J 2013 A review of nanometer resolution position sensors: Operation and performance *Sensors and Actuators A: Physical* **190** 106-126

Foreman M R, Giusca C L, Coupland J M, Török P and Leach R K 2013 Determination of the transfer function for optical surface topography measuring instruments—a review *Meas. Sci. and Technol.* **24** 052001

Gasparin S, Hansen H N and Tosello G 2011 Traceable surface characterization using replica moulding technology *proc. the13th International Conference on Metrology and Properties of Engineering Surfaces*

Giusca C, Leach R K, Helery F. and Gutauskas T 2011 Calibration of the geometrical characteristics of areal surface topography measuring instruments *Journal of Physics: Conference Series* IOP Publishing

Giusca C L, Claverley J D, Sun W, Leach R K, Helmli F and Chavigner M P 2014 Practical estimation of measurement noise and flatness deviation on focus variation microscopes *CIRP Annals-Manufacturing Technology* **63** 545-548

Giusca C L and Leach R K 2013"Calibration of the scales of areal surface topography measuring instruments: part 3. Resolution *Meas. Sci. Technol.* **24** 105010

Giusca C L and Leach R K 2013 *Measurement Good Practice Guide No. 127, Calibration of the metrological characteristics of coherence scanning interferometers (CSI) and phase shifting interferometers (PSI)*

Giusca C L, Leach R K and Forbes A B 2011 A virtual machine-based uncertainty evaluation for a traceable areal surface texture measuring instrument *Measurement* **44** 988-993

Giusca C L, Leach R K, Helary F, Gutauskas T and Nimishakavi L 2012 Calibration of the scales of areal surface topography-measuring instruments: part 1. Measurement noise and residual flatness *Meas. Sci. Technol*. **23** 03500

Giusca C L, Leach R K and Helery F 2012 Calibration of the scales of areal surface topography measuring instruments: part 2. Amplification, linearity and squareness *Meas. Sci. Technol.* **23** 065005

Godi A and Chiffre L D 2014 Functional Surfaces in Mechanical Systems: Classification, Fabrication, and Characterisation *Surface Engineering Techniques and Applications: Research Advancements: Research Advancements* Santo L and Davim J P. USA, Engineering Science Reference.

Godi A, Kühle A and Chiffre L De 2013 A new procedure for characterizing textured surfaces with a deterministic pattern of valley features *Meas. Sci. Technol.* **24** 085009

Graboń W and Pawlus P 2016 Distinguishing the Plateau and Valley Components of Profiles From Various Types of Two-Process Textures *Metrology and Measurement Systems* **23** 593-602

Grabon W, Pawlus P, Galda L, Dzierwa A and Podulka P 2011 Problems of surface topography with oil pockets analysis *Journal of Physics*: Conference Series IOP Publishing

Grossmann P 1987 Depth from focus *Pattern recognition letters* **5** 63-69

Grous A 2013 *Applied metrology for manufacturing engineering* John Wiley & Sons

Guan G, Hirsch M, Syam W P, Leach R K, Huang Z and Clare A T 2016 Loose powder detection and surface characterization in selective laser sintering via optical coherence tomography *Proc. R. Soc. A* The Royal Society

Gupta K K, Kumar R, Kumar H and Sharma M 2013 Study on effect of surface texture on the performance of hydrodynamic journal bearing *Int. J. Eng. Adv. Technol.* **3** 49-54

Haitjema H 2015 Uncertainty in measurement of surface topography *Surface Topography: Metrology and Properties* **3** 035004

Haitjema H and Leach R K 2018 Surface Texture Metrological Characteristics *CIRP Encyclopaedia of production engineering* Laperrière L, Reinhart G, Tolio T and C. S, Springer

Haitjema H and Morel M 2005 Noise bias removal in profile measurements *Measurement* **38** 21-29

Hansen H N, Carneiro K, Haitjema H and Chiffre L De 2006 Dimensional micro and nano metrology *CIRP annals* **55** 721-743

Harris P, Leach R K and Giusca C 2010 *Uncertainty evaluation for the calculation of a surface texture parameter in the profile case* NPL Technical Report MS.

Helmli F, Danzl R, Prantl M and Grabner M 2014 Ultra high speed 3D measurement with the focus variation method *Fringe 2013* Springer 617-622

Hemming B 2007 *Measurement traceability and uncertainty in machine vision applications*

Hiersemenzel F 2014 *Development towards a focus variation based micro-co-ordinate measuring machine* Loughborough University

Hiersemenzel F, Claverly J, Petzing J N and Helmli F 2013 ISO compliant reference artefacts for the verification of focus varation-based optical micro-coordinate measuring machines *The 13th International Conference of the European Society for Precision Engineering & Nanotechnology* Berlin

Hiersemenzel F, Petzing J N, Leach R K, Helmli F and Singh J 2012 Areal texture and angle measurements of tilted surfaces using focus variation methods, Universite de Savoie.

Hiersemenzel F, Singh J, Petzing J, Claverley J, Leach R K and Helmli F 2013 Development of a traceable performance verification route for optical micro-CMMs *Laser Metrology and Machine Performance X (LAMDAMAP X)* 368-375

Hiersemenzel F, Singh J, Petzing J N, Leach R K, Helmli F and Danzl R 2012 The assessment of residual flatness errors in focus variation areal measuring instruments *the 12th euspen International Conference* Stockholm

Hsu S M, Jing Y, Hua D and Zhang H 2014 Friction reduction using discrete surface textures: principle and design *Journal of Physics D: Applied Physics* **47** 335307

Ismail M F, Yanagi K and Fujii A 2010 An outlier correction procedure and its application to areal surface data measured by optical instruments *Meas. Sci. Technol.* **21** 105105

ISO14460-1 *Geometrical Product Specification (GPS) - Geometric Features - Part 1: General terms and definitions*

ISO16610-60 2015 *Geometrical Product Specification (GPS) - Filtration - Part 60: Linear areal filters: Basic concepts*

ISO16610-61 2015 *Geometrical product specification (GPS) — Filtration — Part 61: Linear areal filters — Gaussian filters*

ISO25178-2 2011 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 2: Terms, definitions and surface texture parameters*

ISO25178-3 2012 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 3: Specification operators*

ISO25178-6 2010 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 6: Classification of methods for measuring surface texture* Retrieved 15 May, 2015, from https://www.iso.org/obp/ui/#iso:std:iso:25178:-6:ed-1:v1:en.

ISO25178-70 2012 *Geometrical product specification (GPS) — Surface texture: Areal — Part 70: Physical measurement standards*

ISO25178-70 2014 *Geometrical product specification (GPS) — Surface texture: Areal — Part 70: Material measures* 2015, from https://www.iso.org/obp/ui/#iso:std:iso:25178:-70:ed-1:v1:en.

ISO25178-601 2010 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 601: Nominal characteristics of contact (stylus) instruments*

ISO25178-606 2013 *Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 603: Nominal characteristics of non-contact (phase-shifting interferometric microscopy) instruments* Retrieved 11/12, 2015, from http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=61236.

ISO25178-606 2015 *Geometrical product specification (GPS) - Surface texture: Areal - Part 606: Nominal characteristics of non-contact (focus variation) instruments*

ISO25178:600 2012 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 600: Metrological characteristics for areal-topography measuring methods*

ISO25178:600 2016 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 600: Metrological characteristics for areal-topography measuring methods*

ISO25178:600 2017 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 600: Metrological characteristics for areal-topography measuring methods*

ISO25178:600 2018 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 600: Metrological characteristics for areal-topography measuring methods* ISO Geneva

ISO25178:600 2019 *Geometrical product specifications (GPS) - Surface texture: Areal — Part 600: Metrological characteristics for areal topography measuring methods*

ISO25178:605 2011 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 605: Nominal characteristics of non-contact (point autofocus probe) instruments*

ISO25178:700 2018 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 700: Calibration and verification of areal topography measuring instruments*

ISO25178:700.3 2016 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 700: Calibration and verification of areal topography measuring instruments*

ISO25178:700.3 2018 *Geometrical product specifications (GPS) — Surface texture: Areal — Part 700: Calibration and verification of areal topography measuring instruments*

ISO/DTS15530-2 2007 *Geometrical Product Specifications (GPS)—Coordinate Measuring Machines (CMM): Technique for Determining the Uncertainty of Measurement—Part 2: Use of Multiple Measurement Strategies* (International Organization for Standardisation)

ISO/IEC17025 2005 General Requirements for the Competence of Testing and Calibration Laboratories

ISO/VIM 2004 *International vocabulary of basic and general terms in metrology (VIM)* International Organization

ISO/WD25178-700.2 *2014 Geometrical product specifications (GPS) — Surface texture: Areal — Part 700: Calibration and verification of areal topography measuring instruments*

JCGM200 2008 *The international vocabulary of metrology—basic and general concepts and associated terms (VIM)*

JCGM200 2012 *The international vocabulary of metrology—basic and general concepts and associated terms (VIM)* JCGM (Joint Committee for Guides in Metrology

Jiang X, Scott P J, Whitehouse D J and Blunt L 2007 Paradigm shifts in surface metrology. Part II. The current shift *Proc of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* The Royal Society

Jiang X J and Whitehouse D J 2012 Technological shifts in surface metrology *CIRP Annals-Manufacturing Technology* **61** 815-836

Kacker R, Sommer K D and Kessel R 2007 Evolution of modern approaches to express uncertainty in measurement *Metrologia* **44** 513

Kapłonek W, Nadolny K and Królczyk G M 2016 The use of focus-variation microscopy for the assessment of active surfaces of a new generation of coated abrasive tools *Measurement Science Review* **16** 42-53

Leach R K 2004 Some issues of traceability in the field of surface topography measurement *Wear* **257** 1246-1249

Leach R K 2010 *Fundamental Principles of Engineering Nanometrology* Elsevier

Leach R K 2011 *Optical Measurement of Surface Topography* (Berlin, Springer)

Leach R K 2013 *Characterisation of Areal Surface Texture* Springer

Leach R K 2013 *Introduction to Surface Topography. Characterisation of Areal Surface Texture* Springer

Leach R K 2014 *Fundamental Principles of Engineering Nanometrology* (UK, Elsevier)

Leach R K, Bointon P, Feng X, Lawes S, Piano S, Senin N, Sims-Waterhouse D, Stavroulakis P, Su R and T M Wahyudin S 2018 *Information-rich manufacturing metrology*

Leach R K and de Groot P 2015 *The standards rash–is there a cure?*

Leach R K, de Groot P and Haitjema H 2018 *INFIDELITY AND THE CALIBRATION OF OPTICAL SURFACE TOPOGRAPHY MEASURING INSTRUMENTS*

Leach R K, Flack D, Hughes E and Jones C 2009 Development of a new traceable areal surface texture measuring instrument *Wear* **266** 552-554

Leach R K and Giusca C 2012 Determination of the metrological characteristics of optical surface topography measuring instruments *SPIE Photonics Europe* International Society for Optics and Photonics

Leach R Kand Giusca C 2013 Calibration and adjustment of areal surface topography measuring instruments *In: Buytaert J Recent advances in topography research* (Nova Science Publishers), Chap. 1.

Leach R K, Giusca C, Haitjema H, Evans C and Jiang X 2015 Calibration and verification of areal surface texture measuring instruments *CIRP Annals-Manufacturing Technology* **64** 797-813

Leach R K, Giusca C, Rickens K, Riemer O and Rubert P 2014 Development of material measures for performance verifying surface topography measuring instruments *Surface Topography: Metrology and Properties* **2** 025002

Leach R K and Haitjema H 2010 Bandwidth characteristics and comparisons of surface texture measuring instruments *Meas. Sci. Technol.* **21** 032001

Leach R K and Smith S T 2018 *Basics of Precision Engineering* CRC Press

Leach, R K, Weckenmann A, Coupland J and Hartmann W 2014 Interpreting the probe-surface interaction of surface measuring instruments, or what is a surface? *Surface Topography: Metrology and Properties* **2** 035001

Leach R K 2015 Is one step height enough? *Proc. of ASPE*

Leach R K, Senin N, Feng X, Stavroulakis P, Su R, Syam W P and W T 2017 Information-rich metrology: Changing the game *Commercial Micro Manufacturing* 33-39

Leach, R K, Claverley J, Giusca C, Jones C W, Nimishakavi L, Sun W, Tedaldi M and Yacoot A 2012 Advances in engineering nanometrology at the National Physical Laboratory *Meas. Sci. Technol.* **23** 074002

Leach R K, Giusca C L and Naoi K 2009 Development and characterization of a new instrument for the traceable measurement of areal surface texture *Meas. Sci. Technol.* **20** 125102

Leach R K, Giusca C L and Rubert P 2013 A single set of material measures for the calibration of areal surface topography measuring instruments: the NPL Areal Bento Box *Proc. Met. & Props* 406-413

Macdonald D A 2014 The application of focus variation microscopy for lithic use-wear quantification *Journal of Archaeological Science* **48** 26-33

Maculotti G, Feng X, Galetto M and Leach R 2018 Measurement noise evaluation, noise bandwidth specification and temperature effects in 3D point autofocusing microscopy *euspen's 18th International Conference & Exhibition* Venice

Maculotti G, Feng X, Galetto M and Leach R K 2018 Noise evaluation of a point autofocus surface topography measuring instrument *Meas. Sci. Technol.* **29** 065008

Mansurov N 2015 *What is Distortion?* Retrieved 26/04, 2017, from https://photographylife.com/what-is-distortion/.

Mathioulakis E and Belessiotis V 2000 Uncertainty and traceability in calibration by comparison *Meas. Sci. Technol.* **11** 771

Michigan Metrology 2016 *3D S Parameters - Height (Amplitude) Parameters* Retrieved 24 July, 2016, from http://www.michmet.com/3d_s_height_parameters_spsvsz.htm.

Mitchell-Smith, J. and Clare A 2016 Electrochemical jet machining of titanium: overcoming passivation layers with ultrasonic assistance *Procedia CIRP* **42** 379-383

Morel M 2006 *Uncertainty Estimation of Shape and Roughness Measurement*, Eindhoven University of Technology

Moroni G, Syam W P and Petrò S 2015 Uncertainty in 3D Micro Measurement with Focus Variation Microscopy *4M/ICOMM 2015* Italy **2** 2

Moroni G, Syam W P and Petrò S 2018 A simulation method to estimate task-specific uncertainty in 3D microscopy *Measurement* **122** 402-416

Nikolaev N, Petzing J and Coupland J 2016 Focus variation microscope: linear theory and surface tilt sensitivity *Applied optics* **55** 3555-3565

NPL 2018 *Traceability and Uncertainty* Retrieved Oct, 2015, from http://www.npl.co.uk/educate-explore/factsheets/traceability-and-uncertainty/.

Pentland A P 1987 A new sense for depth of field *IEEE transactions on pattern analysis and machine intelligence* 523-531

Petley B 1983 New definition of the metre *Nature* **303** 373-376

Pham D T, Dimov S S, Petkov P V and Petkov S 2002 Laser milling *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **216** 657-667

Rabinovich S G 2006 *Measurement errors and uncertainties: theory and practice* Springer Science & Business Media

Raghavendra N and Krishnamurthy L 2013 *Engineering Metrology and Measurements* Oxford University Press

Scherer S 2016 *Focus Variation in Optical Metrology - An Interview with Stefan Scherer, CEO of Alicona* Retrieved 15 May, 2018, from http://www.azom.com/article.aspx?ArticleID=10330.

Seewig J 2005 Linear and robust Gaussian regression filters *Journal of Physics: conference series* IOP Publishing

Seewig J 2013 Areal filter *Characterisation of Areal Surface Texture* Springer

Seewig J and Eifler M 2017 Calibration of areal surface topography measuring instruments *Fifth International Conference on Optical and Photonics Engineering* International Society for Optics and Photonics

Senin N, MacAulay G, Giusca C and Leach R K 2014 On the characterisation of periodic patterns in tessellated surfaces *Surface Topography: Metrology and Properties* **2** 025005

Sładek J A 2015 *Coordinate metrology: accuracy of systems and measurements* Springer
Smith G T 2013 *Industrial metrology: surfaces and roundness* (London, Springer Science & Business Media)

Stout K and Blunt L 2001 A contribution to the debate on surface classifications—random, systematic, unstructured, structured and engineered *International Journal of Machine Tools and Manufacture* **41** 2039-2044

Sun W and Claverley J D 2015 Verification of an optical micro-CMM using the focus variation technique: Aspects of probing errors *CIRP Annals-Manufacturing Technology*

Surf Digital Retrieved 15/05/2016, from http://www.digitalsurf.fr/en/downloads.html.

SYAM W P 2015 *UNCERTAINTY EVALUATION AND PERFORMANCE VERIFICATION OF A 3D GEOMETRIC FOCUS-VARIATION MEASUREMENT* PhD Thesis Politecnico di Milano

Syam W P 2018 *Metrologi manufaktur: Pengukuran geometri dan analisis ketidakpastian* INA-rvix

Taylor B N 2009 *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results* (rev, DIANE Publishing).

TechNote(LT05-0010) T 2014 *Understanding Sensor Resolution Specifications and Performance*

Tian Y, Weckenmann A, Hausotte T, Schuler A and He B 2013 Measurement strategies in optical 3-D surface measurement with focus variation *Proc. of 11th International Symposium on Laser Metrology for Precision Measurement and Inspection in Industry* (ISCQM 2013)

Tosello G, Haitjema H, Leach R K, Quagliotti D, Gasparin S and Hansen H N 2016 An international comparison of surface texture parameters quantification on polymer artefacts using optical instruments *CIRP Annals-Manufacturing Technology* **65** 529-532

Valery S, Anna C and Leonid M 2013 *Metrology and Theory of measurement* (Germany, De Gruyter) vdi/vde2617 2004 *Part 6.2. Accuracy of coordinate measuring machines. Characteristics and their testing* Guideline for the application of DIN EN ISO 10360 to coordinate measuring machines with optical distance sensors

Vernhes P, Bloch J F, Mercier C, Blayo A and Pineaux B 2008 Statistical analysis of paper surface microstructure: A multi-scale approach *Applied Surface Science* **254** 7431-7437

Ville J F 2003 *Calibration Procedures for Stylus and Optical Instrumentation Advanced Techniques for Assessment Surface Topography: Development of a Basis for 3D Surface Texture Standards "Surfstand"*. L. Blunt and X. Jiang. UK, Kogan page Science**:** 119.

Vorburger T V, Rhee H G, Renegar T B, Song J F and Zheng A 2007 Comparison of optical and stylus methods for measurement of surface texture *The International Journal of Advanced Manufacturing Technology* **33** 110-118

Whitehouse D J 2002 *Surfaces and their Measurement* Hermes penton Ltd.

Whitehouse D J 2003 *Handbook of Surface and Nanometrology* (UK, IOP Publishing Ltd)

Whitehouse D J 2010 *Handbook of surface and nanometrology*, CRC press

Xie W, Lehmann P and Niehues J 2012 Lateral resolution and transfer characteristics of vertical scanning white-light interferometers *Applied optics* **51** 1795-1803

Xu Z, Fang F, Gao H, Zhu Y, Wu W and Weckenmann A 2012 Nano fabrication of star structure for precision metrology developed by focused ion beam direct writing *CIRP Annals-Manufacturing Technology* **61** 511-514

Yin B, Li X, Fu Y and Yun W 2012 Effect of laser textured dimples on the lubrication performance of cylinder liner in diesel engine *Lubrication Science* **24** 293-312

Zeng W, Jiang Xand Scott P J 2010 Fast algorithm of the robust Gaussian regression filter for areal surface analysis *Meas. Sci. Technol.* **21** 055108

Appendices

Appendix 1

ALICONA script for measurement noise and residual flatness (Ch. 4 and Ch. 5):

```
IF-AUTOMATION 1.0
IFMVERSION 6.1.1.1
END-IF-AUTOMATION
function iterativeCapture(){
var folderName="Anas";
var projectName="residual_flatness_100x";
//var objectName="sample_20X_";
var path="D:\\Anas\\residual_flatness_100x\\";
var fileName;
//====Variables declaration and assignment====================
var model=new SurfaceModel;
var factor=2;
var vector = new Point3DVector;
verResolution=0.01e-6;
latResolution=1.46e-6;
var i;
var n; //total number of measurement
var repeatition; // total number of repetition per position
var delta_x;//movement in X direction
var delta_y;//movement in Y direction
var no_of_row; //total number of row
var no_of_col; //total number of column
var counter_row;
var counter_column;
var current_position= new Point3D;
var new_position= new Point3D;
var original_position= new Point3D;
g_measureDevice.getPos(current_position);
// this is to get start position of the measurement.
//initial valu for new position
new_position.x=current_position.x;
new_position.y=current_position.y;
new_position.z=current_position.z;
original_position.x=current_position.x;
original_position.y=current_position.y;
original_position.z=current_position.z;
zUpper=original_position.z+0.5e-6;
zLower=original_position.z-0.5e-6;
no_of_row=2;
no_of_col=2;
repeatition = 2; //number of repetition in each position = repetition - 1
delta_x=2000e-6;
delta_y=2000e-6;
var accuracyMicrometers = 0.01;
var accuracy = new Point3D;
accuracy.x =  accuracyMicrometers * 1.0E-6;
accuracy.y = accuracyMicrometers * 1.0E-6;
accuracy.z = accuracyMicrometers * 1.0E-6;
n= no_of_row* no_of_col* repeatition; //total number of measurement
counter_row=1;
counter_col=1;
counter=0;
for(i=1;i<=n;i++){
var model=new SurfaceModel;
var objectName="100X_";
```

```
objectName=objectName+i;
//Here is the code to take measurement repetition and move to other
 area in X-Y plane
if((i%repeatition)==0){
if(counter_row==no_of_row+1){
counter_row=1;
current_position.x=original_position.x;
}
if(counter_col==no_of_col+1){
counter_col=1;
}
new_position.x=current_position.x+delta_x*counter_row;
counter_row=counter_row+1;
new_position.y=current_position.y+delta_y*counter_col;
counter_col= counter_col+1;
g_measureDevice.movePos(new_position,true,accuracy);
current_position.x=new_position.x;
current_position.y=new_position.y;
}
g_measureDevice.captureModel(model,zUpper,zLower,verResolution,latR
esolution);
g_database.writeObject(folderName,projectName,objectName,model);
model.getPoints(vector);
fileName=path+objectName+".txt";
vector.writeToFile(fileName,model.ASCII);
//=========== This is for decimation the data points ==============
//model.scale(model.cols()/factor, model.rows()/factor);
//For scaling down the object
//model.getPoints(vector);
//fileName="D:\\Wahyudin\\FileOutput\\"+"Dec 4"+objectName+".txt";
//fileName=path+objectName+".txt";
//vector.writeToFile(fileName,model.ASCII);
model.dispose();
}
}
```

Appendix (2)

MATLAB code for 2D Error map (Ch. 6):

```
fid=fopen(filename,'r');
SOURCE = zeros(1e5,1);
pointCounter=0;

while 1

    readLine=fgetl(fid);
    if (~ischar(readLine)) %stop when reach the EOR reading
        break;
    end

    val=regexp(readLine,'\t','split'); %Splitting the string with certain
delimiter

    pointCounter=pointCounter+1;
    SOURCE(pointCounter,1)=str2double(val(1));
    SOURCE(pointCounter,2)=str2double(val(2));

end
fclose(fid);
SOURCE(pointCounter+1:end,:) = []; %reduce the matrix size
no_of_points=size(SOURCE,1);

%Rotate the points
SOURCE=MATLAB_CODE_rotate_data(SOURCE);

data=SOURCE;
data_CMM=SOURCE;

point_layout=[1 2 3 4 5 6;
    7 8 9 10 11 12;
    13 14 15 16 17 18;
    19 20 21 22 23 24;
    25 26 27 28 29 30;
    31 32 33 34 35 36;];

%plotting the cmm_data: HORISONTAL
for i=1:6
    for j=1:5
        %plot(data(point_layout(i,j):data(point_layout(i,j+1),1),
data(point_layout(i,j):data(point_layout(i,j+1),2),'b-', 'MarkerSize', 50);
        plot([data(point_layout(i,j),1)
data(point_layout(i,j+1),1)],[data(point_layout(i,j),2)
data(point_layout(i,j+1),2)],'b-', 'MarkerSize', 50);
        hold on;
    end
end

%plotting the cmm_data: VERTICAL
for j=1:6
    for i=1:5
        %plot(data(point_layout(i,j):data(point_layout(i,j+1),1),
data(point_layout(i,j):data(point_layout(i,j+1),2),'b-', 'MarkerSize', 50);
```

```
        plot([data(point_layout(i,j),1)
data(point_layout(i+1,j),1)],[data(point_layout(i,j),2)
data(point_layout(i+1,j),2)],'b-', 'MarkerSize', 50);
        hold on;
    end
end

xlim([-0.1e4 2.1e4]);
ylim([-2.1e4 0.1e4]);
axis equal;
xlabel('X/\mum');
ylabel('Y/\mum');


%===================== Data Reading ========================================
fid=fopen(filename,'r');
SOURCE = zeros(1e5,1);
pointCounter=0;

while 1

    readLine=fgetl(fid);
    if (~ischar(readLine)) %stop when reach the EOR reading
        break;
    end

    val=regexp(readLine,'\t','split'); %Splitting the string with certain
delimiter

    pointCounter=pointCounter+1;
    SOURCE(pointCounter,1)=str2double(val(1));
    SOURCE(pointCounter,2)=str2double(val(2));

end
fclose(fid);
SOURCE(pointCounter+1:end,:) = []; %reduce the matrix size

%Rotate the points
SOURCE=MATLAB_CODE_rotate_data(SOURCE);

data=SOURCE;
data_ALICONA=SOURCE;

point_layout=[1 2 3 4 5 6;
    7 8 9 10 11 12;
    13 14 15 16 17 18;
    19 20 21 22 23 24;
    25 26 27 28 29 30;
    31 32 33 34 35 36;];

%Calculating difference between ALICONA and CMM centres
for i=1:36
    delta_x(i)=data_CMM(i,1)-data_ALICONA(i,1);
    delta_y(i)=data_CMM(i,2)-data_ALICONA(i,2);
end
amplification=50;

%plotting the Alicona_data: HORISONTAL
for i=1:6
```

```
    for j=1:5
        %plot([data(point_layout(i,j),1)
data(point_layout(i,j+1),1)],[data(point_layout(i,j),2)
data(point_layout(i,j+1),2)],'r-', 'MarkerSize', 50);

plot([data(point_layout(i,j),1)+delta_x(point_layout(i,j))*amplification
data(point_layout(i,j+1),1)+delta_x(point_layout(i,j+1))*amplification],[da
ta(point_layout(i,j),2)+delta_y(point_layout(i,j))*amplification
data(point_layout(i,j+1),2)+delta_y(point_layout(i,j+1))*amplification],'r-
', 'MarkerSize', 50);
        hold on;
    end
end

%plotting the Alicona_data: VERTICAL
for j=1:6
    for i=1:5
        %plot([data(point_layout(i,j),1)
data(point_layout(i+1,j),1)],[data(point_layout(i,j),2)
data(point_layout(i+1,j),2)],'r-', 'MarkerSize', 50);

plot([data(point_layout(i,j),1)+delta_x(point_layout(i,j))*amplification
data(point_layout(i+1,j),1)+delta_x(point_layout(i+1,j))*amplification],[da
ta(point_layout(i,j),2)+delta_y(point_layout(i,j))*amplification
data(point_layout(i+1,j),2)+delta_y(point_layout(i+1,j))*amplification],'r-
', 'MarkerSize', 50);
        hold on;
    end
end


%%%============CALCULATE sphere distancas from ALICONA data================
%%%HORISONTAL
counter=0;
for i=1:6
    for j=1:5
        counter=counter+1;
        dist_hor(counter)=sqrt(sum((data_ALICONA(point_layout(i,j),1)-
data_ALICONA(point_layout(i,j+1),1))^2+(data_ALICONA(point_layout(i,j),2)-
data_ALICONA(point_layout(i,j+1),2))^2));
    end
end
path='C:\ANAS_error_map_plots\';
name='10X_sphere_distances_HORISONTAL.txt';
filename=[path name];
fid=fopen(filename,'w'); %opening the file
for i=1:30
    fprintf(fid,'%f \n', dist_hor(i));
end
fprintf(fid,'\n');
fclose(fid);

%%%VERTICAL
counter=0;
for i=1:6
    for j=1:5
        counter=counter+1;
        dist_ver(counter)=sqrt(sum((data_ALICONA(point_layout(j,i),1)-
data_ALICONA(point_layout(j+1,i),1))^2+(data_ALICONA(point_layout(j,i),2)-
data_ALICONA(point_layout(j+1,i),2))^2));
```

```
    end
end
path='C:\ANAS_error_map_plots\';
name='10X_sphere_distances_VERTICAL.txt';
filename=[path name];
fid=fopen(filename,'w'); %opening the file
for i=1:30
    fprintf(fid,'%f \n', dist_ver(i));
end
fprintf(fid,'\n');
fclose(fid);

%%%DIAGONAL
counter=0;
for i=1:5 %TOP_LEFT to BOTTOM_RIGHT
    counter=counter+1;
    dist_diag(counter)=sqrt(sum((data_ALICONA(point_layout(i,i),1)-
data_ALICONA(point_layout(i+1,i+1),1))^2+(data_ALICONA(point_layout(i,i),2)
-data_ALICONA(point_layout(i+1,i+1),2))^2));
end
col=6;
for i=1:5 %TOP_RIGHT to BOTTOM_LEFT
    counter=counter+1;
    dist_diag(counter)=sqrt(sum((data_ALICONA(point_layout(i,col),1)-
data_ALICONA(point_layout(i+1,col-
1),1))^2+(data_ALICONA(point_layout(i,col),2)-
data_ALICONA(point_layout(i+1,col-1),2))^2));
    col=col-1;
end
path='C:\ ANAS_error_map_plots\';
name='10X_sphere_distances_DIAGONAL.txt';
filename=[path name];
fid=fopen(filename,'w'); %opening the file
for i=1:10
    fprintf(fid,'%f \n', dist_diag(i));
end
fprintf(fid,'\n');
fclose(fid);
```

Appendix (3)

MATLAB code for Rotate data (Ch. 6):

```
function SOURCE_transformed=MATLAB_CODE_rotate_data(SOURCE)

%line fitting
data_for_fitting=SOURCE(1:6,:);
data_for_fitting(:,3)=0; %convert the matriks into nx3 matrix

%LINEAR LEAST-SQUARE LINE FITTING
%Translation of the data point to its centroid
Mraw=data_for_fitting; %generate M matrix nx2
MrawHom=Mraw;
MrawHom(:,4)=1;
[n m]=size(Mraw);
avgX=sum(Mraw(:,1))/n;
avgY=sum(Mraw(:,2))/n;
avgZ=sum(Mraw(:,3))/n;
T=[1 0 0 avgX; 0 1 0 avgY; 0 0 1 avgZ;0 0 0 1];
MtranslatedHom=inv(T)*MrawHom'; %here we have to inverst T from T12 into
T21=inv(T12)
MtranslatedHom=MtranslatedHom';
Mtranslated=[MtranslatedHom(:,1) MtranslatedHom(:,2) MtranslatedHom(:,3)];

%fitting the line
[U,S,V]=svd(Mtranslated);
singularValue=S(1,1);
a=V(:,1);
for i=2:3
    if(singularValue<=S(i,i))
        singularValue=S(i,i);
        a=V(:,i);
    end
end
a
a=a';
%calculate the degree of rotation
a_ref=[1 0 0];
cos_angle= sum((a.*a_ref))/(sqrt(sum((a).^2))*sqrt(sum((a_ref).^2)))%in
radian
angle=acos(cos_angle)
cos(angle); %for verification only

%translate to point 1 as origin
for i=1:36
    SOURCE(i,1)=SOURCE(i,1)-SOURCE(1,1);
    SOURCE(i,2)=SOURCE(i,2)-SOURCE(1,2);
end

%rotate
rot_z=[cos(angle) -sin(angle) 0
    sin(angle) cos(angle) 0
    0 0 1
    ];

%convert matrix SOURCE into nx4 format
SOURCE(:,3)=0;

```

```
temp=rot_z*SOURCE';
temp=temp';

SOURCE_transformed=temp(:,1:2)

%------------- TRANSFORM the coordinate to its centroid ------------------
%formating data points
SOURCE=0;
for i=1:36
    SOURCE(i,1)=SOURCE_transformed(i,1);
    SOURCE(i,2)=SOURCE_transformed(i,2);
    SOURCE(i,3)=0;
    SOURCE(i,4)=1;
end

%calculate the centroid:
centroid_x=mean(SOURCE(:,1));
centroid_y=mean(SOURCE(:,2));

dx=centroid_x-SOURCE(1,1);
dy=centroid_y-SOURCE(1,2);
dz=0;

T12=[1 0 0 dx
    0 1 0 dy
    0 0 1 dz
    0 0 0 1];

temp=0;
temp=inv(T12)*SOURCE';
temp=temp';
%--------------------------------------------------------------------------
SOURCE_transformed=0;
SOURCE_transformed=temp(:,1:2)
end
```

Appendix (4)

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-2	3.9998	4.0001	3.9998	3.9998
1-2	3.9999	3.9996	3.9998	3.9997
1-2	3.9999	4.0004	3.9998	4.0001
1-2	4	3.9995	4.0007	3.9999
1-2	3.9999	3.9990	3.9998	4.0002
y_j	3.9999	3.999726899	3.999963906	3.999952915
S_j	7.07107E-05	0.00054562	0.000420551	0.000192535
(S_j)^2	5E-09	2.97701E-07	1.76863E-07	3.70699E-08
y_j - y	1.40701E-05	-0.000159031	7.79756E-05	6.69855E-05
(y_j - y)^2	1.97967E-10	2.52909E-08	6.0802E-09	4.48706E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

		Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	3.99988593		
u_{rep}	0.000359386	16	4.17049E-17
u_{geo}	5.4815E-05	3	1.88085E-19
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000919237
standard uncertainty	0.000171431
k factor	2.133028362
Extended uncertainty	0.000365668

Effective degree of freedom: 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2-3	3.9997	4.0003	4.0010	4.0002
2-3	3.9992	4.0000	4.0010	4.0004
2-3	3.9995	4.0000	4.0000	4.0001
2-3	4.0002	4.0008	3.9996	4.0001
2-3	3.9996	4.0013	4.0001	4.0002
y_j	3.99964	4.00048	4.00034	4.0002
S_j	0.000364692	0.000563028	0.000630872	0.000122474
(S_j)^2	1.33E-07	3.17E-07	3.98E-07	1.5E-08
y_j - y	-0.000525	0.000315	0.000175	3.5E-05
(y_j - y)^2	2.75625E-07	9.9225E-08	3.0625E-08	1.225E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

		Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	4.000165		
u_{rep}	0.000464489	16	1.1637E-16
u_{geo}	0.000184097	3	2.39301E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.001198308
standard uncertainty	0.0002333
k factor	2.12631338
Extended uncertainty	0.000496068

Effective degree of freedom: 21

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3-4	4.0003	3.9992	4.0000	4.0000
3-4	4.001	3.9995	4.0000	4.0002
3-4	4.0003	4.0004	4.0007	4.0006
3-4	3.9998	3.9990	4.0005	4.0005
3-4	4	3.9988	4.0005	4.0002
y_j	4.00028	3.999371246	4.000342011	4.000311126
S_j	0.000454973	0.000603437	0.000307924	0.000252589
(S_j)^2	2.07E-07	3.64136E-07	9.48172E-08	6.38011E-08
y_j - y	0.000203904	-0.00070485	0.000265916	0.00023503
$(y_j$ - y)^2	4.1577E-08	4.96814E-07	7.07112E-08	5.52391E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_c)	u_c^4 / v_c
Coverage factor (p)	95.45 %		
y	4.000076096		
u_{rep}	0.000427128	16	8.32097E-17
u_{geo}	0.000235291	3	6.38525E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	4.001109403
standard uncertainty	0.000230508
k factor	2.14049663
Extended uncertainty	0.000493402

Effective degree of freedom: 19

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
4-5	4.0005	4.0015	3.9991	3.9999
4-5	4.0001	4.0009	3.9991	3.9995
4-5	4.0005	3.9997	3.9991	3.9999
4-5	4.0008	4.0010	4.0003	3.9995
4-5	4.0007	4.0012	3.9992	3.9990
y_j	4.00052	4.00086	3.99936	3.99956
S_j	0.000268328	0.00068775	0.000527257	0.000371484
(S_j)^2	7.2E-08	4.73E-07	2.78E-07	1.38E-07
y_j - y	0.000445	0.000785	-0.000715	-0.000515
$(y_j$ - y)^2	1.98025E-07	6.16225E-07	5.11225E-07	2.65225E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_c)	u_c^4 / v_c
Coverage factor (p)	95.45 %		
y	4.000075		
u_{rep}	0.000490153	16	1.443E-16
u_{geo}	0.000364086	3	3.66077E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	4.001108308
standard uncertainty	0.00028982
k factor	2.211800697
Extended uncertainty	0.000641023

Effective degree of freedom: 13

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
5-6	3.9987	3.9993	4.0001	3.9995
5-6	3.9992	3.9996	4.0001	3.9997
5-6	3.9986	3.9994	4.0003	3.9992
5-6	3.9994	3.9995	4.0000	4.0003
5-6	3.9995	3.9991	4.0002	4.0002
y_j	3.99908	3.99938	4.00014	3.99978
S_j	0.000408656	0.000192354	0.000114018	0.000465833
(S_j)^2	1.67E-07	3.7E-08	1.3E-08	2.17E-07
y_j - y	-0.000515	-0.000215	0.000545	0.000185
$(y_j$ - y)^2	2.65225E-07	4.6225E-08	2.97025E-07	3.4225E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_c)	u_c^4 / ν_c
y	3.999595		
u_{rep}	0.000329393	16	2.94306E-17
u_{geo}	0.000231427	3	5.97603E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000628308
standard uncertainty	0.000194667
k factor	2.168942996
Extended uncertainty	0.000422223

Effective degree of freedom 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
31-32	4.0004	3.9999	3.9995	3.9990
31-32	3.9999	4.0003	3.9995	3.9993
31-32	4.0001	3.9995	3.9989	3.9989
31-32	4.0008	4.0002	3.9996	3.9992
31-32	4.0002	4.0001	3.9995	3.9991
y_j	4.00028	4	3.99954	3.9991
S_j	0.000342053	0.000316228	5.47723E-05	0.000158114
(S_j)^2	1.17E-07	1E-07	3E-09	2.5E-08
y_j - y	0.00055	0.00027	-0.00019	-0.00063
$(y_j$ - y)^2	3.025E-07	7.29E-08	3.61E-08	3.969E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_c)	u_c^4 / ν_c
y	3.99973		
u_{rep}	0.000247487	16	9.37891E-18
u_{geo}	0.000259551	3	9.45472E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000763308
standard uncertainty	0.000178599
k factor	2.319809441
Extended uncertainty	0.000414315

Effective degree of freedom 9

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
32-33	3.9996	4.0000	4.0000	4.0010
32-33	4.0002	3.9996	4.0000	4.0009
32-33	4.0001	4.0000	3.9990	4.0012
32-33	3.9996	3.9998	3.9996	4.0004
32-33	3.9994	4.0000	3.9996	4.0006
y_j	3.99978	3.99988	3.99964	4.00082
S_j	0.000349285	0.000178885	0.000409878	0.000319374
(S_j)^2	1.22E-07	3.2E-08	1.68E-07	1.02E-07
y_j - y	-0.00025	-0.00015	-0.00039	0.00079
$(y_j$ - y)^2	6.25E-08	2.25E-08	1.521E-07	6.241E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	4.00003		
u_{rep}	0.000325576	16	2.809E-17
u_{geo}	0.000267893	3	1.07301E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	4.001063308
standard uncertainty	0.000204811
k factor	2.231351317
Extended uncertainty	0.000457005

Effective degree of freedom 12

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
33-34	3.9996	4.0001	3.9996	3.9994
33-34	3.9998	4.0007	3.9996	3.9997
33-34	4.0003	4.0005	4.0008	4.0000
33-34	3.9997	4.0007	4.0000	4.0000
33-34	3.9997	4.0002	4.0004	3.9997
y_j	3.99982	4.00044	4.00008	3.99976
S_j	0.000277489	0.000279285	0.000521536	0.000250998
(S_j)^2	7.7E-08	7.8E-08	2.72E-07	6.3E-08
y_j - y	-0.000205	0.000415	5.5E-05	-0.000265
$(y_j$ - y)^2	4.2025E-08	1.72225E-07	3.025E-09	7.0225E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	4.000025		
u_{rep}	0.00035	16	3.75156E-17
u_{geo}	0.000154785	3	1.19584E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	4.001058308
standard uncertainty	0.00018247
k factor	2.120243265
Extended uncertainty	0.000386882

Effective degree of freedom 22

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
34-35	4.0002	4.0002	3.9999	4.0001
34-35	4.0003	4.0003	3.9999	3.9997
34-35	3.9991	3.9990	4.0001	3.9990
34-35	4.0005	4.0001	4.0002	3.9996
34-35	4	4.0004	3.9997	4.0000
y_j	4.00002	4	3.99996	3.99968
S_j	0.000544977	0.000570088	0.000194936	0.000432435
(S_j)^2	2.97E-07	3.25E-07	3.8E-08	1.87E-07
y_j - y	0.000105	8.5E-05	4.5E-05	-0.000235
$(y_j$ - y)^2	1.1025E-08	7.225E-09	2.025E-09	5.5225E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_c)	u_c^4 / v_c
y	3.999915		
u_{rep}	0.000460163	16	1.12095E-16
u_{geo}	7.932E-05	3	8.24689E-19
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000948308
standard uncertainty	0.000216168
k factor	2.14049663
Extended uncertainty	0.000462708

Effective degree of freedom 19

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
35-36	4.0006	3.9991	4.0011	3.9999
35-36	4.0001	3.9997	4.0011	4.0000
35-36	3.9997	4.0010	4.0004	3.9999
35-36	4.0004	3.9992	4.0002	3.9999
35-36	4.001	3.9993	4.0007	3.9993
y_j	4.00036	3.99966	4.0007	3.9998
S_j	0.00049295	0.000782943	0.000406202	0.000282843
(S_j)^2	2.43E-07	6.13E-07	1.65E-07	8E-08
y_j - y	0.00023	-0.00047	0.00057	-0.00033
$(y_j$ - y)^2	5.29E-08	2.209E-07	3.249E-07	1.089E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_c)	u_c^4 / v_c
y	4.00013		
u_{rep}	0.000524643	16	1.89406E-16
u_{geo}	0.000242831	3	7.24389E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.001163308
standard uncertainty	0.000269439
k factor	2.133028362
Extended uncertainty	0.000574722

Effective degree of freedom 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-7	4.0004	3.9993	4.0008	4.0003
1-7	4.0007	3.9997	4.0008	4.0008
1-7	4.001	3.9991	4.0001	3.9996
1-7	4.0007	3.9995	4.0006	4.0006
1-7	3.9997	3.9998	4.0000	4.0007
y_j	4.0005	3.99948	4.00046	4.0004
S_j	0.000494975	0.000286356	0.000384708	0.000484768
(S_j)^2	2.45E-07	8.2E-08	1.48E-07	2.35E-07
y_j - y	0.00029	-0.00073	0.00025	0.00019
$(y_j$ - y)^2	8.41E-08	5.329E-07	6.25E-08	3.61E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

	Value	Degree of freedom (v_c)	u_c^4 / v_c
y	4.00021		
u_{rep}	0.000421307	16	7.87656E-17
u_{geo}	0.000244199	3	7.40861E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.001243308
standard uncertainty	0.000230682
k factor	2.148852324
Extended uncertainty	0.000495702

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
7-13	3.9998	4.0006	3.9993	3.9995
7-13	3.999	3.9998	3.9993	3.9988
7-13	3.9995	4.0002	4.0001	3.9995
7-13	3.9997	4.0003	3.9997	3.9992
7-13	4.0001	4.0001	4.0003	3.9986
y_j	3.99962	4.0002	3.99974	3.99912
S_j	0.000408656	0.000291548	0.00045607	0.000408656
(S_j)^2	1.67E-07	8.5E-08	2.08E-07	1.67E-07
y_j - y	-5E-05	0.00053	7E-05	-0.00055
$(y_j$ - y)^2	2.5E-09	2.809E-07	4.9E-09	3.025E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

	Value	Degree of freedom (v_c)	u_c^4 / v_c
y	3.99967		
u_{rep}	0.000395917	16	6.14264E-17
u_{geo}	0.000221886	3	5.04984E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000703308
standard uncertainty	0.000215556
k factor	2.14049663
Extended uncertainty	0.000461396

Effective degree of freedom: 19

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
13-19	3.9986	3.9983	4.0002	3.9986
13-19	3.9995	3.9995	4.0002	3.9983
13-19	3.9988	3.9990	3.9994	3.9997
13-19	3.9989	3.9991	3.9995	3.9984
13-19	4.0001	3.9991	3.9994	3.9979
y_j	3.99918	3.999	3.99974	3.99858
S_j	0.000614003	0.00043589	0.0004219	0.000676018
(S_j)^2	3.77E-07	1.9E-07	1.78E-07	4.57E-07
y_j - y	5.5E-05	-0.000125	0.000615	-0.000545
$(y_j$ - y)^2	3.025E-09	1.5625E-08	3.78225E-07	2.97025E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p) 95.45 %

		Degree of freedom (v_e)	u_e^4 / v_e
y	3.999125		
u_{rep}	0.000548179	16	2.25751E-16
u_{geo}	0.000240468	3	6.96611E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000158308
standard uncertainty	0.00027814
k factor	2.133028362
Extended uncertainty	0.000593281

Effective degree of freedom 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
19-25	4.0017	4.0003	3.9991	4.0022
19-25	4.0007	4.0001	3.9991	4.0025
19-25	4.0011	4.0002	3.9993	4.0020
19-25	4.0013	4.0006	4.0003	4.0010
19-25	4.0001	4.0006	3.9994	4.0030
y_j	4.00098	4.00036	3.99944	4.00214
S_j	0.000609918	0.000230217	0.000497996	0.00074027
(S_j)^2	3.72E-07	5.3E-08	2.48E-07	5.48E-07
y_j - y	0.00025	-0.00037	-0.00129	0.00141
$(y_j$ - y)^2	6.25E-08	1.369E-07	1.6641E-06	1.9881E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

		Degree of freedom (v_e)	u_e^4 / v_e
y	4.00073		
u_{rep}	0.000552494	16	2.32944E-16
u_{geo}	0.000566539	3	2.14624E-15
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.001763308
standard uncertainty	0.000379602
k factor	2.3664195
Extended uncertainty	0.000898297

Effective degree of freedom 8

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
25-31	3.9979	4.0002	4.0008	3.9984
25-31	4	3.9994	4.0008	3.9987
25-31	3.9998	3.9996	4.0006	3.9985
25-31	3.9989	3.9994	3.9992	3.9988
25-31	3.9989	3.9995	4.0007	3.9991
y_j	3.9991	3.99962	4.00042	3.9987
S_j	0.000839643	0.000334664	0.000687023	0.000273861
(S_j)^2	7.05E-07	1.12E-07	4.72E-07	7.5E-08
y_j - y	-0.00036	0.00016	0.00096	-0.00076
$(y_j$ - y)^2	1.296E-07	2.56E-08	9.216E-07	5.776E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	3.99946		
u_{rep}	0.000583952	16	2.90703E-16
u_{geo}	0.000371304	3	3.95984E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000493308
standard uncertainty	0.000324765
k factor	2.168942996
Extended uncertainty	0.000704397

Effective degree of freedom: 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-12	3.9993	4.0004	4.0002	4.0011
6-12	3.9996	3.9977	4.0002	4.0018
6-12	3.9998	3.9987	3.9992	4.0013
6-12	4.0017	3.9997	4.0019	4.0018
6-12	4.0019	4.0002	3.9990	4.0012
y_j	4.00046	3.99934	4.0001	4.00144
S_j	0.001238144	0.001128273	0.001148913	0.000336155
(S_j)^2	1.533E-06	1.273E-06	1.32E-06	1.13E-07
y_j - y	0.000125	-0.000995	-0.000235	0.001105
$(y_j$ - y)^2	1.5625E-08	9.90025E-07	5.5225E-08	1.22102E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	4.000335		
u_{rep}	0.001029442	16	2.80768E-15
u_{geo}	0.000436071	3	7.53337E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.001368308
standard uncertainty	0.000512148
k factor	2.14049663
Extended uncertainty	0.001096251

Effective degree of freedom: 19

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
12-18	4.0009	4.0007	3.9995	4.0009
12-18	4.0006	4.0008	3.9995	4.0008
12-18	4.0007	4.0006	3.9999	4.0008
12-18	3.9991	4.0013	4.0005	3.9996
12-18	3.999	4.0006	4.0017	4.0000
y_j	4.00006	4.0008	4.00022	4.00042
S_j	0.000928978	0.000291548	0.000923038	0.000584808
(S_j)^2	8.63E-07	8.5E-08	8.52E-07	3.42E-07
y_j - y	-0.000315	0.000425	-0.000155	4.5E-05
$(y_j$ - y)^2	9.9225E-08	1.80625E-07	2.4025E-08	2.025E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: 4.000375

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000731779	16	7.16901E-16
u_{geo}	0.000159661	3	1.3538E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

$L_{meas std}$: 3.999066667

$u_{meas std}$: 5E-05; Degree of freedom: 8

Calibrated value	4.001408308
standard uncertainty	0.000340997
k factor	2.148852324
Extended uncertainty	0.000732752

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
18-24	3.9992	4.0000	3.9991	3.9975
18-24	3.9992	4.0000	3.9991	3.9973
18-24	3.9991	3.9999	4.0011	3.9972
18-24	3.9996	3.9992	3.9980	3.9991
18-24	3.9998	3.9991	3.9996	3.9985
y_j	3.99938	3.99964	3.99938	3.99792
S_j	0.000303315	0.000450555	0.001125611	0.000837854
(S_j)^2	9.2E-08	2.03E-07	1.267E-06	7.02E-07
y_j - y	0.0003	0.00056	0.0003	-0.00116
$(y_j$ - y)^2	9E-08	3.136E-07	9E-08	1.3456E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: 3.99908

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.00075233	16	8.0089E-16
u_{geo}	0.000391493	3	4.89389E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

$L_{meas std}$: 3.999066667

$u_{meas std}$: 5E-05; Degree of freedom: 8

Calibrated value	4.000113308
standard uncertainty	0.000392839
k factor	2.148852324
Extended uncertainty	0.000844153

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
4-30	4.0007	3.9999	4.0010	4.0004
4-30	4.0007	4.0003	4.0010	3.9999
4-30	4.0009	4.0001	3.9993	4.0008
4-30	4.0012	4.0010	4.0003	4.0005
4-30	4.0009	4.0011	4.0005	4.0010
y_j	4.00088	4.00048	4.00042	4.00052
S_j	0.000204939	0.00054037	0.000697854	0.000420714
(S_j)^2	4.2E-08	2.92E-07	4.87E-07	1.77E-07
y_j - y	0.000305	-9.5E-05	-0.000155	-5.5E-05
$(y_j$ - y)^2	9.3025E-08	9.025E-09	2.4025E-08	3.025E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	4.000575		
u_{rep}	0.0004995	16	1.55626E-16
u_{geo}	0.000103722	3	2.41129E-18
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	4.001608308
standard uncertainty	0.000235362
k factor	2.14049663
Extended uncertainty	0.000503792

Effective degree of freedom: 19

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
0-36	4	4.0001	4.0004	4.0012
0-36	4.0006	3.9994	4.0004	4.0008
0-36	4.0002	4.0004	3.9995	4.0013
0-36	3.9991	3.9991	4.0011	3.9998
0-36	3.9982	3.9996	3.9989	4.0000
y_j	3.99962	3.99972	4.00006	4.00062
S_j	0.000965401	0.000526308	0.000861974	0.000687023
(S_j)^2	9.32E-07	2.77E-07	7.43E-07	4.72E-07
y_j - y	-0.000385	-0.000285	5.5E-05	0.000615
$(y_j$ - y)^2	1.48225E-07	8.1225E-08	3.025E-09	3.78225E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	4.000005		
u_{rep}	0.00077846	16	9.1809E-16
u_{geo}	0.000225592	3	5.39575E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	4.001038308
standard uncertainty	0.000369769
k factor	2.14049663
Extended uncertainty	0.000791488

Effective degree of freedom: 19

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-8	5.6551	5.6558	5.6572	5.6552
1-8	5.656	5.6559	5.6572	5.6554
1-8	5.6562	5.6560	5.6567	5.6553
1-8	5.6563	5.6566	5.6570	5.6550
1-8	5.6565	5.6565	5.6560	5.6558
y_j	5.65602	5.65616	5.65682	5.65534
S_j	0.000544977	0.000364692	0.000501996	0.000296648
(S_j)^2	2.97E-07	1.33E-07	2.52E-07	8.8E-08
y_j - y	-6.5E-05	7.5E-05	0.000735	-0.000745
(y_j - y)^2	4.225E-09	5.625E-09	5.40225E-07	5.55025E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	5.656085		
u_{rep}	0.000438748	16	9.26406E-17
u_{geo}	0.000303466	3	1.76685E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	5.657118308
standard uncertainty	0.000253631
k factor	2.181165682
Extended uncertainty	0.000553212

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
8-15	5.6575	5.6559	5.6562	5.6574
8-15	5.6573	5.6557	5.6562	5.6577
8-15	5.6569	5.6564	5.6572	5.6574
8-15	5.6569	5.6556	5.6560	5.6580
8-15	5.6561	5.6557	5.6578	5.6577
y_j	5.65694	5.65586	5.65668	5.65764
S_j	0.000536656	0.000320936	0.000782304	0.000250998
(S_j)^2	2.88E-07	1.03E-07	6.12E-07	6.3E-08
y_j - y	0.00016	-0.00092	-1E-04	0.00086
(y_j - y)^2	2.56E-08	8.464E-07	1E-08	7.396E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	5.65678		
u_{rep}	0.000516236	16	1.77556E-16
u_{geo}	0.000367605	3	3.80438E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	5.657813308
standard uncertainty	0.000299815
k factor	2.195291287
Extended uncertainty	0.000658182

Effective degree of freedom 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
22	5.6573	5.6579	5.6579	5.6570
22	5.6569	5.6573	5.6579	5.6563
22	5.6565	5.6567	5.6568	5.6574
22	5.6573	5.6573	5.6575	5.6562
22	5.6575	5.6574	5.6564	5.6554
y_j	5.6571	5.65732	5.6573	5.65646
S_j	0.0004	0.000426615	0.000674537	0.000773305
(S_j)^2	1.6E-07	1.82E-07	4.55E-07	5.98E-07
y_j - y	5.5E-05	0.000275	0.000255	-0.000585
(y_j - y)^2	3.025E-09	7.5625E-08	6.5025E-08	3.42225E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	5.657045		
u_{rep}	0.000590551	16	3.04066E-16
u_{geo}	0.000201225	3	3.41578E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

E_{Lprop} -0.000258327

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	5.658078308
standard uncertainty	0.000287539
k factor	2.133028362
Extended uncertainty	0.000613329

Effective degree of freedom 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2-29	5.656	5.6565	5.6566	5.6559
2-29	5.6559	5.6574	5.6566	5.6574
2-29	5.6566	5.6569	5.6573	5.6557
2-29	5.6562	5.6572	5.6564	5.6572
2-29	5.6563	5.6569	5.6576	5.6578
y_j	5.6562	5.65698	5.6569	5.6568
S_j	0.000273861	0.000342053	0.000519615	0.000940744
(S_j)^2	7.5E-08	1.17E-07	2.7E-07	8.85E-07
y_j - y	-0.00052	0.00026	0.00018	8E-05
(y_j - y)^2	2.704E-07	6.76E-08	3.24E-08	6.4E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	5.65672		
u_{rep}	0.000580302	16	2.83501E-16
u_{geo}	0.0001772	3	2.05408E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

E_{Lprop} -0.000258327

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	5.657753308
standard uncertainty	0.000279295
k factor	2.133028362
Extended uncertainty	0.000595745

Effective degree of freedom 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
29-36	5.6579	5.6574	5.6579	5.6579
29-36	5.6587	5.6570	5.6579	5.6561
29-36	5.658	5.6576	5.6560	5.6578
29-36	5.6569	5.6572	5.6576	5.6558
29-36	5.6566	5.6574	5.6561	5.6559
y_j	5.65762	5.65732	5.6571	5.6567
S_j	0.000858487	0.000228035	0.000966954	0.001055936
(S_j)^2	7.37E-07	5.2E-08	9.35E-07	1.115E-06
y_j - y	0.000435	0.000135	-8.5E-05	-0.000485
(y_j - y)^2	1.89225E-07	1.8225E-08	7.225E-09	2.35225E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	5.657185		
u_{rep}	0.000842467	16	1.25936E-15
u_{geo}	0.000193628	3	2.92839E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	5.658218308
standard uncertainty	0.000392592
k factor	2.148852324
Extended uncertainty	0.000843623

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-11	5.6563	5.6575	5.6561	5.6582
-11	5.6571	5.6560	5.6561	5.6584
-11	5.6465	5.6560	5.6563	5.6580
-11	5.6582	5.6570	5.6585	5.6593
-11	5.6574	5.6574	5.6570	5.6581
y_j	5.6551	5.65678	5.6568	5.6584
S_j	0.004855409	0.000736206	0.001019804	0.000524404
(S_j)^2	2.3575E-05	5.42E-07	1.04E-06	2.75E-07
y_j - y	-0.00167	1E-05	3E-05	0.00163
(y_j - y)^2	2.7889E-06	1E-10	9E-10	2.6569E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	5.65677		
u_{rep}	0.002521507	16	1.0106E-13
u_{geo}	0.000673721	3	4.29219E-15
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	5.657803308
standard uncertainty	0.001178084
k factor	2.148852324
Extended uncertainty	0.002531528

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-16	5.6557	5.6541	5.6559	5.6545
1-16	5.6557	5.6561	5.6559	5.6545
1-16	5.6558	5.6579	5.6568	5.6549
1-16	5.6564	5.6555	5.6563	5.6552
1-16	5.6574	5.6556	5.6561	5.6552
y_j	5.6562	5.65584	5.6562	5.65486
S_j	0.000731437	0.001370401	0.000374166	0.000350714
(S_j)^2	5.35E-07	1.878E-06	1.4E-07	1.23E-07
y_j - y	0.000425	6.5E-05	0.000425	-0.000915
$(y_j$ - y)^2	1.80625E-07	4.225E-09	1.80625E-07	8.37225E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 5.655775

E_{Lprop} -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000817924	16	1.1189E-15
u_{geo}	0.000316583	3	2.09272E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	5.656808308
standard uncertainty	0.000402072
k factor	2.14049663
Extended uncertainty	0.000860634

Effective degree of freedom 19

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
uge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
21	5.6574	5.6578	5.6576	5.6578
21	5.6572	5.6566	5.6576	5.6570
21	5.6572	5.6557	5.6579	5.6575
21	5.6565	5.6569	5.6571	5.6571
21	5.656	5.6570	5.6580	5.6574
y_j	5.65686	5.6568	5.65764	5.65736
S_j	0.000589915	0.000758288	0.000350714	0.000320936
(S_j)^2	3.48E-07	5.75E-07	1.23E-07	1.03E-07
y_j - y	-0.000305	-0.000365	0.000475	0.000195
$(y_j$ - y)^2	9.3025E-08	1.33225E-07	2.25625E-07	3.8025E-08

Gauge block measurement		
Measurements No.	Position 1	Position 2
1	3.9991	3.9991
2	3.999	3.999
3	3.9991	3.9991

Coverage factor (p) 95.45 %

y 5.657165

E_{Lprop} -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000535957	16	2.06281E-16
u_{geo}	0.000202052	3	3.47225E-17
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	5.658198308
standard uncertainty	0.000265447
k factor	2.133028362
Extended uncertainty	0.000566206

Effective degree of freedom 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
21-26	5.6571	5.6575	5.6573	5.6564
21-26	5.6566	5.6581	5.6573	5.6569
21-26	5.6567	5.6576	5.6561	5.6563
21-26	5.6577	5.6580	5.6566	5.6566
21-26	5.6585	5.6581	5.6565	5.6565
y_j	5.65732	5.65786	5.65676	5.65654
S_j	0.00078867	0.000288097	0.000527257	0.000230217
(S_j)^2	6.22E-07	8.3E-08	2.78E-07	5.3E-08
y_j - y	0.0002	0.00074	-0.00036	-0.00058
$(y_j - y)$^2	4E-08	5.476E-07	1.296E-07	3.364E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

Coverage factor (p) 95.45 %

y 5.65712

E_{Lprop} -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.00050892	16	1.67703E-16
u_{geo}	0.000296311	3	1.60601E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	5.658153308
standard uncertainty	0.000276687
k factor	2.158263401
Extended uncertainty	0.000597164

Effective degree of freedom 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
uge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
31	5.6562	5.6574	5.6560	5.6575
31	5.6569	5.6562	5.6560	5.6577
31	5.6568	5.6561	5.6562	5.6573
31	5.6567	5.6566	5.6569	5.6577
31	5.6548	5.6567	5.6565	5.6579
y_j	5.65628	5.6566	5.65632	5.65762
S_j	0.000870057	0.000514782	0.000383406	0.000228035
(S_j)^2	7.57E-07	2.65E-07	1.47E-07	5.2E-08
y_j - y	-0.000425	-0.000105	-0.000385	0.000915
$(y_j - y)$^2	1.80625E-07	1.1025E-08	1.48225E-07	8.37225E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

Coverage factor (p) 95.45 %

y 5.656705

E_{Lprop} -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000552494	16	2.32944E-16
u_{geo}	0.000313196	3	2.00458E-16
E_L	-0.001033308		
u_{corr}	5.27033E-05	800	9.6441E-21
u_{temp}	5.31061E-06	∞	0

	Value	Degree of freedom
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	5.657738308
standard uncertainty	0.000297286
k factor	2.148852324
Extended uncertainty	0.000638823

Effective degree of freedom 18

Appendix (5)

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	0.750000	0.749800	0.748600	0.747900
	0.750300	0.749400	0.748200	0.748200
	0.749500	0.749200	0.748300	0.748001
	0.749300	0.749200	0.748500	0.748200
	0.749200	0.749900	0.748700	0.748400
y_j	0.749660181	0.749500037	0.748460116	0.748140168
S_j	0.000472347	0.000331646	0.000207365	0.000194879
(S_j)^2	2.23111E-07	1.09989E-07	4.30003E-08	3.79778E-08
y_j - y	0.000720056	0.000559912	-0.00048001	-0.000799957
$(y_j$ - y)^2	5.1848E-07	3.13501E-07	2.30409E-07	6.39932E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.500
2	0.5013	0.5013	0.501
3	0.5002	0.5002	0.500

Coverage factor (p) 95.45 %

y 0.748940126

E_{Lprop} 0.0016

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000321745	16	2.67908E-17
u_{geo}	0.000376643	3	4.19256E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value 0.747740126

standard uncertainty 0.000346295

k factor 2.168942996

Extended uncertainty 0.000751093

Effective degree of freedom 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	0.748900	0.751400	0.750000	0.750000
	0.748600	0.751201	0.750100	0.749700
	0.749100	0.751400	0.750100	0.749901
	0.749400	0.751201	0.750300	0.750100
	0.749400	0.750801	0.749900	0.750000
y_j	0.74908012	0.751200588	0.750080231	0.749940423
S_j	0.000342135	0.000244817	0.000148367	0.000151626
(S_j)^2	1.17056E-07	5.99356E-08	2.20129E-08	2.29905E-08
y_j - y	-0.00099522	0.001125248	4.89016E-06	-0.000134918
$(y_j$ - y)^2	9.90464E-07	1.26618E-06	2.39137E-11	1.82028E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

y 0.75007534

E_{Lprop} 0.0016

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000235582	16	7.70028E-18
u_{geo}	0.0004354	3	7.48705E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value 0.748875340

standard uncertainty 0.000349634

k factor 2.231351317

Extended uncertainty 0.000780156

Effective degree of freedom 12

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-4	0.750600	0.749900	0.750800	0.751300
-4	0.750400	0.749702	0.750900	0.751300
-4	0.750400	0.750300	0.750900	0.750900
-4	0.750400	0.750700	0.750700	0.751300
-4	0.750600	0.750501	0.750800	0.751200
y_j	0.750480125	0.750220611	0.750820119	0.751200053
S_j	0.000109567	0.000414324	8.3764E-05	0.000173219
(S_j)^2	1.20049E-08	1.71664E-07	7.01641E-09	3.0005E-08
y_j - y	-0.000200102	-0.000459616	0.000139892	0.000519826
$(y_j$ - y)^2	4.00407E-08	2.11247E-07	1.95697E-08	2.70219E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.50
2	0.5013	0.5013	0.50
3	0.5002	0.5002	0.50

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.750680227		
u_{rep}	0.000234889	16	7.61005E-18
u_{geo}	0.000212343	3	4.23559E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{meas std}$	0.5008	
$u_{meas std}$	0.000482183	8

Calibrated value	0.749480227
standard uncertainty	0.000293356
k factor	2.195291287
Extended uncertainty	0.000644003

Effective degree of freedom 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-5	0.750800	0.749800	0.751100	0.749500
-5	0.751100	0.750600	0.750900	0.749700
-5	0.751100	0.749800	0.750600	0.749600
-5	0.750800	0.749800	0.750700	0.749600
-5	0.750400	0.749800	0.751100	0.749600
y_j	0.750840073	0.749960029	0.750880177	0.749600207
S_j	0.000288061	0.000357754	0.000228007	7.07367E-05
(S_j)^2	8.29793E-08	1.27988E-07	5.19872E-08	5.00368E-09
y_j - y	0.000519952	-0.000360092	0.000560056	-0.000719915
$(y_j$ - y)^2	2.7035E-07	1.29666E-07	3.13662E-07	5.18277E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.750320122		
u_{rep}	0.000258824	16	1.1219E-17
u_{geo}	0.000320411	3	2.19577E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{meas std}$	0.5008	
$u_{meas std}$	0.000482183	8

Calibrated value	0.749120122
standard uncertainty	0.000320647
k factor	2.181165682
Extended uncertainty	0.000699385

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	0.749500	0.750400	0.749000	0.749500
	0.749300	0.749900	0.749600	0.749600
	0.749400	0.750100	0.750000	0.750100
	0.749900	0.750000	0.749401	0.749700
	0.749900	0.749800	0.749200	0.750000
y_j	0.749600047	0.750040055	0.749440249	0.749780141
S_j	0.00028287	0.00023023	0.000384783	0.00025876
(S_j)^2	8.00157E-08	5.30059E-08	1.48058E-07	6.69567E-08
y_j - y	-0.000115076	0.000324932	-0.000274874	6.50183E-05
(y_j - y)^2	1.32426E-08	1.05581E-07	7.55555E-08	4.22738E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p): 95.45 %

y: 0.749715123

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000294973	16	1.89264E-17
u_{geo}	0.000128649	3	5.70665E-18
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

E_{Lprop}: 0.0016

$L_{measstd}$: 0.5008

$u_{measstd}$: 0.000482183 — Degree of freedom: 8

Calibrated value	0.748515123
standard uncertainty	0.000292045
k factor	2.181165682
Extended uncertainty	0.000636999

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
32	0.749600	0.750301	0.750000	0.750400
32	0.750500	0.750401	0.749300	0.750601
32	0.749300	0.750100	0.749600	0.750500
32	0.749900	0.749700	0.750100	0.750600
32	0.749900	0.749500	0.750300	0.750300
y_j	0.749840051	0.750000317	0.749860245	0.750480242
S_j	0.000445006	0.000387505	0.000403857	0.000130469
(S_j)^2	1.98031E-07	1.5016E-07	1.63101E-07	1.70221E-08
y_j - y	-0.000205163	-4.48967E-05	-0.000184969	0.000435029
(y_j - y)^2	4.2092E-08	2.01571E-09	3.42134E-08	1.8925E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p): 95.45 %

y: 0.750045214

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000363426	16	4.36117E-17
u_{geo}	0.000149324	3	1.0358E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

E_{Lprop}: 0.0016

$L_{measstd}$: 0.5008

$u_{measstd}$: 0.000482183 — Degree of freedom: 8

Calibrated value	0.748845214
standard uncertainty	0.000309421
k factor	2.148852324
Extended uncertainty	0.000664899

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
uge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
33	0.748400	0.750500	0.749200	0.749001
33	0.748800	0.750500	0.749400	0.748500
33	0.749200	0.751100	0.749400	0.748900
33	0.748600	0.751600	0.749300	0.748801
33	0.749000	0.751400	0.749100	0.748800
y_j	0.748800105	0.751020025	0.749280056	0.748800479
S_j	0.000316253	0.000506943	0.00013033	0.000187289
(S_j)^2	1.00016E-07	2.56991E-07	1.69858E-08	3.50772E-08
y_j - y	-0.000675061	0.001544859	-0.000195111	-0.000674687
(y_j - y)^2	4.55707E-07	2.38659E-06	3.80681E-08	4.55203E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p)	95.45 %		
y	0.749475167		
		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000319793	16	2.61466E-17
u_{geo}	0.000527223	3	1.60967E-15
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	Degree of freedom
$u_{measstd}$	0.000482183	8

Calibrated value	0.748275167
standard uncertainty	0.00039204
k factor	2.254866004
Extended uncertainty	0.000883998

Effective degree of freedom: 11

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
33-34	0.75090006	0.7499	0.7506	0.7512
33-34	0.750800007	0.7498	0.7504	0.7513
33-34	0.750600107	0.7494	0.7502	0.7519
33-34	0.750800107	0.7491	0.7506	0.7513
33-34	0.750800107	0.7499	0.7504	0.7515
y_j	0.750780077	0.749620323	0.750440087	0.751440444
S_j	0.000109527	0.000356077	0.000167356	0.0002794
(S_j)^2	1.19962E-08	1.26791E-07	2.8008E-08	7.80646E-08
y_j - y	0.000209844	-0.00094991	-0.000130146	0.000870212
(y_j - y)^2	4.40347E-08	9.02329E-07	1.6938E-08	7.57268E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.500
2	0.5013	0.5013	0.501
3	0.5002	0.5002	0.500

Coverage factor (p)	95.45 %		
y	0.750570233		
		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000247417	16	9.36818E-18
u_{geo}	0.000378657	3	4.28293E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	Degree of freedom
$u_{measstd}$	0.000482183	8

Calibrated value	0.749370233
standard uncertainty	0.000334424
k factor	2.195291287
Extended uncertainty	0.000734157

Effective degree of freedom: 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
35	0.750000	0.749900	0.750900	0.748900
35	0.749300	0.750200	0.751100	0.749300
35	0.749400	0.749900	0.751400	0.749200
35	0.749400	0.749600	0.750700	0.749500
35	0.749200	0.750000	0.750800	0.749500
y_j	0.749460072	0.749920168	0.750980185	0.749280125
S_j	0.000313146	0.000216644	0.00027756	0.000249015
(S_j)^2	9.80602E-08	4.69346E-08	7.70395E-08	6.20083E-08
y_j - y	-0.000450066	1.00304E-05	0.001070047	-0.000630012
$(y_j - y)$^2	2.02559E-07	1.00609E-10	1.145E-06	3.96915E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

		Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.749910138		
u_{rep}	0.000266478	16	1.26063E-17
u_{geo}	0.000381289	3	4.40328E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748710138
standard uncertainty	0.000338081
k factor	2.195291287
Extended uncertainty	0.000742185

Effective degree of freedom 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
5-36	0.750300	0.750400	0.749200	0.749900
5-36	0.750900	0.749900	0.749500	0.749700
5-36	0.750900	0.750500	0.749500	0.749700
5-36	0.751001	0.750100	0.749600	0.749500
5-36	0.751100	0.750100	0.749700	0.749500
y_j	0.750840285	0.750200136	0.749500064	0.749660088
S_j	0.000313199	0.000244888	0.000187111	0.000167295
(S_j)^2	9.80938E-08	5.997E-08	3.50107E-08	2.79875E-08
y_j - y	0.000790142	0.000149993	-0.000550079	-0.000390055
$(y_j - y)$^2	6.24324E-07	2.24978E-08	3.02587E-07	1.52143E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

		Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.750050143		
u_{rep}	0.000235086	16	7.63568E-18
u_{geo}	0.000302979	3	1.75552E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748850143
standard uncertainty	0.000312655
k factor	2.181165682
Extended uncertainty	0.000681952

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ige block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	0.749500327	0.7498	0.7488	0.7504
	0.749300107	0.7496	0.7494	0.7499
	0.750000007	0.7508	0.7490	0.7496
	0.749600107	0.7504	0.7490	0.7496
	0.74930006	0.7503	0.7500	0.7497
y_j	0.749540121	0.750180077	0.749240436	0.749840675
S_j	0.000288059	0.000481698	0.000477585	0.000336088
(S_j)^2	8.29782E-08	2.32032E-07	2.28088E-07	1.12955E-07
y_j - y	-0.000160206	0.00047975	-0.000459891	0.000140347
$(y_j$ - y)^2	2.5666E-08	2.3016E-07	2.115E-07	1.96974E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	0.749700327		
u_{rep}	0.000404986	16	6.72509E-17
u_{geo}	0.000201458	3	3.43159E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748500327
standard uncertainty	0.00032665
k factor	2.133028362
Extended uncertainty	0.000696753

Effective degree of freedom 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-13	0.75000096	0.7500	0.7504	0.7503
-13	0.749900427	0.7501	0.7503	0.7503
-13	0.749200667	0.7494	0.7501	0.7506
-13	0.749900327	0.7496	0.7500	0.7502
-13	0.75010024	0.7496	0.7498	0.7500
y_j	0.749820524	0.749740088	0.750120163	0.750280132
S_j	0.000356291	0.00029659	0.000238739	0.000216796
(S_j)^2	1.26943E-07	8.79655E-08	5.69965E-08	4.70006E-08
y_j - y	-0.000169703	-0.000250139	0.000129936	0.000289905
$(y_j$ - y)^2	2.8799E-08	6.25693E-08	1.68833E-08	8.40451E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	0.749990227		
u_{rep}	0.000282359	16	1.58908E-17
u_{geo}	0.000126589	3	5.34983E-18
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748790227
standard uncertainty	0.000289314
k factor	2.195291287
Extended uncertainty	0.000635128

Effective degree of freedom 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3-19	0.7495	0.7503	0.7504	0.7488
3-19	0.74980006	0.7503	0.7502	0.7492
3-19	0.75010024	0.7507	0.7504	0.7494
3-19	0.749900327	0.7500	0.7506	0.7493
3-19	0.749700007	0.7505	0.7507	0.7506
y_j	0.749800127	0.750360008	0.750461169	0.749461053
S_j	0.000223723	0.000260761	0.000194579	0.000676555
(S_j)^2	5.0052E-08	6.79961E-08	3.78608E-08	4.57727E-07
y_j - y	-0.000220462	0.000339419	0.00044058	-0.000559536
$(y_j$ - y)^2	4.86037E-08	1.15205E-07	1.9411E-07	3.13081E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.750020589		
u_{rep}	0.000391674	16	5.88357E-17
u_{geo}	0.000236467	3	6.5139E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748820589
standard uncertainty	0.00032926
k factor	2.133028362
Extended uncertainty	0.00070232

Effective degree of freedom 20

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ige block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
25	0.750700666	0.7498	0.7500	0.7509
25	0.75010054	0.7490	0.7501	0.7504
25	0.749900167	0.7490	0.7504	0.7506
25	0.74980006	0.7496	0.7502	0.7508
25	0.75030054	0.7493	0.7499	0.7506
y_j	0.750160394	0.749340011	0.750120792	0.750660456
S_j	0.000358007	0.000357766	0.000192836	0.000195056
(S_j)^2	1.28169E-07	1.27997E-07	3.71856E-08	3.80467E-08
y_j - y	8.99814E-05	-0.000730402	5.03786E-05	0.000590042
$(y_j$ - y)^2	8.09665E-09	5.33488E-07	2.53801E-09	3.4815E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.750070413		
u_{rep}	0.000287836	16	1.71601E-17
u_{geo}	0.000272683	3	1.15184E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748870413
standard uncertainty	0.000314499
k factor	2.168942996
Extended uncertainty	0.000682131

Effective degree of freedom 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ige block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
31	0.749400007	0.7497	0.7504	0.7505
31	0.749700427	0.7501	0.7499	0.7510
31	0.750000007	0.7502	0.7499	0.7503
31	0.750300007	0.7500	0.7502	0.7507
31	0.749700107	0.7503	0.7504	0.7507
y_j	0.749820111	0.750060048	0.750160237	0.750640152
S_j	0.000342007	0.000230189	0.000251192	0.000260679
(S_j)^2	1.16969E-07	5.29868E-08	6.30974E-08	6.79535E-08
y_j - y	-0.000350026	-0.000110089	-9.89973E-06	0.000470015
$(y_j$ - y)^2	1.22518E-07	1.21196E-08	9.80046E-11	2.20914E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p): 95.45 %

y: 0.750170137

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.00027432	16	1.4157E-17
u_{geo}	0.000172155	3	1.82996E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748970137
standard uncertainty	0.000293617
k factor	2.181165682
Extended uncertainty	0.000640426

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ige block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2	0.750200107	0.7493	0.7495	0.7496
2	0.7503	0.7495	0.7502	0.7499
2	0.75	0.7499	0.7499	0.7500
2	0.750200027	0.7491	0.7496	0.7496
2	0.749800007	0.7497	0.7499	0.7495
y_j	0.750100028	0.749500147	0.749820177	0.749720156
S_j	0.000200014	0.000316128	0.000277579	0.000216807
(S_j)^2	4.00057E-08	9.99366E-08	7.70501E-08	4.70052E-08
y_j - y	0.000314901	-0.00028498	3.50503E-05	-6.4971E-05
$(y_j$ - y)^2	9.91626E-08	8.12137E-08	1.22852E-09	4.22123E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p): 95.45 %

y: 0.749785127

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000256904	16	1.08898E-17
u_{geo}	0.000124441	3	4.99585E-18
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748585127
standard uncertainty	0.000284293
k factor	2.211800697
Extended uncertainty	0.000628798

Effective degree of freedom: 13

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
18	0.749300027	0.7505	0.7499	0.7499
18	0.749600007	0.7505	0.7495	0.7500
18	0.749300027	0.7508	0.7496	0.7494
18	0.749400007	0.7508	0.7498	0.7497
18	0.74920006	0.7505	0.7497	0.7496
y_j	0.749360025	0.750620145	0.74970082	0.749720666
S_j	0.000151639	0.000164245	0.000158003	0.000238732
(S_j)^2	2.29945E-08	2.69764E-08	2.4965E-08	5.6993E-08
y_j - y	-0.000490389	0.000769731	-0.000149594	-0.000129749
$(y_j$ - y)^2	2.40481E-07	5.92486E-07	2.23783E-08	1.68347E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p): 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	0.749850414		
u_{rep}	0.00018161	16	2.71957E-18
u_{geo}	0.000269595	3	1.10055E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748650414
standard uncertainty	0.00029752
k factor	2.211800697
Extended uncertainty	0.000658054

Effective degree of freedom: 13

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
24	0.7500015	0.7508	0.7509	0.7499
24	0.750200007	0.7505	0.7503	0.7498
24	0.75020024	0.7499	0.7503	0.7501
24	0.749800107	0.7500	0.7502	0.7500
24	0.749900107	0.7498	0.7505	0.7507
y_j	0.750020392	0.750200131	0.750440498	0.75010046
S_j	0.000178856	0.000430087	0.000279142	0.000353508
(S_j)^2	3.19894E-08	1.84975E-07	7.79205E-08	1.24968E-07
y_j - y	-0.000169978	9.76039E-06	0.000250128	-8.99103E-05
$(y_j$ - y)^2	2.88926E-08	9.52653E-11	6.25641E-08	8.08386E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p): 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	0.75019037		
u_{rep}	0.00032398	16	2.75432E-17
u_{geo}	9.11207E-05	3	1.43624E-18
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748990370
standard uncertainty	0.000294651
k factor	2.181165682
Extended uncertainty	0.000642683

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
30	0.749800027	0.7498	0.7496	0.7505
30	0.749600167	0.7499	0.7501	0.7503
30	0.75020006	0.7504	0.7497	0.7504
30	0.750300107	0.7502	0.7500	0.7498
30	0.750600167	0.7508	0.7500	0.7494
y_j	0.750100105	0.750220101	0.749880233	0.750080077
S_j	0.000400012	0.000402493	0.000216862	0.000465815
(S_j)^2	1.6001E-07	1.62001E-07	4.7029E-08	2.16983E-07
y_j - y	2.9976E-05	0.000149972	-0.000189896	9.94801E-06
$(y_j$ - y)^2	8.9856E-10	2.24916E-08	3.60605E-08	9.89628E-11

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p)	95.45 %		
y	0.750070129		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000382761	16	5.36598E-17
u_{geo}	7.04448E-05	3	5.13043E-19
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	Degree of freedom
$u_{measstd}$	0.000482183	8

Calibrated value	0.748870129
standard uncertainty	0.000307071
k factor	2.158263401
Extended uncertainty	0.000662741

Effective degree of freedom: 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
36	0.750500167	0.7493	0.7500	0.7499
36	0.749900327	0.7494	0.7497	0.7499
36	0.749800167	0.7494	0.7502	0.7498
36	0.74950024	0.7495	0.7497	0.7504
36	0.74960054	0.7493	0.7496	0.7505
y_j	0.749860288	0.749380185	0.749840235	0.750100085
S_j	0.000391077	8.39469E-05	0.000250972	0.000324012
(S_j)^2	1.52941E-07	7.04709E-09	6.29872E-08	1.04984E-07
y_j - y	6.50897E-05	-0.000415013	4.50363E-05	0.000304887
$(y_j$ - y)^2	4.23667E-09	1.72236E-07	2.02827E-09	9.2956E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p)	95.45 %		
y	0.749795198		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000286339	16	1.68059E-17
u_{geo}	0.000150404	3	1.0661E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	Degree of freedom
$u_{measstd}$	0.000482183	8

Calibrated value	0.748595198
standard uncertainty	0.000292924
k factor	2.181165682
Extended uncertainty	0.000638915

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-8	1.060165218	1.0597	1.0593	1.0609
-8	1.060023797	1.0592	1.0590	1.0610
-8	1.059741124	1.0602	1.0589	1.0605
-8	1.059811653	1.0600	1.0588	1.0608
-8	1.060165218	1.0600	1.0594	1.0607
y_j	1.059981402	1.05982581	1.059076354	1.060787824
S_j	0.000197435	0.000372147	0.000257964	0.000183129
(S_j)^2	3.89806E-08	1.38493E-07	6.65452E-08	3.35361E-08
y_j - y	6.35548E-05	-9.20375E-05	-0.000841494	0.000869976
$(y_j$ - y)^2	4.03921E-09	8.4709E-09	7.08112E-07	7.56859E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	1.059917847		
u_{rep}	0.000263418	16	1.2037E-17
u_{geo}	0.000350889	3	3.1582E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	1.058717847
standard uncertainty	0.000329256
k factor	2.181165682
Extended uncertainty	0.000718162

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-15	1.060660172	1.0621	1.0600	1.0599
-15	1.05967026	1.0621	1.0604	1.0595
-15	1.060306677	1.0619	1.0602	1.0597
-15	1.060448155	1.0622	1.0601	1.0596
-15	1.060306621	1.0621	1.0607	1.0595
y_j	1.060278377	1.062074415	1.060264204	1.059629017
S_j	0.000369458	0.000132244	0.00030249	0.000162884
(S_j)^2	1.36499E-07	1.74885E-08	9.15003E-08	2.65313E-08
y_j - y	-0.000283126	0.001512911	-0.000297299	-0.000932487
$(y_j$ - y)^2	8.01604E-08	2.2889E-06	8.83866E-08	8.69531E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	1.060561503		
u_{rep}	0.000260777	16	1.15616E-17
u_{geo}	0.000526544	3	1.60139E-15
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	1.059361503
standard uncertainty	0.000382967
k factor	2.283681613
Extended uncertainty	0.000874576

Effective degree of freedom: 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
15-22	1.060801631	1.0591	1.0613	1.0612
15-22	1.061862369	1.0597	1.0613	1.0617
15-22	1.061650159	1.0594	1.0612	1.0615
15-22	1.06143801	1.0585	1.0617	1.0617
15-22	1.061013841	1.0592	1.0612	1.0619
y_j	1.061353202	1.059175295	1.061339	1.061565362
S_j	0.000439893	0.000447232	0.000221359	0.000261808
$(S_j)^2$	1.93506E-07	2.00016E-07	4.89997E-08	6.85434E-08
y_j - y	0.000494987	-0.001682919	0.000480785	0.000707147
$(y_j - y)^2$	2.45012E-07	2.83222E-06	2.31154E-07	5.00057E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.500
2	0.5013	0.5013	0.501
3	0.5002	0.5002	0.500

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	1.060858215		
u_{rep}	0.000357444	16	4.08106E-17
u_{geo}	0.000563356	3	2.09841E-15
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	1.059658215
standard uncertainty	0.000410666
k factor	2.283681613
Extended uncertainty	0.000937831

Effective degree of freedom 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
22-29	1.059882357	1.0627	1.0612	1.0591
22-29	1.05952881	1.0626	1.0614	1.0590
22-29	1.05938738	1.0626	1.0616	1.0592
22-29	1.05938738	1.0630	1.0608	1.0592
22-29	1.059811729	1.0626	1.0614	1.0595
y_j	1.059599531	1.062696861	1.061282474	1.059203572
S_j	0.00023454	0.000176222	0.000297467	0.000209743
$(S_j)^2$	5.5009E-08	3.10541E-08	8.84865E-08	4.39922E-08
y_j - y	-0.001096079	0.002001252	0.000586864	-0.001492038
$(y_j - y)^2$	1.20139E-06	4.00501E-06	3.4441E-07	2.22618E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.500
2	0.5013	0.5013	0.501
3	0.5002	0.5002	0.500

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	1.06069561		
u_{rep}	0.000233742	16	7.46258E-18
u_{geo}	0.000805035	3	8.75021E-15
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	1.059495610
standard uncertainty	0.000486517
k factor	2.516528348
Extended uncertainty	0.001224333

Effective degree of freedom 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
29-36	1.061155149	1.0600	1.0605	1.0614
29-36	1.061013841	1.0597	1.0604	1.0611
29-36	1.061155149	1.0598	1.0608	1.0613
29-36	1.061013916	1.0591	1.0608	1.0609
29-36	1.06101401	1.0597	1.0601	1.0608
y_j	1.061070413	1.059656194	1.060518975	1.061098588
S_j	7.7353E-05	0.000340469	0.000300126	0.000236643
(S_j)^2	5.98349E-09	1.15919E-07	9.00753E-08	5.59999E-08
y_j - y	0.000484371	-0.000929848	-6.70676E-05	0.000512545
$(y_j$ - y)^2	2.34615E-07	8.64618E-07	4.49806E-09	2.62703E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

		Degree of freedom (v_e)	u_e^4 / v_e
y	1.060586042		
u_{rep}	0.000258833	16	1.12206E-17
u_{geo}	0.000337446	3	2.7013E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
L_{meassd}	0.5008	
u_{meassd}	0.000482183	8

Calibrated value	1.059386042
standard uncertainty	0.000324988
k factor	2.181165682
Extended uncertainty	0.000708853

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-11	1.060306809	1.0614	1.0604	1.0604
6-11	1.060589652	1.0609	1.0609	1.0607
6-11	1.060377669	1.0607	1.0612	1.0612
6-11	1.061084775	1.0608	1.0611	1.0604
6-11	1.060307149	1.0609	1.0609	1.0607
y_j	1.060533211	1.060943094	1.060900727	1.06070274
S_j	0.00032938	0.00028279	0.000294154	0.00028975
(S_j)^2	1.08491E-07	7.99702E-08	8.65266E-08	8.39552E-08
y_j - y	-0.000236732	0.000173151	0.000130784	-6.72028E-05
$(y_j$ - y)^2	5.60421E-08	2.99812E-08	1.71045E-08	4.51622E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

		Degree of freedom (v_e)	u_e^4 / v_e
y	1.060769943		
u_{rep}	0.000299559	16	2.01313E-17
u_{geo}	9.47118E-05	3	1.67639E-18
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
L_{meassd}	0.5008	
u_{meassd}	0.000482183	8

Calibrated value	1.059569943
standard uncertainty	0.000289725
k factor	2.195291287
Extended uncertainty	0.000636031

Effective degree of freedom 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
ı6	1.060023967	1.0607	1.0600	1.0592
ı6	1.060589652	1.0615	1.0596	1.0590
ı6	1.060094571	1.0619	1.0592	1.0588
ı6	1.059740935	1.0616	1.0592	1.0596
ı6	1.059528886	1.0611	1.0594	1.0587
y_j	1.059995602	1.061339777	1.05947233	1.059062372
S_j	0.000401925	0.00047041	0.000313907	0.000366063
(S_j)^2	1.61543E-07	2.21285E-07	9.85374E-08	1.34002E-07
y_j - y	2.80821E-05	0.001372257	-0.000495191	-0.000905149
$(y_j$ - y)^2	7.88602E-10	1.88309E-06	2.45214E-07	8.19294E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

		Degree of freedom (ν_e)	u_e^4 / ν_e
y	1.05996752		
u_{rep}	0.000392227	16	5.91685E-17
u_{geo}	0.00049568	3	1.25767E-15
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	1.058767520
standard uncertainty	0.000394898
k factor	2.211800697
Extended uncertainty	0.000873435

Effective degree of freedom 13

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
21	1.061013728	1.0613	1.0626	1.0617
21	1.060094486	1.0605	1.0623	1.0623
21	1.06030664	1.0604	1.0624	1.0619
21	1.060801744	1.0604	1.0621	1.0615
21	1.060872325	1.0612	1.0621	1.0622
y_j	1.060617784	1.060773528	1.062300676	1.061918927
S_j	0.000395618	0.000449114	0.000220236	0.000329384
(S_j)^2	1.56514E-07	2.01704E-07	4.85039E-08	1.08494E-07
y_j - y	-0.000784944	-0.0006292	0.000897947	0.000516198
$(y_j$ - y)^2	6.16138E-07	3.95893E-07	8.06308E-07	2.6646E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

		Degree of freedom (ν_e)	u_e^4 / ν_e
y	1.061402729		
u_{rep}	0.000358892	16	4.1476E-17
u_{geo}	0.000416813	3	6.28818E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	1.060202729
standard uncertainty	0.000364616
k factor	2.181165682
Extended uncertainty	0.000795289

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-26	1.060660257	1.0591	1.0587	1.0607
1-26	1.061225895	1.0601	1.0595	1.0603
1-26	1.061084587	1.0600	1.0595	1.0607
1-26	1.060872702	1.0597	1.0592	1.0612
1-26	1.06129657	1.0595	1.0602	1.0607
y_j	1.061028002	1.05969856	1.059429814	1.060730941
S_j	0.000261652	0.000401842	0.000537585	0.00029998
(S_j)^2	6.84618E-08	1.61477E-07	2.88997E-07	8.9988E-08
y_j - y	0.000806173	-0.000523269	-0.000792015	0.000509112
$(y_j$ - y)^2	6.49914E-07	2.73811E-07	6.27288E-07	2.59195E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	1.060221829		
u_{rep}	0.000390168	16	5.79357E-17
u_{geo}	0.000388395	3	4.74082E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{meas std}$	0.5008	
$u_{meas std}$	0.000482183	8

Calibrated value	1.059021829
standard uncertainty	0.000363194
k factor	2.158263401
Extended uncertainty	0.000783868

Effective degree of freedom 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-31	1.060448	1.061650	1.062075	1.060872
6-31	1.060872	1.060731	1.061226	1.061156
6-31	1.060802	1.061297	1.061297	1.061084
6-31	1.060731	1.061438	1.062145	1.060731
6-31	1.060660	1.061509	1.061650	1.061085
y_j	1.060702766	1.061325138	1.061678501	1.06098567
S_j	0.000162824	0.000355703	0.000426046	0.000177536
(S_j)^2	2.65117E-08	1.26525E-07	1.81515E-07	3.15189E-08
y_j - y	-0.000470253	0.000152119	0.000505482	-0.000187348
$(y_j$ - y)^2	2.21138E-07	2.31403E-08	2.55512E-07	3.50994E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	1.061173019		
u_{rep}	0.000302519	16	2.09387E-17
u_{geo}	0.000211126	3	4.13928E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{meas std}$	0.5008	
$u_{meas std}$	0.000482183	8

Calibrated value	1.059973019
standard uncertainty	0.000305284
k factor	2.168942996
Extended uncertainty	0.000662143

Effective degree of freedom 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
15-16	0.751000	0.749001	0.751800	0.750700
15-16	0.751000	0.749400	0.751500	0.750501
15-16	0.750900	0.749400	0.752000	0.751300
15-16	0.750600	0.748700	0.751600	0.750900
15-16	0.750901	0.749300	0.751900	0.751700
y_j	0.750880429	0.749160403	0.751760045	0.75102028
S_j	0.000164253	0.000304868	0.000207357	0.00048136
$(S_j)^2$	2.6979E-08	9.29442E-08	4.29969E-08	2.31708E-07
$y_j - y$	0.00017514	-0.001544886	0.001054756	0.000314991
$(y_j - y)^2$	3.06739E-08	2.38667E-06	1.11251E-06	9.9219E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.750705289		
u_{rep}	0.000314097	16	2.4333E-17
u_{geo}	0.00054993	3	1.90541E-15
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.749505289
standard uncertainty	0.000398859
k factor	2.283681613
Extended uncertainty	0.000910866

Effective degree of freedom: 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
15-21	0.749500	0.750100	0.751500	0.749800
15-21	0.749601	0.749900	0.751200	0.750300
15-21	0.749401	0.749400	0.751100	0.750300
15-21	0.749701	0.749401	0.751500	0.749900
15-21	0.749001	0.750100	0.750600	0.750600
y_j	0.749440789	0.749780215	0.751180222	0.750180039
S_j	0.000270271	0.000356329	0.000370067	0.000327115
$(S_j)^2$	7.30463E-08	1.26971E-07	1.3695E-07	1.07004E-07
$y_j - y$	-0.000704528	-0.000365101	0.001034906	3.47226E-05
$(y_j - y)^2$	4.96359E-07	1.33299E-07	1.07103E-06	1.20566E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
y	0.750145316		
u_{rep}	0.000333156	16	3.07985E-17
u_{geo}	0.000376596	3	4.19046E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748945316
standard uncertainty	0.000348433
k factor	2.168942996
Extended uncertainty	0.000755732

Effective degree of freedom: 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
30	0.749800	0.749600	0.751000	0.750700
30	0.749900	0.749600	0.750500	0.750000
30	0.749900	0.749200	0.751200	0.750000
30	0.750100	0.749400	0.751100	0.750100
30	0.749900	0.749600	0.750800	0.749800
y_j	0.749920048	0.749480036	0.750920138	0.75012016
S_j	0.000109559	0.000178912	0.000277587	0.000342085
$(S_j)^2$	1.20033E-08	3.20095E-08	7.70543E-08	1.17022E-07
y_j - y	-0.000190048	-0.00063006	0.000810043	1.00643E-05
$(y_j$ - y$)^2$	3.61181E-08	3.96975E-07	6.56169E-07	1.01291E-10

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	0.750110096		
u_{rep}	0.000243972	16	8.85727E-18
u_{geo}	0.000301298	3	1.71689E-16
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748910096
standard uncertainty	0.000313609
k factor	2.181165682
Extended uncertainty	0.000684033

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.75	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	0.75	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
9-35	0.750800	0.749700	0.749901	0.750700
9-35	0.750200	0.749500	0.749600	0.750900
9-35	0.750500	0.749601	0.750401	0.750401
9-35	0.750900	0.750002	0.749801	0.750100
9-35	0.750500	0.749600	0.749700	0.750600
y_j	0.750580069	0.749680684	0.74972058	0.75054034
S_j	0.000277469	0.000193149	0.000130422	0.00030484
$(S_j)^2$	7.69891E-08	3.73066E-08	1.70098E-08	9.29273E-08
y_j - y	0.000449651	-0.000449734	-0.000409838	0.000409921
$(y_j$ - y$)^2$	2.02186E-07	2.02261E-07	1.67967E-07	1.68036E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	0.750130418		
u_{rep}	0.000236766	16	7.85631E-18
u_{geo}	0.000248403	3	7.93209E-17
E_L	0.0012		
u_{corr}	0.000252488	9	4.51562E-16
u_{temp}	9.95739E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.748930418
standard uncertainty	0.000300647
k factor	2.181165682
Extended uncertainty	0.000655761

Effective degree of freedom: 15

Appendix (6)

Stitching 5x

Horizontal1

	1	2	3	4	5
L	0.004001	0.004001	0.004001	0.004001	0.004001
σ1	0.259403	0.241083	0.744631	0.407013	0.607471
σ2	0.000171	0.000233	0.000231	0.00029	0.000195
σ3	0.046811	0.046812	0.046812	0.046812	0.046807
σ4	0.004681	0.004681	0.004681	0.004681	0.004681
σ_{total}	0.263634	0.24563	0.746116	0.409723	0.60929

Vertical1

	1	2	3	4	5
L	0.004001	0.004001	0.004	0.004002	0.004
σ1	0.239937	0.42981	0.506968	0.455065	0.166409
σ2	0.00023	0.000215	0.000278	0.000379	0.000324
σ3	0.046814	0.046808	0.046802	0.046821	0.046806
σ4	0.004681	0.004681	0.00468	0.004682	0.004681
σ_{total}	0.244506	0.432377	0.509145	0.457491	0.17293

Diagonal1

	1	2	3	4	5
L	0.005657	0.005657	0.005658	0.005657	0.005658
σ1	0.410882	0.655984	0.439901	0.987645	0.755075
σ2	0.000253	0.0003	0.000287	0.000279	0.000393
σ3	0.066187	0.066187	0.066199	0.066187	0.066199
σ4	0.006619	0.006619	0.00662	0.006619	0.00662
σ_{total}	0.416232	0.659348	0.444903	0.989883	0.758

σ1= standard deviation /sqrt(3)
σ2= standard uncertainty calibration of each length
σ3= (L*11.7*1) L=m /σ_{steel}=11.7 /ΔT=(21-20 C˚)
σ4= (L*10%*11.7*1)
L= calibrated value of length

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	-3.15437	-3.51956	-1.57083	-1.80401	-5.98387
Difference2	-2.89464	-4.54167	-4.59927	-3.04527	-5.66216
Difference3	-3.95069	-4.06373	-3.86407	-3.46429	-8.03755
Mean	-3.33324	-4.04165	-3.34472	-2.77119	-6.56119
SD	0.449299	0.417568	1.289739	0.704967	1.052171
SD/sqrt(3)	0.259403	0.241083	0.744631	0.407013	0.607471
	0.259403	0.241083	0.744631	0.407013	0.607471

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	-0.95031	-1.42211	-5.44237	-6.36042	-4.93567
Difference2	-1.80169	-2.15855	-4.06126	-6.36042	-4.93567
Difference3	-0.89272	-0.34562	-3.32384	-4.68841	-4.32424
Mean	-1.21491	-1.30876	-4.27583	-5.80308	-4.73186
SD	0.415583	0.744453	0.878094	0.788195	0.288229
SD/sqrt(3)	0.239937	0.42981	0.506968	0.455065	0.166409

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	-6.162	-9.30429	-9.62691	-4.59953	-12.5902
Difference2	-4.42106	-6.65048	-7.97987	-8.34161	-11.7672
Difference3	-5.21424	-7.25127	-8.04321	-8.10339	-9.49748
Mean	-5.26577	-7.73535	-8.55	-7.01484	-11.285
SD	0.711669	1.136198	0.76193	1.710652	1.307828
SD/sqrt(3)	0.410882	0.655984	0.439901	0.987645	0.755075

NOStitching 5x

Horizontal1

	1	2	3	4	5
L	0.004001	0.004001	0.004001	0.004001	0.004001
σ1	0.83557	0.344805	0.193671	0.098142	0.462276
σ2	0.000171	0.000233	0.000231	0.00029	0.000195
σ3	0.046811	0.046812	0.046812	0.046812	0.046807
σ4	0.004681	0.004681	0.004681	0.004681	0.004681
σ_{total}	0.836893	0.348	0.199304	0.108836	0.464663

Vertical1

	1	2	3	4	5
L	0.004001	0.004001	0.004	0.004002	0.004
σ1	0.228039	0.174396	0.343423	0.508731	0.624497
σ2	0.00023	0.000215	0.000278	0.000379	0.000324
σ3	0.046814	0.046808	0.046802	0.046821	0.046806
σ4	0.004681	0.004681	0.00468	0.004682	0.004681
σ_{total}	0.232842	0.180629	0.346629	0.510902	0.626266

Diagonal1

	1	2	3	4	5
L	0.005657	0.005657	0.005658	0.005657	0.005658
σ1	0.540908	0.814386	0.438778	0.194281	0.935505
σ2	0.000253	0.0003	0.000287	0.000279	0.000393
σ3	0.066187	0.066187	0.066199	0.066187	0.066199
σ4	0.006619	0.006619	0.00662	0.006619	0.00662
σ_{total}	0.544983	0.817098	0.443793	0.205353	0.937868

σ1= standard deviation /sqrt(3)
σ2= standard uncertainty calibration of each length
σ3= (L*11.7*1) L=m /σ_{steel}=11.7 /ΔT=(21-20 C˚)
σ4= (L*10%*11.7*1)
L= uncertainty calculation of length

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	0.707757	3.525121	6.968984	8.922901	12.39222
Difference2	-2.60765	2.632385	6.209487	9.293297	10.89709
Difference3	0.136999	4.082393	6.860786	8.943369	10.5454
Mean	-0.58763	3.4133	6.679753	9.053189	11.27824
SD	1.44725	0.597221	0.335449	0.169987	0.800685
SD/sqrt(3)	0.83557	0.344805	0.193671	0.098142	0.462276

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	2.605533	1.670291	2.731725	5.098249	6.197867
Difference2	1.942447	2.248775	1.449322	3.139674	3.555312
Difference3	2.884123	2.35904	2.689491	3.333544	4.710372
Mean	2.477368	2.092702	2.290179	3.857156	4.821183
SD	0.394975	0.302063	0.594826	0.881148	1.08166
SD/sqrt(3)	0.228039	0.174396	0.343423	0.508731	0.624497

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	-0.74527	2.654456	3.965443	5.743857	9.401351
Difference2	-1.24455	0.030823	2.220218	6.350174	6.687872
Difference3	0.94491	3.289676	3.653851	6.530591	10.55311
Mean	-0.3483	1.991652	3.279837	6.208207	8.880778
SD	0.936881	1.410559	0.759986	0.336505	1.620343
SD/sqrt(3)	0.540908	0.814386	0.438778	0.194281	0.935505

Stitching 10x

Horizontal1	1	2	3	4	5
L	0.004001	0.004001	0.004001	0.004001	0.004001
σ1	0.50355	0.47857	0.516405	0.345264	0.5838
σ2	0.000171	0.000233	0.000231	0.00029	0.000195
σ3	0.046811	0.046812	0.046812	0.046812	0.046807
σ4	0.004681	0.004681	0.004681	0.004681	0.004681
σtotal	0.505743	0.480877	0.518544	0.348455	0.585692

Vertical1	1	2	3	4	5
L	0.004001	0.004001	0.004	0.004002	0.004
σ1	0.206186	0.294832	0.331344	0.547049	0.411302
σ2	0.00023	0.000215	0.000278	0.000379	0.000324
σ3	0.046814	0.046808	0.046802	0.046821	0.046806
σ4	0.004681	0.004681	0.00468	0.004682	0.004681
σtotal	0.211486	0.298561	0.334665	0.549069	0.413983

Diagonal1	1	2	3	4	5
L	0.005657	0.005657	0.005658	0.005657	0.005658
σ1	0.168829	0.431065	0.115921	0.218326	0.3029
σ2	0.000253	0.0003	0.000287	0.000279	0.000393
σ3	0.066187	0.066187	0.066199	0.066187	0.066199
σ4	0.006619	0.006619	0.00662	0.006619	0.00662
σtotal	0.18146	0.436167	0.133656	0.228234	0.31013

σ1= standard deviation /sqrt(3)
σ2= standard uncertainty calibration of each length
σ3= (L*11.7*1) L=m /σ_{steel}=11.7 /ΔT=(21-20 C°)
σ4= (L*10%*11.7*1)
L= calibrated value of length

σ1 calculation (Horizontal1)

	L1	L2	L3	L4	L5
Difference1	-2.94076	-2.83245	-1.78305	-2.27474	-4.88644
Difference2	-1.55076	-3.08245	-2.82305	-2.71474	-3.18644
Difference3	-0.84076	-1.21245	-0.63305	-1.28474	-2.47644
Mean	-1.77743	-2.37579	-1.74639	-2.09141	-3.51644
SD	0.872175	0.828908	0.89444	0.598015	1.011171
SD/sqrt(3)	0.50355	0.47857	0.516405	0.345264	0.5838
	0.50355	0.47857	0.516405	0.345264	0.5838

σ1 calculation (Vertical1)

	L1	L2	L3	L4	L5
Difference1	-0.08987	-0.83051	-1.95735	-0.4797	-2.60245
Difference2	-0.7807	-0.09655	-2.9573	-2.21317	-3.7341
Difference3	-0.90002	-1.34073	-3.31302	-2.68298	-4.31862
Mean	-0.5902	-0.75593	-2.74256	-1.79195	-3.55173
SD	0.357125	0.510663	0.573904	0.947517	0.712396
SD/sqrt(3)	0.206186	0.294832	0.331344	0.547049	0.411302

σ1 calculation (Diagonal1)

	L1	L2	L3	L4	L5
Difference1	-5.29944	-4.27425	-6.5325	-6.583	-7.7869
Difference2	-4.79359	-5.74334	-7.0154	-7.43992	-8.5743
Difference3	-4.60733	-4.06547	-6.85468	-6.70687	-9.0602
Mean	-4.90012	-4.69435	-6.80086	-6.90993	-8.47389
SD	0.29242	0.746626	0.200781	0.378152	0.524656
SD/sqrt(3)	0.168829	0.431065	0.115921	0.218326	0.30291

NOStitching 10x

Horizontal1	1	2	3	4	5
L	0.004001	0.004001	0.004001	0.004001	0.004001
σ1	0.427404	0.244146	0.030307	0.253903	0.194727
σ2	0.000171	0.000233	0.000231	0.00029	0.000195
σ3	0.046811	0.046812	0.046812	0.046812	0.046807
σ4	0.004681	0.004681	0.004681	0.004681	0.004681
σtotal	0.429985	0.248638	0.055963	0.258225	0.200328

Vertical1	1	2	3	4	5
L	0.004001	0.004001	0.004	0.004002	0.004
σ1	0.19112	0.525027	0.452473	0.244452	0.599434
σ2	0.00023	0.000215	0.000278	0.000379	0.000324
σ3	0.046814	0.046808	0.046802	0.046821	0.046806
σ4	0.004681	0.004681	0.00468	0.004682	0.004681
σtotal	0.196826	0.52713	0.454911	0.248939	0.601277

Diagonal1	1	2	3	4	5
L	0.005657	0.005657	0.005658	0.005657	0.00565
σ1	0.244163	0.647634	0.365096	0.847454	1.17560
σ2	0.000253	0.0003	0.000287	0.000279	0.00039
σ3	0.066187	0.066187	0.066199	0.066187	0.066199
σ4	0.006619	0.006619	0.00662	0.006619	0.00662
σtotal	0.253062	0.651041	0.371108	0.85006	1.177486

σ1= standard deviation /sqrt(3)
σ2= standard uncertainty calibration of each length
σ3= (L*11.7*1) L=m /σ_{steel}=11.7 /ΔT=(21-20 C°)
σ4= (L*10%*11.7*1)
L= uncertainty calculation of length

σ1 calculation (Horizontal1)

	L1	L2	L3	L4	L5
Difference1	1.229237	2.897545	6.296948	8.405256	11.02356
Difference2	-0.57076	2.477545	6.196948	9.215256	11.75356
Difference3	0.519237	3.507545	6.316948	9.425256	11.05356
Mean	0.39257	2.960878	6.270281	9.015256	11.2769
SD	0.740285	0.422874	0.052493	0.439773	0.337277
SD/sqrt(3)	0.427404	0.244146	0.030307	0.253903	0.194727

σ1 calculation (Vertical1)

	L1	L2	L3	L4	L5
Difference1	2.321336	2.896817	3.270479	3.627024	5.730658
Difference2	1.598583	0.893792	1.35126	2.911863	3.195342
Difference3	2.278292	2.739248	2.274377	3.919922	4.289875
Mean	2.06607	2.176619	2.298705	3.48627	4.405292
SD	0.33103	0.909374	0.783707	0.423403	1.038251
SD/sqrt(3)	0.19112	0.525027	0.452473	0.244452	0.599434

σ1 calculation (Diagonal1)

	L1	L2	L3	L4	L5
Difference1	-0.86155	2.257287	3.578085	7.487302	9.73071
Difference2	-1.54638	1.142401	2.467661	6.084607	6.62662
Difference3	-0.53086	3.874718	3.958129	9.652962	11.5596
Mean	-0.97959	2.424802	3.334625	7.741624	9.305668
SD	0.422903	1.121735	0.632365	1.467833	2.036208
SD/sqrt(3)	0.244163	0.647634	0.365096	0.847454	1.175605

Appendix (7)

5x

Horizontal	1	2	3
L	0.000753	0.001502	0.002253
σ1	0.94767	0.993733	0.452262
σ2	0.000346	0.00035	0.000293
σ3	0.008812	0.017577	0.026364
σ4	0.000881	0.001758	0.002636
σ_{total}	0.947711	0.99389	0.453037

Vertical	1	2	3
L	0.000746	0.001497	0.002247
σ1	0.413889	1.306672	3.524275
σ2	0.000327	0.000289	0.000329
σ3	0.008733	0.017517	0.02629
σ4	0.000873	0.001752	0.002629
σ_{total}	0.413982	1.306791	3.524374

Diagonal	1	2	3
L	0.001062	0.002124	0.003189
σ1	0.952082	1.385093	1.130169
σ2	0.000329	0.000383	0.000411
σ3	0.012425	0.024851	0.037311
σ4	0.001243	0.002485	0.003731
σ_{total}	0.952164	1.385318	1.130791

σ1= standard deviation /sqrt(3)
σ2= standard uncertainty calibration of each length
σ3= (L*11.7*1) L=m /σ_{steel}=11.7 /ΔT=(21-20 C˚)
σ4= (L*10%*11.7*1)
L= uncertainty calculation of length

σ1 calculation (Horizontal)	L1	L2	L3
Difference1	-3.35993	-5.78753	-7.15771
Difference2	-5.46054	-3.51615	-6.34042
Difference3	-7.37918	-7.72787	-8.2525
Mean	-5.39988	-5.67718	-7.25021
SD	1.641412	1.721195	0.78334
SD/sqrt(3)	0.94767	0.993733	0.452262

σ1 calculation (Vertical)	L1	L2	L3
Difference1	3.098154	2.685972	7.195268
Difference2	1.887945	0.475506	-7.612
Difference3	1.391165	-2.82212	-2.00715
Mean	2.125755	0.113119	-0.80796
SD	0.716876	2.263222	6.104224
SD/sqrt(3)	0.413889	1.306672	3.524275

σ1 calculation (Diagonal)	L1	L2	L3
Difference1	-2.15457	-2.95827	-9.35158
Difference2	-2.72303	-6.92309	-14.083
Difference3	-5.90216	-8.69696	-11.0437
Mean	-3.59325	-6.19277	-11.4927
SD	1.649055	2.399051	1.95751
SD/sqrt(3)	0.952082	1.385093	1.130169

Appendix (8) – X value

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-2	3.9998395	3.9995	4.0006	4.0003
-2	3.9995633	4.0001	4.0006	4.0001
-2	3.9996315	3.9996	4.0010	3.9996
-2	3.999381	3.9997	4.0004	3.9999
-2	3.9999899	4.0000	4.0010	3.9997
y_j	3.99968104	3.99978194	4.0007463	3.99993284
S_j	0.000238141	0.000247735	0.000279497	0.000264209
(S_j)^2	5.67112E-08	6.13727E-08	7.81186E-08	6.98064E-08
y_j - y	-0.00035449	-0.00025359	0.00071077	-0.00010269
$(y_j$ - y)^2	1.25663E-07	6.43079E-08	5.05194E-07	1.05452E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	4.00003553		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.00025788	16	1.10564E-17
u_{geo}	0.000242506	3	7.20525E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	Degree of freedom
$u_{measstd}$	5E-05	8

Calibrated value	4.000035530
standard uncertainty	0.00016734
k factor	2.319809441
Extended uncertainty	0.000388197

Effective degree of freedom: 9

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ige block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	7.9994186	7.9995286	8.0004	8.0001
	7.9994102	7.9997	8.0004	7.9998
	7.9995236	8.0000	8.0008	7.9997
	7.9993863	7.9992	8.0011	7.9999
	7.9998038	7.9990	8.0008	7.9999
y_j	7.9995085	7.99949486	8.00071012	7.99988506
S_j	0.000173283	0.000412332	0.000284892	0.00015649
(S_j)^2	3.0027E-08	1.70018E-07	8.11633E-08	2.44892E-08
y_j - y	-0.000391135	-0.000404775	0.000810485	-1.4575E-05
$(y_j$ - y)^2	1.52987E-07	1.63843E-07	6.56886E-07	2.12431E-10

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	7.999899635		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000276449	16	1.46017E-17
u_{geo}	0.000284887	3	1.3723E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	Degree of freedom
$u_{measstd}$	5E-05	8

Calibrated value	7.999899635
standard uncertainty	0.000188613
k factor	2.3664195
Extended uncertainty	0.000446338

Effective degree of freedom: 8

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	11.9991632	11.9998016	12.0014	12.0003
	11.9986938	11.9998	12.0014	12.0002
	11.9990304	12.0001	12.0008	11.9998
	11.9995247	12.0000	12.0007	11.9999
	11.9994871	12.0002	12.0009	12.0001
y_j	11.99917984	11.99997624	12.00106228	12.00007384
S_j	0.000343577	0.000189063	0.000349414	0.000195976
(S_j)^2	1.18045E-07	3.5745E-08	1.2209E-07	3.84065E-08
y_j - y	-0.00089321	-9.681E-05	0.00098923	7.9E-07
(y_j - y)^2	7.97824E-07	9.37218E-09	9.78576E-07	6.241E-13

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: 12.00007305

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000280307	16	1.54338E-17
u_{geo}	0.000385765	3	4.61369E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	12.000073050
standard uncertainty	0.000230039
k factor	2.648654254
Extended uncertainty	0.000609294

Effective degree of freedom: 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	15.9994451	15.9991	16.0015	16.0003
	15.9996318	15.9992	16.0015	16.0004
	15.9993634	16.0004	16.0015	16.0004
	15.9993881	15.9991	16.0012	16.0004
	15.9994282	15.9990	16.0014	16.0004
y_j	15.99945132	15.9993637	16.00140426	16.0003848
S_j	0.000105916	0.000594877	0.000100407	6.88192E-05
(S_j)^2	1.12182E-08	3.53879E-07	1.00815E-08	4.73609E-09
y_j - y	-0.0006997	-0.00078732	0.00125324	0.00023378
$(y_j - y)$^2	4.8958E-07	6.19873E-07	1.57061E-06	5.46531E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: 16.00015102

E_{Lprop}: -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000308186	16	2.25524E-17
u_{geo}	0.000477381	3	1.08198E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value: 16.000151020

standard uncertainty: 0.000275625

k factor: 2.648654254

Extended uncertainty: 0.000730035

Effective degree of freedom: 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-6	19.9999926	20.0005	20.0006	20.0001
-6	19.9997619	20.0001	20.0006	19.9999
-6	19.9998882	20.0002	20.0006	20.0003
-6	20.0001115	20.0001	20.0015	19.9999
-6	20.0001676	20.0002	20.0006	19.9994
y_j	19.99998436	20.0002104	20.00077622	19.99994038
S_j	0.000164731	0.000165197	0.000428737	0.000335025
(S_j)^2	2.71361E-08	2.72902E-08	1.83815E-07	1.12242E-07
y_j - y	-0.00024348	-1.744E-05	0.00054838	-0.00028746
$(y_j - y)$^2	5.92825E-08	3.04154E-10	3.00721E-07	8.26333E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p): 95.45 %

y: 20.00022784

E_{Lprop}: -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000296008	16	1.91935E-17
u_{geo}	0.000192124	3	2.83849E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value: 20.000227840

standard uncertainty: 0.000163561

k factor: 2.181165682

Extended uncertainty: 0.000356753

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-32	23.9986056	23.9998	24.0007	23.9996
1-32	23.9988974	23.9998	24.0007	23.9996
1-32	23.9984906	23.9996	24.0009	23.9995
1-32	23.9995371	23.9996	24.0015	24.0003
1-32	23.9996635	23.9993	24.0008	23.9996
y_j	23.99903884	23.9996008	24.00092184	23.99972286
S_j	0.000535428	0.000211381	0.000338788	0.00030323
(S_j)^2	2.86683E-07	4.46819E-08	1.14777E-07	9.19486E-08
y_j - y	-0.000782245	-0.000220285	0.001100755	-9.8225E-05
$(y_j$ - y)^2	6.11907E-07	4.85255E-08	1.21166E-06	9.64815E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	23.99982109		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000366773	16	4.52409E-17
u_{geo}	0.000395995	3	5.12291E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327		
$L_{meas std}$	3.999066667		
$u_{meas std}$	5E-05	Degree of freedom	8

Calibrated value	23.999821085
standard uncertainty	0.000257114
k factor	2.428809082
Extended uncertainty	0.00062448

Effective degree of freedom: 7

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
32-33	3.999373	3.9995	4.0010	3.9997
32-33	3.9989798	4.0001	4.0010	3.9996
32-33	3.9991755	4.0001	4.0007	3.9995
32-33	3.9993756	3.9993	4.0010	3.9995
32-33	3.999338	3.9994	4.0010	3.9998
y_j	3.99924838	3.99968394	4.00092686	3.99961608
S_j	0.000171168	0.000404423	0.000155205	0.000108776
(S_j)^2	2.92984E-08	1.63558E-07	2.40885E-08	1.18322E-08
y_j - y	-0.000620435	-0.000184875	0.001058045	-0.000252735
$(y_j$ - y)^2	3.8494E-07	3.41788E-08	1.11946E-06	6.3875E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	3.999868815		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000239153	16	8.17794E-18
u_{geo}	0.000365428	3	3.71507E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327		
$L_{meas std}$	3.999066667		
$u_{meas std}$	5E-05	Degree of freedom	8

Calibrated value	3.999868815
standard uncertainty	0.000211715
k factor	2.648654254
Extended uncertainty	0.00056076

Effective degree of freedom: 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
h of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
e block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
easurement repetition name	Position 1	Position 2	Position 3	Position 4
	7.9993676	8.0001	8.0007	7.9998
	7.998938	8.0000	8.0007	7.9997
	7.9996097	8.0001	8.0015	7.9998
	7.999576	7.9999	8.0010	7.9998
	7.9993268	7.9997	8.0010	8.0001
y_j	7.99936362	7.99997848	8.0009433	7.99984964
S_j	0.000268414	0.00016176	0.000340727	0.000158669
(S_j)^2	7.20461E-08	2.61663E-08	1.16095E-07	2.51758E-08
y_j - y	-0.00067014	-5.528E-05	0.00090954	-0.00018412
$(y_j$ - y)^2	4.49088E-07	3.05588E-09	8.27263E-07	3.39002E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	8.00003376		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000244685	16	8.9613E-18
u_{geo}	0.000330821	3	2.49533E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327		
$L_{meassstd}$	3.999066667	Degree of freedom	
$u_{meassstd}$	5E-05	8	

Calibrated value	8.000033760
standard uncertainty	0.00019833
k factor	2.648654254
Extended uncertainty	0.000525307

Effective degree of freedom: 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
4-35	12.0001553	12.0008	12.0009	11.9996
4-35	12.0000871	12.0002	12.0009	11.9996
4-35	12.0001253	12.0000	12.0011	11.9994
4-35	12.0002616	12.0006	12.0016	11.9998
4-35	12.0004185	12.0005	12.0012	11.9994
y_j	12.00020956	12.0004053	12.00111394	11.9995699
S_j	0.000133608	0.000307553	0.000294438	0.000163272
(S_j)^2	1.78511E-08	9.45891E-08	8.66935E-08	2.66576E-08
y_j - y	-0.000115115	8.0625E-05	0.000789265	-0.000754775
$(y_j$ - y)^2	1.32515E-08	6.50039E-09	6.22939E-07	5.69685E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	12.00032468		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000237588	16	7.9659E-18
u_{geo}	0.000317854	3	2.12653E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327	
$L_{meassstd}$	3.999066667	Degree of freedom
$u_{meassstd}$	5E-05	8

Calibrated value	12.000324675
standard uncertainty	0.000191174
k factor	2.516528348
Extended uncertainty	0.000481094

Effective degree of freedom: 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
5-36	15.9995483	16.0000	16.0013	16.0003
5-36	15.999489	16.0001	16.0013	16.0000
5-36	15.9996474	16.0000	16.0014	16.0002
5-36	15.9992625	16.0000	16.0010	16.0000
5-36	15.9998919	16.0004	16.0014	15.9997
y_j	15.99956782	16.00009194	16.00128044	16.00005336
S_j	0.000229769	0.000161194	0.000140596	0.000209625
(S_j)^2	5.27937E-08	2.59837E-08	1.97673E-08	4.39425E-08
y_j - y	-0.00068057	-0.00015645	0.00103205	-0.00019503
$(y_j$ - y)^2	4.63176E-07	2.44766E-08	1.06513E-06	3.80367E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 16.00024839

E_{Lprop} -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000188737	16	3.17228E-18
u_{geo}	0.000364099	3	3.66131E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{meas std}$ 3.999066667

$u_{meas std}$ 5E-05 Degree of freedom 8

Calibrated value	16.000248390
standard uncertainty	0.000200665
k factor	2.86931517
Extended uncertainty	0.000575771

Effective degree of freedom 4

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-7	19.9992774	19.9998	20.0010	19.9995
-7	19.9991049	19.9995	20.0010	19.9999
-7	19.9991282	19.9998	20.0006	19.9997
-7	19.999142	19.9997	20.0010	19.9997
-7	19.9993529	19.9999	20.0005	19.9997
y_j	19.99920108	19.9997157	20.00080412	19.99968912
S_j	0.000108313	0.000170638	0.000238785	0.000133036
(S_j)^2	1.17316E-08	2.91173E-08	5.70181E-08	1.76985E-08
y_j - y	-0.000651425	-0.000136805	0.000951615	-0.000163385
$(y_j$ - y)^2	4.24355E-07	1.87156E-08	9.05571E-07	2.66947E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 19.99985251

E_{Lprop} -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000169975	16	2.08678E-18
u_{geo}	0.000338543	3	2.73662E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{meas std}$ 3.999066667

$u_{meas std}$ 5E-05 Degree of freedom 8

Calibrated value	19.999852505
standard uncertainty	0.000185556
k factor	2.86931517
Extended uncertainty	0.000532419

Effective degree of freedom 4

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
ıge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3	23.9992722	23.9997	24.0009	23.9999
3	23.9990763	23.9997	24.0009	23.9997
3	23.9993174	23.9998	24.0007	23.9995
3	23.9997928	24.0000	24.0010	23.9998
3	23.9997547	23.9997	24.0008	24.0004
y_j	23.99944268	23.99979368	24.00087514	23.99986976
S_j	0.000315806	0.00012995	9.4535E-05	0.000350623
(S_j)^2	9.97333E-08	1.68869E-08	8.93687E-09	1.22936E-07
y_j - y	-0.000552635	-0.000201635	0.000879825	-0.000125555
$(y_j$ - y)^2	3.05405E-07	4.06567E-08	7.74092E-07	1.57641E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	23.99999532		
u_{rep}	0.000249246	16	9.64828E-18
u_{geo}	0.000307668	3	1.86677E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	23.999995315
standard uncertainty	0.000189973
k factor	2.516528348
Extended uncertainty	0.000478072

Effective degree of freedom: 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3-19	3.9996275	3.9997	4.0016	3.9998
3-19	3.9998995	3.9999	4.0016	3.9999
3-19	3.9996711	3.9996	4.0009	3.9999
3-19	3.9995995	4.0004	4.0003	3.9996
3-19	3.9998897	4.0003	4.0010	3.9996
y_j	3.99973746	3.99995772	4.0010744	3.99974372
S_j	0.000145741	0.000355693	0.000520235	0.000156658
(S_j)^2	2.12404E-08	1.26518E-07	2.70644E-07	2.45418E-08
y_j - y	-0.000390865	-0.000170605	0.000946075	-0.000384605
$(y_j$ - y)^2	1.52775E-07	2.91061E-08	8.95058E-07	1.47921E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	4.000128325		
u_{rep}	0.00033277	16	3.06562E-17
u_{geo}	0.000319487	3	2.17055E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	4.000128325
standard uncertainty	0.000218323
k factor	2.319809441
Extended uncertainty	0.000506469

Effective degree of freedom: 9

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
25	7.9994407	8.0000	8.0015	8.0005
25	7.9989762	7.9999	8.0015	7.9999
25	7.9992685	8.0000	8.0005	7.9999
25	7.9993773	7.9998	8.0009	7.9999
25	7.9992678	8.0000	8.0007	8.0007
y_j	7.9992661	7.9999521	8.0010182	8.00015848
S_j	0.000178116	7.09823E-05	0.000459444	0.000392135
(S_j)^2	3.17253E-08	5.03848E-09	2.11089E-07	1.5377E-07
y_j - y	-0.00083262	-0.00014662	0.00091948	5.976E-05
$(y_j$ - y)^2	6.93256E-07	2.14974E-08	8.45443E-07	3.57126E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 8.00009872

		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000316868	16	2.52032E-17
u_{geo}	0.00036099	3	3.53786E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop} -0.000258327

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 — Degree of freedom 8

Calibrated value	8.000098720
standard uncertainty	0.000229477
k factor	2.428809082
Extended uncertainty	0.000557355

Effective degree of freedom 7

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
5-31	11.999664	11.9989	12.0001	12.0001
5-31	11.9994354	11.9989	12.0001	12.0001
5-31	11.9992445	11.9995	12.0006	11.9997
5-31	11.9993947	11.9988	12.0008	12.0001
5-31	11.9991429	11.9992	12.0008	12.0002
y_j	11.9993763	11.9990669	12.0004937	12.00002752
S_j	0.000199029	0.000312588	0.000331606	0.000209687
(S_j)^2	3.96124E-08	9.77112E-08	1.09962E-07	4.39686E-08
y_j - y	-0.000364805	-0.000674205	0.000752595	0.000286415
$(y_j$ - y)^2	1.33083E-07	4.54552E-07	5.66399E-07	8.20336E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 11.99974111

		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.00026984	16	1.32546E-17
u_{geo}	0.000320945	3	2.21045E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop} -0.000258327

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 — Degree of freedom 8

Calibrated value	11.999741105
standard uncertainty	0.000200784
k factor	2.516528348
Extended uncertainty	0.000505278

Effective degree of freedom 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-12	15.9996739	16.0004	16.0010	15.9998
-12	15.9992338	16.0001	16.0010	15.9999
-12	15.9993368	15.9997	16.0009	15.9999
-12	15.9993152	16.0000	16.0007	15.9998
-12	16.0002997	16.0002	16.0012	15.9998
y_j	15.99957188	16.0000896	16.00094296	15.99983534
S_j	0.000440334	0.000249247	0.000178982	7.18483E-05
(S_j)^2	1.93894E-07	6.21243E-08	3.20346E-08	5.16217E-09
y_j - y	-0.000538065	-2.0345E-05	0.000833015	-0.000274605
$(y_j$ - y)^2	2.89514E-07	4.13919E-10	6.93914E-07	7.54079E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

Coverage factor (p) 95.45 %

		Degree of freedom (v_e)	u_e^4 / v_e
y	16.00010995		
u_{rep}	0.000270747	16	1.34336E-17
u_{geo}	0.000297104	3	1.62328E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	16.000109945
standard uncertainty	0.000191647
k factor	2.428809082
Extended uncertainty	0.000465473

Effective degree of freedom 7

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2-18	19.999131	20.0001	20.0008	19.9998
2-18	19.9991453	19.9998	20.0008	19.9999
2-18	19.9992045	20.0000	20.0004	19.9997
2-18	19.9992115	19.9999	20.0005	19.9999
2-18	19.9989894	19.9999	20.0006	20.0002
y_j	19.99913634	19.99993246	20.00062026	19.99990218
S_j	8.94357E-05	0.000115599	0.000192203	0.000182542
(S_j)^2	7.99874E-09	1.33632E-08	3.69418E-08	3.33216E-08
y_j - y	-0.00076147	3.465E-05	0.00072245	4.37E-06
$(y_j$ - y)^2	5.79837E-07	1.20062E-09	5.21934E-07	1.90969E-11

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p) 95.45 %

		Degree of freedom (v_e)	u_e^4 / v_e
y	19.99989781		
u_{rep}	0.000151348	16	1.31175E-18
u_{geo}	0.000303176	3	1.76011E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	19.999897810
standard uncertainty	0.000166013
k factor	2.86931517
Extended uncertainty	0.000476343

Effective degree of freedom 4

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3-24	23.9996091	23.9996	24.0006	23.9998
3-24	23.9995351	24.0001	24.0006	24.0007
3-24	23.9993662	24.0004	24.0006	24.0003
3-24	24.0001178	23.9999	24.0015	24.0003
3-24	23.9999698	23.9998	24.0007	23.9999
y_j	23.9997196	23.99994326	24.00081818	24.00019576
S_j	0.000313171	0.000295703	0.000399532	0.000347646
(S_j)^2	9.80763E-08	8.74403E-08	1.59626E-07	1.20858E-07
y_j - y	-0.0004496	-0.00022594	0.00064898	2.656E-05
$(y_j$ - y)^2	2.0214E-07	5.10489E-08	4.21175E-07	7.05434E-10

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	24.0001692		
u_{rep}	0.000341321	16	3.39306E-17
u_{geo}	0.000237183	3	6.59315E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	24.000169200
standard uncertainty	0.000193298
k factor	2.211800697
Extended uncertainty	0.000427536

Effective degree of freedom 13

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
24-30	3.9994548	3.9989	4.0009	4.0003
24-30	3.9989634	3.9996	4.0009	4.0005
24-30	3.9990219	3.9994	4.0008	4.0003
24-30	3.9992444	3.9991	4.0011	4.0005
24-30	3.9992083	3.9992	4.0007	4.0001
y_j	3.99917856	3.99925398	4.00087132	4.00033934
S_j	0.000195169	0.000256459	0.000174837	0.000138889
(S_j)^2	3.8091E-08	6.57714E-08	3.05679E-08	1.92903E-08
y_j - y	-0.00073224	-0.00065682	0.00096052	0.00042854
$(y_j$ - y)^2	5.36175E-07	4.31413E-07	9.22599E-07	1.83647E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	3.9999108		
u_{rep}	0.000196036	16	3.69219E-18
u_{geo}	0.000415716	3	6.2222E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	3.999910800
standard uncertainty	0.00022559
k factor	2.86931517
Extended uncertainty	0.000647289

Effective degree of freedom 4

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
0-36	7.9991549	7.9998	8.0010	7.9994
0-36	7.9994235	7.9994	8.0010	8.0000
0-36	8.0003135	7.9995	8.0009	7.9998
0-36	7.9997145	8.0001	8.0010	7.9994
0-36	7.9993372	7.9997	8.0009	7.9997
y_j	7.99958872	7.99970124	8.00094068	7.99965718
S_j	0.000452738	0.00030623	4.54881E-05	0.000264352
(S_j)^2	2.04972E-07	9.37768E-08	2.06917E-09	6.98818E-08
y_j - y	-0.000383235	-0.000270715	0.000968725	-0.000314775
$(y_j$ - y)^2	1.46869E-07	7.32866E-08	9.38428E-07	9.90833E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 7.999971955

E_{Lprop} -0.000258327

		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000304425	16	2.14716E-17
u_{geo}	0.000323737	3	2.28838E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	7.999971955
standard uncertainty	0.00021151
k factor	2.428809082
Extended uncertainty	0.000513717

Effective degree of freedom 7

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-8	11.9992021	11.9997	12.0008	12.0005
1-8	11.998981	12.0000	12.0008	12.0003
1-8	11.99989013	11.9999	12.0006	12.0006
1-8	11.9994738	12.0000	12.0009	12.0002
1-8	11.9995698	12.0001	12.0006	12.0002
y_j	11.9992256	11.99993102	12.00074648	12.00036548
S_j	0.000293951	0.000140663	0.000132467	0.000188698
(S_j)^2	8.64072E-08	1.97861E-08	1.75476E-08	3.56068E-08
y_j - y	-0.000841545	-0.000136125	0.000679335	0.000298335
$(y_j$ - y)^2	7.08198E-07	1.853E-08	4.61496E-07	8.90038E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 12.00006715

E_{Lprop} -0.000258327

		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000199592	16	3.96745E-18
u_{geo}	0.000326245	3	2.36011E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	12.000067145
standard uncertainty	0.000185947
k factor	2.86931517
Extended uncertainty	0.000533541

Effective degree of freedom 4

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
8-15	15.9995625	15.9993	16.0008	16.0004
8-15	15.9989982	15.9994	16.0008	16.0003
8-15	15.9987856	15.9999	16.0008	16.0002
8-15	15.9996244	15.9994	16.0005	16.0005
8-15	15.9994394	15.9997	16.0002	16.0003
y_j	15.99928202	15.9995291	16.0006136	16.00033648
S_j	0.000370016	0.000253395	0.000237716	0.000129325
(S_j)^2	1.36912E-07	6.42088E-08	5.65091E-08	1.67249E-08
y_j - y	-0.00065828	-0.0004112	0.0006733	0.00039618
$(y_j$ - y)^2	4.33333E-07	1.69085E-07	4.53333E-07	1.56959E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 15.9999403

E_{Lprop} -0.000258327

		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000261894	16	1.1761E-17
u_{geo}	0.000317898	3	2.1277E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	15.999940300
standard uncertainty	0.00019744
k factor	2.516528348
Extended uncertainty	0.000496863

Effective degree of freedom 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
15-22	19.9992067	20.0002	20.0009	20.0003
15-22	19.999152	20.0002	20.0009	20.0001
15-22	19.9992075	20.0004	20.0004	20.0004
15-22	19.9994883	20.0005	20.0014	20.0002
15-22	19.9996162	20.0006	20.0007	20.0004
y_j	19.99933414	20.00037344	20.00085184	20.00029886
S_j	0.000205412	0.000181098	0.000382869	0.000133808
(S_j)^2	4.21942E-08	3.27963E-08	1.46589E-07	1.79045E-08
y_j - y	-0.00088043	0.00015887	0.00063727	8.429E-05
$(y_j$ - y)^2	7.75157E-07	2.52397E-08	4.06113E-07	7.1048E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 20.00021457

E_{Lprop} -0.000258327

		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000244685	16	8.96134E-18
u_{geo}	0.000318017	3	2.13087E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	20.000214570
standard uncertainty	0.000193023
k factor	2.516528348
Extended uncertainty	0.000485748

Effective degree of freedom 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2-29	23.9997215	23.9995	24.0006	23.9996
2-29	23.9998972	24.0000	24.0006	23.9997
2-29	23.9998773	24.0001	24.0009	23.9996
2-29	23.999848	23.9995	24.0009	23.9998
2-29	23.999915	23.9995	24.0006	23.9994
y_j	23.9998518	23.99969412	24.00070468	23.99959166
S_j	7.69711E-05	0.000289136	0.000184008	0.000149358
$(S_j)^2$	5.92455E-09	8.35996E-08	3.3859E-08	2.23079E-08
y_j - y	-0.000108765	-0.000266445	0.000744115	-0.000368905
$(y_j - y)^2$	1.18298E-08	7.09929E-08	5.53707E-07	1.36091E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

Coverage factor (p)	95.45 %		
y	23.99996057		
		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000190847	16	3.31654E-18
u_{geo}	0.000253742	3	8.63633E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327
$L_{meas std}$	3.999066667
$u_{meas std}$	5E-05
Degree of freedom	8

Calibrated value	23.999960565
standard uncertainty	0.000152908
k factor	2.516528348
Extended uncertainty	0.000384797

Effective degree of freedom: 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
9-36	3.998912	3.9991	4.0011	3.9997
9-36	3.9983603	4.0000	4.0011	4.0003
9-36	3.9990022	3.9999	4.0009	3.9996
9-36	3.9982504	3.9997	4.0010	3.9999
9-36	3.9987146	3.9998	4.0014	4.0001
y_j	3.9986479	3.99969758	4.00110004	3.9999215
S_j	0.000331831	0.00037247	0.00017032	0.000295494
$(S_j)^2$	1.10112E-07	1.38734E-07	2.9009E-08	8.73166E-08
y_j - y	-0.001193855	-0.000144175	0.001258285	7.9745E-05
$(y_j - y)^2$	1.42529E-06	2.07864E-08	1.58328E-06	6.35927E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	3.999841755		
		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000302147	16	2.08359E-17
u_{geo}	0.000502968	3	1.33327E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327
$L_{meas std}$	3.999066667
$u_{meas std}$	5E-05
Degree of freedom	8

Calibrated value	3.999841755
standard uncertainty	0.000285487
k factor	2.86931517
Extended uncertainty	0.000819151

Effective degree of freedom: 4

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-11	7.999313	7.9994	8.0004	8.0003
-11	7.999726	7.9995	8.0004	8.0002
-11	7.9995108	7.9993	8.0009	8.0006
-11	7.9995143	7.9994	8.0012	8.0004
-11	7.9994371	7.9992	8.0008	8.0004
y_j	7.99950024	7.99933124	8.00074628	8.00038344
S_j	0.000150268	0.000139301	0.000335077	0.000155708
(S_j)^2	2.25806E-08	1.94046E-08	1.12276E-07	2.4245E-08
y_j - y	-0.00049006	-0.00065906	0.00075598	0.00039314
$(y_j$ - y)^2	2.40159E-07	4.3436E-07	5.71506E-07	1.54559E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 7.9999903

E_{Lprop} -0.000258327

		Degree of freedom (v_e)	$u_e{}^4$ / v_e
u_{rep}	0.00021125	16	4.97884E-18
u_{geo}	0.000341636	3	2.83801E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{meisstd}$	3.999066667	
$u_{meisstd}$	5E-05	8

Calibrated value	7.999990300
standard uncertainty	0.000195203
k factor	2.648654254
Extended uncertainty	0.000517025

Effective degree of freedom 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-16	12.0001744	12.0001	12.0009	11.9998
1-16	11.9998851	12.0002	12.0009	11.9996
1-16	11.9998239	12.0002	12.0009	11.9995
1-16	12.000004	12.0002	12.0006	11.9997
1-16	12.0001392	12.0003	12.0012	11.9995
y_j	12.00000532	12.00019306	12.00090864	11.99961142
S_j	0.000153199	6.6452E-05	0.000180708	0.000137656
(S_j)^2	2.34699E-08	4.41587E-09	3.26554E-08	1.89493E-08
y_j - y	-0.00017429	1.345E-05	0.00072903	-0.00056819
$(y_j$ - y)^2	3.0377E-08	1.80902E-10	5.31485E-07	3.2284E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 12.00017961

E_{Lprop} -0.000258327

		Degree of freedom (v_e)	$u_e{}^4$ / v_e
u_{rep}	0.00014097	16	9.87301E-19
u_{geo}	0.000271551	3	1.13284E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{meisstd}$	3.999066667	
$u_{meisstd}$	5E-05	8

Calibrated value	12.000179610
standard uncertainty	0.000149698
k factor	2.86931517
Extended uncertainty	0.000429532

Effective degree of freedom 4

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{αW}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{αM}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
16-21	15.9994744	15.9994	16.0007	16.0002
16-21	15.9993796	15.9993	16.0007	16.0003
16-21	15.9989969	15.9999	16.0006	16.0004
16-21	15.9989541	15.9997	16.0009	16.0001
16-21	15.9989304	15.9994	16.0004	16.0001
y_j	15.99914708	15.99955614	16.00064384	16.00021552
S_j	0.000258819	0.000238912	0.000185755	0.000118782
(S_j)^2	6.69874E-08	5.70792E-08	3.45049E-08	1.41092E-08
y_j - y	-0.000743565	-0.000334505	0.000753195	0.000324875
$(y_j$ - y)^2	5.52889E-07	1.11894E-07	5.67303E-07	1.05544E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 15.99989065

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_c)	u_c^4 / v_c
u_{rep}	0.000207774	16	4.65916E-18
u_{geo}	0.00033387	3	2.58862E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	15.999890645
standard uncertainty	0.000191053
k factor	2.648654254
Extended uncertainty	0.000506034

Effective degree of freedom 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{αW}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{αM}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
21-26	20.0001619	19.9997	20.0002	20.0002
21-26	20.0001415	20.0004	20.0002	20.0004
21-26	20.0000616	20.0003	20.0010	20.0003
21-26	19.9998442	20.0000	20.0009	20.0008
21-26	19.9998496	19.9999	20.0013	20.0006
y_j	20.00001176	20.0000496	20.0007014	20.0004517
S_j	0.000155105	0.000284617	0.000516053	0.000244847
(S_j)^2	2.40577E-08	8.10066E-08	2.66311E-07	5.99503E-08
y_j - y	-0.000291855	-0.000254015	0.000397785	0.000148085
$(y_j$ - y)^2	8.51793E-08	6.45236E-08	1.58233E-07	2.19292E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 20.00030362

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_c)	u_c^4 / v_c
u_{rep}	0.000328377	16	2.9069E-17
u_{geo}	0.000165797	3	1.57423E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	20.000303615
standard uncertainty	0.000168637
k factor	2.148852324
Extended uncertainty	0.000362376

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-31	23.9987049	23.9991	24.0005	23.9993
6-31	23.9987345	23.9993	24.0005	23.9992
6-31	23.9986436	23.9998	24.0004	23.9994
6-31	23.9990719	23.9990	24.0003	23.9997
6-31	23.999179	23.9991	24.0007	23.9999
y_j	23.99886678	23.99923292	24.00048096	23.99950374
S_j	0.000241386	0.000324726	0.000139915	0.000297956
(S_j)^2	5.8267E-08	1.05447E-07	1.95763E-08	8.87779E-08
y_j - y	-0.00065432	-0.00028818	0.00095986	-1.736E-05
$(y_j$ - y)^2	4.28135E-07	8.30477E-08	9.21331E-07	3.0137E-10

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 23.9995211

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000260801	16	1.15658E-17
u_{geo}	0.000345545	3	2.97014E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05, Degree of freedom 8

Calibrated value	23.999521100
standard uncertainty	0.000208456
k factor	2.516528348
Extended uncertainty	0.000524584

Effective degree of freedom 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	3.9991747	4.0000	4.0011	4.0004
26-31	3.9992224	3.9996	4.0011	4.0003
26-31	3.9996324	4.0002	4.0013	4.0004
26-31	3.9987937	3.9996	4.0011	4.0004
26-31	3.9999793	3.9995	4.0012	4.0003
y_j	3.9993605	3.99976604	4.00115124	4.00035324
S_j	0.000455988	0.000325502	0.00010852	5.07655E-05
(S_j)^2	2.07925E-07	1.05951E-07	1.17766E-08	2.57713E-09
y_j - y	-0.000797255	-0.000391715	0.000993485	0.000195485
$(y_j$ - y)^2	6.35616E-07	1.53441E-07	9.87012E-07	3.82144E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 4.000157755

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000286457	16	1.68336E-17
u_{geo}	0.000388832	3	4.76219E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05, Degree of freedom 8

Calibrated value	4.000157755
standard uncertainty	0.000232828
k factor	2.648654254
Extended uncertainty	0.000616682

Effective degree of freedom 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
31	7.9995388	7.9998	8.0006	7.9994
31	7.9991834	7.9998	8.0006	7.9996
31	7.9997636	7.9998	8.0009	7.9993
31	7.9995995	7.9997	8.0008	7.9996
31	8.0001743	7.9996	8.0007	7.9995
y_j	7.99965192	7.9997537	8.0007229	7.99945958
S_j	0.000360697	0.000100349	0.000144209	0.00014048
(S_j)^2	1.30102E-07	1.00698E-08	2.07963E-08	1.97347E-08
y_j - y	-0.000245105	-0.000143325	0.000825875	-0.000437445
(y_j - y)^2	6.00765E-08	2.05421E-08	6.8207E-07	1.91358E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	7.999897025		
u_{rep}	0.000212546	16	5.10212E-18
u_{geo}	0.000281964	3	1.31685E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	7.999897025
standard uncertainty	0.000170033
k factor	2.516528348
Extended uncertainty	0.000427892

Effective degree of freedom: 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-31	11.9991271	11.9998	12.0006	12.0003
6-31	11.9993918	11.9994	12.0006	12.0005
6-31	11.9998071	11.9997	11.9999	12.0005
6-31	11.9991162	11.9995	12.0004	12.0000
6-31	11.9995539	11.9996	12.0003	12.0001
y_j	11.99939922	11.9996194	12.00036132	12.00026858
S_j	0.000293469	0.000172961	0.000274995	0.000232115
(S_j)^2	8.61242E-08	2.99156E-08	7.56224E-08	5.38773E-08
y_j - y	-0.00051291	-0.00029273	0.00044919	0.00035645
(y_j - y)^2	2.63077E-07	8.56909E-08	2.01772E-07	1.27057E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	11.99991213		
u_{rep}	0.00024776	16	9.42026E-18
u_{geo}	0.000237626	3	6.64259E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	11.999912130
standard uncertainty	0.000162461
k factor	2.319809441
Extended uncertainty	0.000376878

Effective degree of freedom: 9

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-31	15.9987398	16.0000	16.0002	15.9998
6-31	15.9991538	16.0001	16.0002	16.0002
6-31	16.0001668	16.0003	16.0007	16.0005
6-31	15.9988088	16.0002	16.0004	16.0000
6-31	15.9992726	15.9998	16.0007	15.9998
y_j	15.99922836	16.00008096	16.00044772	16.00004534
S_j	0.000570725	0.000197102	0.000239447	0.000301742
(S_j)^2	3.25727E-07	3.88492E-08	5.7335E-08	9.10482E-08
y_j - y	-0.000722235	0.000130365	0.000497125	9.4745E-05
$(y_j$ - y)^2	5.21623E-07	1.6995E-08	2.47133E-07	8.97662E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 15.9999506

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000358106	16	4.11136E-17
u_{geo}	0.000257347	3	9.13763E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	15.999950595
standard uncertainty	0.000205438
k factor	2.211800697
Extended uncertainty	0.000454388

Effective degree of freedom 13

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-31	19.998977	20.0002	20.0001	19.9998
6-31	19.9994446	20.0004	20.0001	19.9995
6-31	19.9992317	19.9993	20.0008	19.9996
6-31	19.999368	20.0004	20.0006	19.9995
6-31	19.9992713	20.0002	20.0004	19.9998
y_j	19.99925852	20.00008802	20.00040974	19.99965046
S_j	0.000178008	0.00044494	0.000294003	0.000161077
(S_j)^2	3.16869E-08	1.97972E-07	8.64378E-08	2.59457E-08
y_j - y	-0.000593165	0.000236335	0.000558055	-0.000201225
$(y_j$ - y)^2	3.51845E-07	5.58542E-08	3.11425E-07	4.04915E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y 19.99985169

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000292422	16	1.82801E-17
u_{geo}	0.000251598	3	8.34804E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05 Degree of freedom 8

Calibrated value	19.999851685
standard uncertainty	0.000181459
k factor	2.283681613
Extended uncertainty	0.000414395

Effective degree of freedom 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	23.9995058	23.9993	24.0012	23.9998
26-31	23.9995277	24.0001	24.0012	23.9995
26-31	23.9989355	24.0003	24.0012	23.9995
26-31	23.9997019	23.9996	24.0008	23.9994
26-31	24.0002655	23.9995	24.0011	23.9992
y_j	23.99958728	23.99976152	24.00109978	23.99947246
S_j	0.000476478	0.000433914	0.00015127	0.000222586
(S_j)^2	2.27032E-07	1.88281E-07	2.28825E-08	4.95444E-08
y_j - y	-0.00039298	-0.00021874	0.00111952	-0.0005078
$(y_j$ - y)^2	1.54433E-07	4.78472E-08	1.25333E-06	2.57861E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: 23.99998026

E_{Lprop}: -0.000258327

		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000349192	16	3.71703E-17
u_{geo}	0.000377874	3	4.24764E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	23.999980260
standard uncertainty	0.000245121
k factor	2.428809082
Extended uncertainty	0.000595352

Effective degree of freedom: 7

Appendix (8) Y value

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ıge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
	-4.0018424	-4.0033153	-4.0003957	-4.0015622
	-4.0012022	-4.0026328	-4.0003957	-4.0011197
	-4.0009048	-4.0032967	-4.0011075	-4.0018444
	-4.0011478	-4.0023741	-4.001665	-4.0015724
	-4.0005493	-4.0023274	-4.0010972	-4.0013226
y_j	-4.0011293	-4.00278926	-4.00093222	-4.00148426
S_j	0.000474597	0.000485892	0.000540975	0.000275037
(S_j)^2	2.25242E-07	2.36091E-07	2.92654E-07	7.56455E-08
y_j - y	0.00045446	-0.0012055	0.00065154	9.95E-05
$(y_j$ - y)^2	2.06534E-07	1.45323E-06	4.24504E-07	9.90025E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

		Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-4.00158376		
u_{rep}	0.000455421	16	1.07545E-16
u_{geo}	0.000417749	3	6.34482E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-4.001583760
standard uncertainty	0.000291736
k factor	2.319809441
Extended uncertainty	0.000676773

Effective degree of freedom: 9

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2-3	-3.9997227	-4.0018768	-3.9996865	-3.9989517
2-3	-3.9990281	-4.0016688	-3.9996865	-3.998897
2-3	-3.9987092	-4.0022012	-4.0004514	-4.0005811
2-3	-3.9994139	-4.0011143	-4.0002703	-3.9988637
2-3	-3.9993373	-4.0009743	-4.0008946	-3.9986524
y_j	-3.99924224	-4.00156708	-4.00019786	-3.99918918
S_j	0.000387083	0.000515941	0.000519123	0.000786333
(S_j)^2	1.49833E-07	2.66195E-07	2.69489E-07	6.18319E-07
y_j - y	0.00080685	-0.00151799	-0.00014877	0.00085991
$(y_j$ - y)^2	6.51007E-07	2.30429E-06	2.21325E-08	7.39445E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

		Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-4.00004909		
u_{rep}	0.000570928	16	2.65623E-16
u_{geo}	0.000556543	3	1.99872E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-4.000049090
standard uncertainty	0.00037766
k factor	2.3664195
Extended uncertainty	0.000893701

Effective degree of freedom: 8

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3-4	-4.0018147	-4.0025312	-4.0010428	-4.0009141
3-4	-4.0014229	-4.0015556	-4.0010428	-3.9989581
3-4	-4.0015127	-4.0016382	-4.000748	-4.0020755
3-4	-4.0017206	-4.0015763	-4.0009828	-3.9999311
3-4	-3.9995809	-4.001834	-4.0008914	-3.9991093
y_j	-4.00121036	-4.00182706	-4.00094156	-4.00019762
S_j	0.000924296	0.000408687	0.000124681	0.001306872
(S_j)^2	8.54324E-07	1.67025E-07	1.55453E-08	1.70792E-06
y_j - y	-0.00016621	-0.00078291	0.00010259	0.00084653
$(y_j$ - y)^2	2.76258E-08	6.12948E-07	1.05247E-08	7.16613E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -4.00104415

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000828373	16	1.17718E-15
u_{geo}	0.000337603	3	2.70636E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$: 3.999066667

$u_{measstd}$: 5E-05 — Degree of freedom: 8

Calibrated value	-4.001044150
standard uncertainty	0.000407105
k factor	2.148852324
Extended uncertainty	0.000874808

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
4-5	-3.9995596	-4.0011863	-4.0014668	-4.0001521
4-5	-3.9992964	-4.0012761	-4.0014668	-3.9995963
4-5	-4.0004689	-4.0018171	-4.0013087	-3.9999288
4-5	-3.9996352	-4.0005866	-4.0002206	-3.9991229
4-5	-3.9991091	-4.0005953	-4.0008437	-3.9997203
y_j	-3.99961384	-4.00109228	-4.00106132	-3.99970408
S_j	0.000522029	0.000517372	0.000534835	0.000387579
(S_j)^2	2.72514E-07	2.67674E-07	2.86048E-07	1.50218E-07
y_j - y	0.00075404	-0.0007244	-0.00069344	0.0006638
$(y_j$ - y)^2	5.68576E-07	5.24755E-07	4.80859E-07	4.4063E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -4.00036788

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000494078	16	1.48978E-16
u_{geo}	0.000409758	3	5.87313E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$: 3.999066667

$u_{measstd}$: 5E-05 — Degree of freedom: 8

Calibrated value	-4.000367880
standard uncertainty	0.000301327
k factor	2.254866004
Extended uncertainty	0.000679453

Effective degree of freedom: 11

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
5-6	-4.0001436	-4.0020782	-4.0020347	-3.9994124
5-6	-4.0001166	-4.0017994	-4.0020347	-3.9987282
5-6	-4.0001282	-4.0007896	-4.0007507	-3.9999793
5-6	-3.9992347	-4.0021428	-3.9997543	-3.9982913
5-6	-3.9989637	-4.0021586	-4.0003385	-3.999231
y_j	-3.99971736	-4.00179372	-4.00098258	-3.99912844
S_j	0.000572457	0.000579701	0.00102362	0.000647323
(S_j)^2	3.27707E-07	3.36053E-07	1.0478E-06	4.19028E-07
y_j - y	0.000688165	-0.001388195	-0.000577055	0.001277085
$(y_j$ - y)^2	4.73571E-07	1.92709E-06	3.32992E-07	1.63095E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-4.000405525		
u_{rep}	0.000729826	16	7.0928E-16
u_{geo}	0.000603089	3	2.75603E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-4.000405525
standard uncertainty	0.000444363
k factor	2.254866004
Extended uncertainty	0.001001979

Effective degree of freedom: 11

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
31-32	-4.0016091	-4.0015753	-4.0019979	-3.9997026
31-32	-4.0015153	-4.0030766	-4.0019979	-3.9992389
31-32	-4.0012979	-4.0020591	-4.0014602	-3.999709
31-32	-3.999442	-4.001657	-3.9998115	-3.9982223
31-32	-3.9990116	-4.0017039	-4.000892	-3.9987038
y_j	-4.00057518	-4.00201438	-4.0012319	-3.99911532
S_j	0.001245393	0.000621937	0.000916338	0.00064797
(S_j)^2	1.551E-06	3.86805E-07	8.39675E-07	4.19865E-07
y_j - y	0.000159015	-0.001280185	-0.000497705	0.001618875
$(y_j$ - y)^2	2.52858E-08	1.63887E-06	2.4771E-07	2.62076E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-4.000734195		
u_{rep}	0.000894057	16	1.59735E-15
u_{geo}	0.000614588	3	2.97232E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-4.000734195
standard uncertainty	0.000504279
k factor	2.195291287
Extended uncertainty	0.001107039

Effective degree of freedom: 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
32-33	-8.0022309	-8.0026989	-8.0011937	-8.0018809
32-33	-8.0019757	-8.0023264	-8.0011937	-8.0019593
32-33	-8.0019432	-8.0024232	-8.0012221	-8.0014692
32-33	-8.0018493	-8.0018485	-8.0022162	-8.0022141
32-33	-8.0002623	-8.0021004	-8.0010932	-8.0020183
y_j	-8.00165228	-8.00227948	-8.00138378	-8.00190836
S_j	0.000789762	0.000322716	0.000467911	0.00027467
(S_j)^2	6.23724E-07	1.04146E-07	2.1894E-07	7.54435E-08
y_j - y	0.000153695	-0.000473505	0.000422195	-0.000102385
$(y_j$ - y)^2	2.36222E-08	2.24207E-07	1.78249E-07	1.04827E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	-8.001805975		
u_{rep}	0.000505533	16	1.63282E-16
u_{geo}	0.000190736	3	2.75731E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-8.001805975
standard uncertainty	0.000245373
k factor	2.148852324
Extended uncertainty	0.000527269

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
33-34	-7.9999481	-8.0013024	-8.0008862	-7.999621
33-34	-8.0006241	-8.0013602	-8.0008862	-7.9994852
33-34	-8.0000363	-8.0016105	-8.0004215	-7.9994066
33-34	-8.0002512	-8.0018358	-8.0013657	-7.9991054
33-34	-8.0007437	-8.0020742	-8.0000131	-7.9994586
y_j	-8.00032068	-8.00163662	-8.00071454	-7.99941536
S_j	0.000351968	0.000324015	0.000514984	0.000190517
(S_j)^2	1.23881E-07	1.04986E-07	2.65209E-07	3.62968E-08
y_j - y	0.00020112	-0.00111482	-0.00019274	0.00110644
$(y_j$ - y)^2	4.04493E-08	1.24282E-06	3.71487E-08	1.22421E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	-8.0005218		
u_{rep}	0.000364133	16	4.39523E-17
u_{geo}	0.000460492	3	9.36798E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-8.000521800
standard uncertainty	0.000282014
k factor	2.516528348
Extended uncertainty	0.000709696

Effective degree of freedom: 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
34-35	-8.0008262	-8.0025324	-8.0002921	-8.0003697
34-35	-7.9998001	-8.0011455	-8.0002921	-8.0001841
34-35	-8.0001518	-8.0006287	-8.0005491	-8.0006771
34-35	-8.0004591	-8.0014876	-8.0010034	-8.0003563
34-35	-8.0000646	-8.0019752	-8.0012358	-7.9999943
y_j	-8.00026036	-8.00155388	-8.0006745	-8.0003163
S_j	0.000394214	0.00073521	0.000427615	0.000252878
(S_j)^2	1.55405E-07	5.40534E-07	1.82854E-07	6.39473E-08
y_j - y	0.0004409	-0.00085262	2.676E-05	0.00038496
(y_j - y)^2	1.94393E-07	7.26961E-07	7.16098E-10	1.48194E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

		Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	-8.00070126		
u_{rep}	0.000485474	16	1.38869E-16
u_{geo}	0.000298645	3	1.65721E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-8.000701260
standard uncertainty	0.000263504
k factor	2.181165682
Extended uncertainty	0.000574745

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
35-36	-8.0012585	-8.0015816	-8.0017031	-8.0013681
35-36	-8.0010929	-8.001083	-8.0017031	-8.000948
35-36	-8.0010064	-8.0012434	-8.0001132	-8.0008025
35-36	-8.0009733	-8.0011226	-8.0017929	-8.0007215
35-36	-8.000804	-8.0013424	-8.0008482	-7.9999396
y_j	-8.00102702	-8.0012746	-8.0012321	-8.00075594
S_j	0.000166562	0.000199771	0.000734421	0.00051995
(S_j)^2	2.7743E-08	3.99085E-08	5.39374E-07	2.70348E-07
y_j - y	4.5395E-05	-0.000202185	-0.000159685	0.000316475
(y_j - y)^2	2.06071E-09	4.08788E-08	2.54993E-08	1.00156E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

		Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	-8.001072415		
u_{rep}	0.000468341	16	1.20279E-16
u_{geo}	0.000118531	3	4.11232E-18
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-8.001072415
standard uncertainty	0.000217672
k factor	2.148852324
Extended uncertainty	0.000467745

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-7	-8.0015853	-8.0024484	-8.0012707	-8.0014061
1-7	-8.0021669	-8.0015468	-8.0012707	-8.0016574
1-7	-8.0017152	-8.0010939	-8.0004091	-8.0014788
1-7	-8.0010588	-8.001956	-8.0015952	-8.0010458
1-7	-7.9996857	-8.0017773	-8.0007331	-8.0005906
y_j	-8.00124238	-8.00176448	-8.00105576	-8.00123574
S_j	0.000955621	0.000500413	0.000475834	0.000423728
(S_j)^2	9.13211E-07	2.50413E-07	2.26418E-07	1.79545E-07
y_j - y	8.221E-05	-0.00043989	0.00026883	8.885E-05
$(y_j$ - y)^2	6.75848E-09	1.93503E-07	7.22696E-08	7.89432E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	-8.00132459		
u_{rep}	0.000626416	16	3.84938E-16
u_{geo}	0.000152869	3	1.13771E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-8.001324590
standard uncertainty	0.000290382
k factor	2.158263401
Extended uncertainty	0.00062672

Effective degree of freedom: 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
7-13	-8.0009897	-8.0019044	-8.0021947	-8.0008224
7-13	-8.0011848	-8.0007559	-8.0021947	-8.0010328
7-13	-8.0010271	-8.0007842	-8.0006896	-8.0009663
7-13	-8.001122	-8.0013103	-8.001729	-8.0000346
7-13	-8.0009814	-8.0019433	-7.9998689	-7.999898
y_j	-8.001061	-8.00133962	-8.00133538	-8.00055082
S_j	8.89051E-05	0.000577383	0.001024621	0.000541143
(S_j)^2	7.90413E-09	3.33372E-07	1.04985E-06	2.92835E-07
y_j - y	1.0705E-05	-0.000267915	-0.000263675	0.000520885
(y_j - y)^2	1.14597E-10	7.17784E-08	6.95245E-08	2.71321E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_c)	u_c^4 / v_c
y	-8.001071705		
u_{rep}	0.000648837	16	4.43081E-16
u_{geo}	0.000185459	3	2.4646E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop} -0.000258327

$L_{meas std}$ 3.999066667

$u_{meas std}$ 5E-05 — Degree of freedom 8

Calibrated value -8.001071705

standard uncertainty 0.000304625

k factor 2.148852324

Extended uncertainty 0.000654595

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
13-19	-12.0019917	-12.0033	-12.0005	-12.0013
13-19	-12.0009418	-12.0021	-12.0005	-12.0008
13-19	-12.0014118	-12.0026	-12.0013	-12.0009
13-19	-12.0015468	-12.0022	-12.0019	-12.0014
13-19	-12.0003973	-12.0022	-12.0014	-12.0007
y_j	-12.00125788	-12.00245826	-12.0011141	-12.00103642
S_j	0.000609541	0.000491934	0.000630278	0.000333939
(S_j)^2	3.71541E-07	2.41999E-07	3.9725E-07	1.11515E-07
y_j - y	0.000208785	-0.000991595	0.000352565	0.000430245
(y_j - y)^2	4.35912E-08	9.83261E-07	1.24302E-07	1.85111E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_c)	u_c^4 / v_c
y	-12.00146667		
u_{rep}	0.000529695	16	1.96808E-16
u_{geo}	0.0003337	3	2.58334E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop} -0.000258327

$L_{meas std}$ 3.999066667

$u_{meas std}$ 5E-05 — Degree of freedom 8

Calibrated value -12.001466665

standard uncertainty 0.000289748

k factor 2.181165682

Extended uncertainty 0.000631989

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
19-25	-12.0005093	-12.0013	-12.0007	-12.0006
19-25	-12.001008	-12.0013	-12.0007	-11.9985
19-25	-12.0004875	-12.0011	-12.0011	-11.9998
19-25	-12.0007119	-12.0014	-12.0005	-11.9989
19-25	-12.0001984	-12.0012	-12.0008	-11.9992
y_j	-12.00058302	-12.0012525	-12.00076532	-11.99940198
S_j	0.000299879	0.00011452	0.00022087	0.000803054
(S_j)^2	8.99273E-08	1.31148E-08	4.87837E-08	6.44895E-07
y_j - y	-8.2315E-05	-0.000751795	-0.000264615	0.001098725
(y_j - y)^2	6.77576E-09	5.65196E-07	7.00211E-08	1.2072E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-12.00050071		
u_{rep}	0.000446296	16	9.91819E-17
u_{geo}	0.000392555	3	4.94719E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-12.000500705
standard uncertainty	0.00027993
k factor	2.283681613
Extended uncertainty	0.000639271

Effective degree of freedom: 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
25-31	-12.0006194	-12.0012	-12.0005	-12.0002
25-31	-12.0008154	-12.0008	-12.0005	-12.0004
25-31	-12.0006705	-12.0016	-12.0017	-12.0004
25-31	-12.0005593	-12.0011	-12.0004	-12.0005
25-31	-11.9999346	-12.0010	-12.0014	-12.0006
y_j	-12.00051984	-12.00114968	-12.00092106	-12.00038596
S_j	0.000340598	0.000286992	0.000604997	0.000150237
(S_j)^2	1.16007E-07	8.23647E-08	3.66021E-07	2.25711E-08
y_j - y	0.000224295	-0.000405545	-0.000176925	0.000358175
(y_j - y)^2	5.03082E-08	1.64467E-07	3.13025E-08	1.28289E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-12.00074414		
u_{rep}	0.000383068	16	5.38324E-17
u_{geo}	0.000176627	3	2.02764E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-12.000744135
standard uncertainty	0.000192737
k factor	2.148852324
Extended uncertainty	0.000414163

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-12	-12.0003435	-11.9992	-12.0000	-11.9983
6-12	-12.0005833	-12.0012	-12.0000	-11.9984
6-12	-12.0005768	-12.0026	-12.0006	-11.9989
6-12	-12.0006669	-12.0004	-12.0004	-11.9988
6-12	-12.0014163	-12.0003	-12.0003	-11.9984
y_j	-12.00071736	-12.00074264	-12.00026296	-11.99857614
S_j	0.000408829	0.001239058	0.000299641	0.000277142
(S_j)^2	1.67141E-07	1.53526E-06	8.9785E-08	7.68078E-08
y_j - y	-0.000642585	-0.000667865	-0.000188185	0.001498635
$(y_j$ - y)^2	4.12915E-07	4.46044E-07	3.54136E-08	2.24591E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	-12.00007478		
u_{rep}	0.000683557	16	5.45805E-16
u_{geo}	0.000511556	3	1.4267E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-12.000074775
standard uncertainty	0.000398588
k factor	2.231351317
Extended uncertainty	0.00088939

Effective degree of freedom: 12

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
12-18	-12.0005186	-12.0022	-12.0016	-12.0005
12-18	-12.0013867	-12.0014	-12.0016	-12.0001
12-18	-12.0003932	-12.0024	-12.0014	-12.0011
12-18	-12.0018293	-12.0021	-12.0013	-11.9996
12-18	-12.0014468	-12.0017	-12.0011	-11.9991
y_j	-12.00111492	-12.00196608	-12.0013985	-12.00009632
S_j	0.000626663	0.000424731	0.000212725	0.000767785
(S_j)^2	3.92706E-07	1.80397E-07	4.52517E-08	5.89494E-07
y_j - y	2.9035E-05	-0.000822125	-0.000254545	0.001047635
$(y_j$ - y)^2	8.43031E-10	6.7589E-07	6.47932E-08	1.09754E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	-12.00114396		
u_{rep}	0.000549511	16	2.27953E-16
u_{geo}	0.000391478	3	4.89317E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-12.001143955
standard uncertainty	0.000314176
k factor	2.211800697
Extended uncertainty	0.000694894

Effective degree of freedom: 13

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
18-24	-12.0017589	-12.0026	-12.0017	-12.0017
18-24	-12.0017457	-12.0016	-12.0017	-12.0019
18-24	-12.0017274	-12.0014	-12.0006	-12.0018
18-24	-12.0002517	-12.0026	-12.0022	-11.9997
18-24	-11.9999413	-12.0025	-12.0016	-11.9999
y_j	-12.001085	-12.00214976	-12.00154236	-12.00098956
S_j	0.00090909	0.000614533	0.000606035	0.001092781
(S_j)^2	8.26446E-07	3.77651E-07	3.67278E-07	1.19417E-06
y_j - y	0.00035667	-0.00070809	-0.00010069	0.00045211
(y_j - y)^2	1.27213E-07	5.01391E-07	1.01385E-08	2.04403E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

		Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-12.00144167		
u_{rep}	0.000831496	16	1.19504E-15
u_{geo}	0.00026507	3	1.0285E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-12.001441670
standard uncertainty	0.000394769
k factor	2.148852324
Extended uncertainty	0.000848301

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
4-30	-16.0006277	-16.0016	-16.0007	-16.0000
4-30	-16.0003845	-16.0016	-16.0007	-15.9991
4-30	-16.0002848	-16.0017	-16.0008	-16.0007
4-30	-16.0004081	-16.0013	-16.0014	-15.9998
4-30	-16.0004337	-16.0013	-16.0008	-15.9986
y_j	-16.00042776	-16.00148344	-16.00085828	-15.99962426
S_j	0.000125207	0.000201049	0.000321547	0.000808096
(S_j)^2	1.56767E-08	4.04209E-08	1.03393E-07	6.5302E-07
y_j - y	0.000170675	-0.000885005	-0.000259845	0.000974175
(y_j - y)^2	2.913E-08	7.83234E-07	6.75194E-08	9.49017E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

		Degree of freedom (v_e)	u_e^4 / v_e
Coverage factor (p)	95.45 %		
y	-16.00059844		
u_{rep}	0.000450697	16	1.03152E-16
u_{geo}	0.000390395	3	4.83923E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-16.000598435
standard uncertainty	0.000280584
k factor	2.283681613
Extended uncertainty	0.000640765

Effective degree of freedom: 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
30-36	-16.0007557	-16.0020	-15.9997	-16.0009
30-36	-16.0001118	-16.0010	-15.9997	-16.0007
30-36	-15.999499	-16.0014	-16.0006	-16.0011
30-36	-15.9998659	-16.0014	-15.9993	-16.0009
30-36	-16.0005498	-16.0014	-16.0006	-16.0006
y_j	-16.00015644	-16.0014493	-15.99998518	-16.00082158
S_j	0.000508055	0.000345469	0.000571957	0.00018308
(S_j)^2	2.5812E-07	1.19349E-07	3.27135E-07	3.35181E-08
y_j - y	0.000446685	-0.000846175	0.000617945	-0.000218455
$(y_j$ - y)^2	1.99527E-07	7.16012E-07	3.81856E-07	4.77226E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y -16.00060313

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.00042957	16	8.51287E-17
u_{geo}	0.000334803	3	2.61768E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05, Degree of freedom 8

Calibrated value	-16.000603125
standard uncertainty	0.000254812
k factor	2.231351317
Extended uncertainty	0.000568576

Effective degree of freedom 12

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-8	-16.0007266	-16.0000	-16.0009	-16.0003
1-8	-16.0008803	-16.0006	-16.0009	-15.9990
1-8	-16.0006587	-16.0011	-16.0019	-16.0005
1-8	-16.000291	-16.0005	-16.0010	-15.9996
1-8	-15.9995852	-16.0003	-16.0013	-15.9996
y_j	-16.00042836	-16.00051672	-16.00120656	-15.99980758
S_j	0.000518662	0.000399794	0.000414171	0.000625944
(S_j)^2	2.6901E-07	1.59835E-07	1.71537E-07	3.91806E-07
y_j - y	6.1445E-05	-2.6915E-05	-0.000716755	0.000682225
$(y_j$ - y)^2	3.77549E-09	7.24417E-10	5.13738E-07	4.65431E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y -16.00048981

E_{Lprop} -0.000258327

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000498043	16	1.53818E-16
u_{geo}	0.000286308	3	1.39989E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$ 3.999066667

$u_{measstd}$ 5E-05, Degree of freedom 8

Calibrated value	-16.000489805
standard uncertainty	0.000264769
k factor	2.168942996
Extended uncertainty	0.000574268

Effective degree of freedom 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE (u_{aW}) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	u_{aM}	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
8-15	-16.0014299	-16.0022	-16.0014	-16.0001
8-15	-16.0012503	-16.0010	-16.0014	-15.9994
8-15	-16.000748	-16.0011	-16.0015	-16.0006
8-15	-16.0009197	-16.0012	-16.0015	-15.9991
8-15	-16.0006263	-16.0013	-16.0013	-15.9984
y_j	-16.00099484	-16.0013515	-16.00144212	-15.9995227
S_j	0.000337985	0.000497898	6.89704E-05	0.00085501
(S_j)^2	1.14234E-07	2.47903E-07	4.75692E-09	7.31042E-07
y_j - y	-0.00016705	-0.00052371	-0.00061433	0.00130509
$(y_j$ - y)^2	2.79057E-08	2.74272E-07	3.77401E-07	1.70326E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %					
y	-16.00082779			E_{Lprop}	-0.000258327	
		Degree of freedom (v_e)	u_e^4 / v_e			
u_{rep}	0.000523912	16	1.88353E-16	$L_{measstd}$	3.999066667	Degree of freedom
u_{geo}	0.000445612	3	8.21459E-16	$u_{measstd}$	5E-05	8
E_L						
u_{corr}		0	0			
u_{temp}		∞	0			

Calibrated value	-16.000827790	Effective degree of freedom	10
standard uncertainty	0.000323325		
k factor	2.283681613		
Extended uncertainty	0.000738372		

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE (u_{aW}) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	u_{aM}	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
15-22	-15.9996951	-16.0010	-16.0010	-15.9992
15-22	-15.9997941	-16.0002	-16.0010	-15.9982
15-22	-16.0002218	-16.0005	-16.0007	-15.9993
15-22	-16.0007365	-16.0007	-15.9984	-15.9992
15-22	-16.0004518	-16.0004	-16.0013	-15.9993
y_j	-16.00017986	-16.00056636	-16.00045754	-15.99905294
S_j	0.000438566	0.00029275	0.001172013	0.000476069
(S_j)^2	1.9234E-07	8.57023E-08	1.37361E-06	2.26641E-07
y_j - y	-0.000115685	-0.000502185	-0.000393365	0.001011235
$(y_j$ - y)^2	1.3383E-08	2.5219E-07	1.54736E-07	1.0226E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %					
y	-16.00006418			E_{Lprop}	-0.000258327	
		Degree of freedom (v_e)	u_e^4 / v_e			
u_{rep}	0.000685255	16	5.5125E-16	$L_{measstd}$	3.999066667	Degree of freedom
u_{geo}	0.000346759	3	3.01212E-16	$u_{measstd}$	5E-05	8
E_L						
u_{corr}		0	0			
u_{temp}		∞	0			

Calibrated value	-16.000064175	Effective degree of freedom	18
standard uncertainty	0.000352101		
k factor	2.148852324		
Extended uncertainty	0.000756614		

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
22-29	-16.0010024	-16.0026	-16.0008	-15.9992
22-29	-16.0008534	-16.0016	-16.0008	-15.9993
22-29	-16.0008941	-16.0012	-16.0016	-15.9990
22-29	-15.999839	-16.0018	-16.0002	-15.9988
22-29	-15.9997054	-16.0016	-16.0012	-15.9985
y_j	-16.00045886	-16.00177374	-16.0009088	-15.99894728
S_j	0.000630964	0.000514762	0.000546001	0.000312542
(S_j)^2	3.98115E-07	2.6498E-07	2.98117E-07	9.76822E-08
y_j - y	6.331E-05	-0.00125157	-0.00038663	0.00157489
(y_j - y)^2	4.00816E-09	1.56643E-06	1.49483E-07	2.48028E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y -16.00052217

E_{Lprop} -0.000258327

		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000514513	16	1.75196E-16
u_{geo}	0.000591622	3	2.55232E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-16.000522170
standard uncertainty	0.000374765
k factor	2.428809082
Extended uncertainty	0.000910233

Effective degree of freedom 7

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
29-36	-20.0023106	-20.0018	-19.9998	-20.0022
29-36	-20.0011168	-20.0017	-19.9998	-20.0016
29-36	-20.0013049	-20.0019	-20.0001	-20.0017
29-36	-20.0017868	-20.0019	-20.0018	-20.0018
29-36	-20.0005491	-20.0018	-20.0001	-20.0015
y_j	-20.00141364	-20.00182554	-20.00031578	-20.00176474
S_j	0.00066917	7.32735E-05	0.000820938	0.000263538
(S_j)^2	4.47788E-07	5.369E-09	6.7394E-07	6.94525E-08
y_j - y	-8.3715E-05	-0.000495615	0.001014145	-0.000434815
(y_j - y)^2	7.0082E-09	2.45634E-07	1.02849E-06	1.89064E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.99
2	3.999	3.999	3.9
3	3.9991	3.9991	3.99

Coverage factor (p) 95.45 %

y -20.00132993

E_{Lprop} -0.000258327

		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000546935	16	2.23708E-16
u_{geo}	0.000350023	3	3.12714E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

		Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-20.001329925
standard uncertainty	0.00030076
k factor	2.181165682
Extended uncertainty	0.000656007

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
6-11	-20.0011524	-20.0007	-20.0011	-19.9995
6-11	-20.0013846	-20.0020	-20.0011	-19.9990
6-11	-20.0010938	-20.0016	-20.0011	-19.9998
6-11	-20.0015344	-20.0014	-20.0010	-19.9995
6-11	-20.0018005	-20.0012	-20.0010	-19.9992
y_j	-20.00139314	-20.00136398	-20.00105106	-19.99940004
S_j	0.00028876	0.000476082	7.33914E-05	0.000300196
(S_j)^2	8.33824E-08	2.26654E-07	5.3863E-09	9.01179E-08
y_j - y	-0.000591085	-0.000561925	-0.000249005	0.001402015
(y_j - y)^2	3.49381E-07	3.1576E-07	6.20035E-08	1.96565E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -20.00080206

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.00031841	16	2.56974E-17
u_{geo}	0.000473708	3	1.04906E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-20.000802055
standard uncertainty	0.000276364
k factor	2.648654254
Extended uncertainty	0.000731992

Effective degree of freedom: 5

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
11-16	-19.9992592	-20.0017	-20.0018	-19.9991
11-16	-19.9993672	-20.0005	-20.0018	-19.9987
11-16	-19.9994779	-20.0002	-20.0011	-20.0003
11-16	-19.9984339	-20.0008	-20.0005	-19.9992
11-16	-19.9985109	-20.0010	-20.0006	-19.9992
y_j	-19.99900982	-20.00084288	-20.00116102	-19.99928748
S_j	0.000497397	0.000563822	0.000583003	0.000593334
(S_j)^2	2.47404E-07	3.17896E-07	3.39893E-07	3.52045E-07
y_j - y	0.00106548	-0.00076758	-0.00108572	0.00078782
(y_j - y)^2	1.13525E-06	5.89179E-07	1.17879E-06	6.2066E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -20.0000753

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000560633	16	2.46976E-16
u_{geo}	0.000541901	3	1.79654E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
$L_{measstd}$	3.999066667	
$u_{measstd}$	5E-05	8

Calibrated value	-20.000075300
standard uncertainty	0.000369156
k factor	2.319809441
Extended uncertainty	0.000856371

Effective degree of freedom: 9

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
16-21	-19.9997918	-20.0019	-20.0006	-20.0008
16-21	-20.0003063	-20.0013	-20.0006	-19.9997
16-21	-20.000302	-20.0014	-20.0004	-20.0012
16-21	-20.0004052	-20.0013	-20.0002	-19.9996
16-21	-20.0002366	-20.0010	-20.0006	-19.9993
y_j	-20.00020838	-20.00137862	-20.00049006	-20.0001226
S_j	0.000240534	0.000299993	0.000190869	0.000817487
$(S_j)^2$	5.78566E-08	8.99957E-08	3.64311E-08	6.68285E-07
$y_j - y$	0.000341535	-0.000828705	5.9855E-05	0.000427315
$(y_j - y)^2$	1.16646E-07	6.86752E-07	3.58262E-09	1.82598E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	-20.00054992		
		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000461673	16	1.13574E-16
u_{geo}	0.000287167	3	1.41676E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	Degree of freedom
$u_{measstd}$	5E-05	8

Calibrated value	-20.000549915
standard uncertainty	0.000251485
k factor	2.181165682
Extended uncertainty	0.00054853

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
21-26	-19.9995735	-20.0013	-20.0018	-19.9989
21-26	-19.9989438	-20.0008	-20.0018	-20.0001
21-26	-19.9991137	-20.0008	-20.0019	-19.9989
21-26	-19.9999309	-20.0010	-20.0005	-19.9993
21-26	-19.9995458	-20.0012	-20.0014	-19.9995
y_j	-19.99942154	-20.00102052	-20.00145344	-19.99933518
S_j	0.000394012	0.000251856	0.000583764	0.000487296
$(S_j)^2$	1.55245E-07	6.34316E-08	3.40781E-07	2.37458E-07
$y_j - y$	0.00088613	-0.00071285	-0.00114577	0.00097249
$(y_j - y)^2$	7.85226E-07	5.08155E-07	1.31279E-06	9.45737E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p)	95.45 %		
y	-20.00030767		
		Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	0.000446351	16	9.92303E-17
u_{geo}	0.000544052	3	1.82524E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}	-0.000258327	
$L_{measstd}$	3.999066667	Degree of freedom
$u_{measstd}$	5E-05	8

Calibrated value	-20.000307670
standard uncertainty	0.000337408
k factor	2.516528348
Extended uncertainty	0.000849096

Effective degree of freedom: 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	-20.0016986	-20.0025	-20.0018	-19.9995
26-31	-20.0015743	-20.0019	-20.0018	-19.9992
26-31	-20.001729	-20.0014	-20.0009	-19.9999
26-31	-20.0010183	-20.0029	-20.0005	-19.9993
26-31	-20.0006826	-20.0028	-20.0017	-19.9995
y_j	-20.00134056	-20.0022864	-20.0013382	-19.99946972
S_j	0.000466496	0.000633117	0.000604056	0.000258398
(S_j)^2	2.17619E-07	4.00837E-07	3.64883E-07	6.67697E-08
y_j - y	-0.00023184	-0.00117768	-0.00022948	0.001639
$(y_j$ - y)^2	5.37498E-08	1.38693E-06	5.26611E-08	2.68632E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -20.00110872

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000512374	16	1.72301E-16
u_{geo}	0.000590174	3	2.52743E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$: 3.999066667

$u_{measstd}$: 5E-05 — Degree of freedom: 8

Calibrated value	-20.001108720
standard uncertainty	0.000373606
k factor	2.428809082
Extended uncertainty	0.000907419

Effective degree of freedom: 7

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	-24.0002086	-24.0021	-24.0006	-24.0006
26-31	-24.0010735	-24.0011	-24.0006	-24.0003
26-31	-24.00114	-24.0015	-24.0007	-24.0002
26-31	-24.000663	-24.0013	-24.0010	-24.0007
26-31	-23.9994031	-24.0013	-24.0008	-24.0006
y_j	-24.00049764	-24.00146404	-24.00072154	-24.00047928
S_j	0.00071644	0.000373288	0.000175863	0.000215889
(S_j)^2	5.13287E-07	1.39344E-07	3.09279E-08	4.66081E-08
y_j - y	0.000292985	-0.000673415	6.9085E-05	0.000311345
$(y_j$ - y)^2	8.58402E-08	4.53488E-07	4.77274E-09	9.69357E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.999
2	3.999	3.999	3.99
3	3.9991	3.9991	3.999

Coverage factor (p): 95.45 %

y: -24.00079063

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000427249	16	8.33036E-17
u_{geo}	0.000231127	3	5.94513E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

$L_{measstd}$: 3.999066667

$u_{measstd}$: 5E-05 — Degree of freedom: 8

Calibrated value	-24.000790625
standard uncertainty	0.000223301
k factor	2.158263401
Extended uncertainty	0.000481942

Effective degree of freedom: 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20$°C) = ($T_W - 20$°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	-24.0012783	-24.0024	-24.0010	-24.0010
26-31	-24.001595	-24.0019	-24.0010	-24.0011
26-31	-24.0016059	-24.0015	-24.0010	-24.0012
26-31	-24.0013509	-24.0016	-24.0008	-24.0012
26-31	-24.0003128	-24.0017	-24.0011	-24.0012
y_j	-24.00122858	-24.00181524	-24.00096024	-24.0011558
S_j	0.000532147	0.000351959	0.00012099	8.45081E-05
(S_j)^2	2.8318E-07	1.23875E-07	1.46386E-08	7.14163E-09
y_j - y	6.1385E-05	-0.000525275	0.000329725	0.000134165
$(y_j$ - y)^2	3.76812E-09	2.75914E-07	1.08719E-07	1.80002E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -24.00128997

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000327428	16	2.87344E-17
u_{geo}	0.000184029	3	2.38949E-17
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-24.001289965
standard uncertainty	0.000172941
k factor	2.168942996
Extended uncertainty	0.000375098

Effective degree of freedom: 16

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20$°C) = ($T_W - 20$°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	-24.0011258	-24.0013	-24.0009	-23.9999
26-31	-23.999274	-24.0007	-24.0009	-23.9999
26-31	-23.9997366	-24.0015	-24.0009	-24.0001
26-31	-23.9997692	-24.0011	-24.0010	-23.9996
26-31	-23.9992079	-24.0013	-24.0010	-23.9997
y_j	-23.9998227	-24.0011754	-24.00092762	-23.99986336
S_j	0.00077256	0.000269668	6.32846E-05	0.000189073
(S_j)^2	5.96849E-07	7.27209E-08	4.00494E-09	3.57487E-08
y_j - y	0.00062457	-0.00072813	-0.00048035	0.00058391
$(y_j$ - y)^2	3.90088E-07	5.30173E-07	2.30736E-07	3.40951E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -24.00044727

E_{Lprop}: -0.000258327

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000421107	16	7.86156E-17
u_{geo}	0.000352603	3	3.22035E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

	Value	Degree of freedom
$L_{meas std}$	3.999066667	
$u_{meas std}$	5E-05	8

Calibrated value	-24.000447270
standard uncertainty	0.00025797
k factor	2.254866004
Extended uncertainty	0.000581687

Effective degree of freedom: 11

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	-24.0003851	-24.0010	-24.0012	-23.9982
26-31	-24.0000509	-24.0008	-24.0012	-23.9987
26-31	-23.9997132	-24.0009	-24.0004	-23.9993
26-31	-24.0001334	-24.0007	-24.0003	-23.9982
26-31	-23.999614	-24.0009	-24.0004	-23.9987
y_j	-23.99997932	-24.00085188	-24.00070458	-23.9986309
S_j	0.000315357	0.000136355	0.000473255	0.000473309
$(S_j)^2$	9.94501E-08	1.85927E-08	2.2397E-07	2.24022E-07
$y_j - y$	6.235E-05	-0.00081021	-0.00066291	0.00141077
$(y_j - y)^2$	3.88752E-09	6.5644E-07	4.3945E-07	1.99027E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y -24.00004167

		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000376176	16	5.00618E-17
u_{geo}	0.000507449	3	1.38142E-15
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop} -0.000258327

$L_{meas std}$ 3.999066667

$u_{meas std}$ 5E-05 Degree of freedom 8

Calibrated value	-24.000041670
standard uncertainty	0.00030443
k factor	2.516528348
Extended uncertainty	0.000766107

Effective degree of freedom 6

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	-24.0007855	-24.0005	-24.0014	-24.0008
26-31	-24.0002997	-24.0008	-24.0014	-23.9995
26-31	-24.0013551	-24.0022	-24.0016	-24.0014
26-31	-24.0001242	-24.0001	-24.0012	-23.9981
26-31	-23.99963	-24.0003	-24.0011	-23.9977
y_j	-24.0004389	-24.00076432	-24.00133486	-23.99951392
S_j	0.000658082	0.000822005	0.000173979	0.001611597
$(S_j)^2$	4.33071E-07	6.75692E-07	3.02689E-08	2.59725E-06
$y_j - y$	7.41E-05	-0.00025132	-0.00082186	0.00099908
$(y_j - y)^2$	5.49081E-09	6.31617E-08	6.75454E-07	9.98161E-07

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p) 95.45 %

y -24.000513

		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000966473	16	2.18121E-15
u_{geo}	0.000381037	3	4.39163E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop} -0.000258327

$L_{meas std}$ 3.999066667

$u_{meas std}$ 5E-05 Degree of freedom 8

Calibrated value	-24.000513000
standard uncertainty	0.000472346
k factor	2.148852324
Extended uncertainty	0.001015003

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
4	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	4	4.000100	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
26-31	-24.0017408	-24.0027	-24.0022	-24.0008
26-31	-24.0022379	-24.0013	-24.0022	-23.9999
26-31	-24.0019566	-24.0017	-24.0005	-24.0011
26-31	-24.0001407	-24.0020	-24.0016	-23.9992
26-31	-23.998886	-24.0023	-24.0005	-23.9995
y_j	-24.0009924	-24.00200538	-24.00140202	-24.00009704
S_j	0.001432076	0.000527103	0.000850285	0.000821909
(S_j)^2	2.05084E-06	2.77838E-07	7.22985E-07	6.75534E-07
y_j - y	0.00013181	-0.00088117	-0.00027781	0.00102717
(y_j - y)^2	1.73739E-08	7.76461E-07	7.71784E-08	1.05508E-06

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	3.9991	3.9991	3.9991
2	3.999	3.999	3.999
3	3.9991	3.9991	3.9991

Coverage factor (p): 95.45 %

y: -24.00112421

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.000965298	16	2.17063E-15
u_{geo}	0.000400634	3	5.36723E-16
E_L			
u_{corr}		0	0
u_{temp}		∞	0

E_{Lprop}: -0.000258327

$L_{measstd}$: 3.999066667

$u_{measstd}$: 5E-05 — Degree of freedom: 8

Calibrated value	-24.001124210
standard uncertainty	0.000475906
k factor	2.148852324
Extended uncertainty	0.001022652

Effective degree of freedom: 18

Appendix (9)

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.07	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-1	0.070100	0.070500	0.070800	0.070300
1-1	0.070200	0.070600	0.070600	0.070200
1-1	0.070100	0.070500	0.070400	0.070100
1-1	0.070200	0.070500	0.070500	0.070200
1-1	0.070200	0.070500	0.070400	0.070200
y_j	0.07016	0.07052	0.07054	0.0702
S_j	5.47723E-05	4.47214E-05	0.000167332	7.07107E-05
$(S_j)^2$	3E-09	2E-09	2.8E-08	5E-09
y_j - y	-0.000195	0.000165	0.000185	-0.000155
$(y_j - y)^2$	3.8025E-08	2.7225E-08	3.4225E-08	2.4025E-08

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	0.070355		
u_{rep}	9.74679E-05	16	2.25625E-19
u_{geo}	0.000101448	3	2.20663E-18
E_L	0.000112		
u_{corr}	2.35655E-05	9	3.42661E-20
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.070243000
standard uncertainty	7.09102E-05
k factor	2.283681613
Extended uncertainty	0.000161936

Effective degree of freedom: 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.17	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.17	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2-2	0.172100	0.172200	0.172400	0.172200
2-2	0.172100	0.172200	0.172400	0.172200
2-2	0.172200	0.172300	0.172300	0.172100
2-2	0.172000	0.172300	0.172200	0.172100
2-2	0.172100	0.172200	0.172100	0.172200
y_j	0.1721	0.17224	0.17228	0.17216
S_j	7.07107E-05	5.47723E-05	0.000130384	5.47723E-05
$(S_j)^2$	5E-09	3E-09	1.7E-08	3E-09
y_j - y	-9.5E-05	4.5E-05	8.5E-05	-3.5E-05
$(y_j - y)^2$	9.025E-09	2.025E-09	7.225E-09	1.225E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	0.172195		
u_{rep}	8.3666E-05	16	1.225E-19
u_{geo}	4.03113E-05	3	5.5013E-20
E_L	0.000272		
u_{corr}	5.72305E-05	9	1.19198E-18
u_{temp}	2.25701E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.171923000
standard uncertainty	7.12856E-05
k factor	2.148852324
Extended uncertainty	0.000153182

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.27	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
Gauge block	-	0.27	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3-3	0.272300	0.272500	0.272400	0.272300
3-3	0.272100	0.272500	0.272300	0.272300
3-3	0.272100	0.272500	0.272200	0.272200
3-3	0.272100	0.272300	0.272200	0.272200
3-3	0.272300	0.272500	0.272200	0.272300
y_j	0.27218	0.27246	0.27226	0.27226
S_j	0.000109545	8.94427E-05	8.94427E-05	5.47723E-05
(S_j)^2	1.2E-08	8E-09	8E-09	3E-09
y_j - y	-0.00011	0.00017	-3E-05	-3E-05
$(y_j$ - y)^2	1.21E-08	2.89E-08	9E-10	9E-10

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	0.27229		
u_{rep}	8.80341E-05	16	1.50156E-19
u_{geo}	5.97216E-05	3	2.65023E-19
E_L	0.000432		
u_{corr}	9.08955E-05	9	7.58452E-18
u_{temp}	3.58466E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{meas std}$	0.5008	
$u_{meas std}$	0.000482183	8

Calibrated value	0.271858000
standard uncertainty	0.000103459
k factor	2.195291287
Extended uncertainty	0.000227123

Effective degree of freedom: 14

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.37	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
auge block	-	0.37	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
-4	0.371600	0.371700	0.371800	0.371800
-4	0.371600	0.371800	0.371700	0.371800
-4	0.371600	0.371700	0.371600	0.371700
-4	0.371500	0.371800	0.371600	0.371800
-4	0.371700	0.371700	0.371600	0.371600
y_j	0.3716	0.37174	0.37166	0.37174
S_j	7.07107E-05	5.47723E-05	8.94427E-05	8.94427E-05
(S_j)^2	5E-09	3E-09	8E-09	8E-09
y_j - y	-8.5E-05	5.5E-05	-2.5E-05	5.5E-05
$(y_j$ - y)^2	7.225E-09	3.025E-09	6.25E-10	3.025E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.5009
2	0.5013	0.5013	0.5013
3	0.5002	0.5002	0.5002

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	0.371685		
u_{rep}	7.74597E-05	16	9E-20
u_{geo}	3.40343E-05	3	2.79528E-20
E_L	0.000592		
u_{corr}	0.000124561	9	2.67473E-17
u_{temp}	4.91231E-07	∞	0

		Degree of freedom
E_{Lprop}	0.0016	
$L_{meas std}$	0.5008	
$u_{meas std}$	0.000482183	8

Calibrated value	0.371093000
standard uncertainty	0.000130404
k factor	2.283681613
Extended uncertainty	0.000297801

Effective degree of freedom: 10

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE $[K^{-1}]$	Uncertainty of CTE ($u_{\alpha W}$) $[K^{-1}]$	$(u^2_{TW} + u^2_{TWS})$ $[K^2]$	$u_{\alpha M}$	$(T_M - 20°C) = (T_W - 20°C)$
0.47	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
Gauge block	-	0.47	0.500000	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
5-5	0.471600	0.471700	0.471900	0.471900
5-5	0.471600	0.471700	0.471900	0.471900
5-5	0.471600	0.471800	0.471800	0.471600
5-5	0.471600	0.471700	0.471800	0.471800
5-5	0.471700	0.471700	0.471800	0.471800
y_j	0.47162	0.47172	0.47184	0.4718
S_j	4.47214E-05	4.47214E-05	5.47723E-05	0.000122474
$(S_j)^2$	2E-09	2E-09	3E-09	1.5E-08
$y_j - y$	-0.000125	-2.5E-05	9.5E-05	5.5E-05
$(y_j - y)^2$	1.5625E-08	6.25E-10	9.025E-09	3.025E-09

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.5009	0.5009	0.50
2	0.5013	0.5013	0.50
3	0.5002	0.5002	0.50

Coverage factor (p) 95.45 %

	Value	Degree of freedom (v_c)	u_c^4 / v_c
y	0.471745		
u_{rep}	7.4162E-05	16	7.5625E-20
u_{geo}	4.85627E-05	3	1.1587E-19
E_L	0.000752		
u_{corr}	0.000158226	9	6.96409E-17
u_{temp}	6.23996E-07	∞	0

	Value	Degree of freedom
E_{Lprop}	0.0016	
$L_{measstd}$	0.5008	
$u_{measstd}$	0.000482183	8

Calibrated value	0.470993000
standard uncertainty	0.000163479
k factor	2.283681613
Extended uncertainty	0.000373333

Effective degree of freedom: 10

Appendix (10)

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-2	70.898330	71.509355	69.054491	69.676326
1-2	71.498909	69.665606	69.708478	69.676285
1-2	70.887795	70.890429	70.890429	70.279378
1-2	70.279337	68.454289	68.446105	67.232298
1-2	70.890429	70.276680	69.054491	69.665606
y_i	70.89096003	70.15927187	69.4307989	69.30597864
S_i	0.431204621	1.174922679	0.93011583	1.188620344
(S_i)^2	0.185937425	1.380443302	0.865115457	1.412818322
y_i - y	0.94420767	0.21251951	-0.515953456	-0.640773724
$(y_i$ - y)^2	0.891528123	0.045164542	0.266207969	0.410590965

artefact measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p): 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	69.94675236		
u_{rep}	0.980346177	16	0.00230918
u_{geo}	0.366684651	3	0.000376643
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

		Degree of freedom
E_{Lprop}	0.007556675	
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	69.946223393
standard uncertainty	0.475215889
k factor	2.148852324
Extended uncertainty	1.021168768

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
2-3	70.300589	69.689685	71.540640	71.501480
2-3	69.668246	70.300590	71.501480	71.522409
2-3	70.890388	71.522409	70.890429	71.501480
2-3	70.287308	69.665606	71.509314	70.287307
2-3	69.668246	70.898331	71.498869	72.109983
y_i	70.16295516	70.41532413	71.38814631	71.38453191
S_i	0.513088699	0.800113555	0.278730599	0.666435758
(S_i)^2	0.263260013	0.640181701	0.077690747	0.444136619
y_i - y	-0.674784216	-0.422415248	0.550406933	0.546792531
$(y_i$ - y)^2	0.455333738	0.178434642	0.302947792	0.298982072

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p): 95.45 %

	Value	Degree of freedom (v_e)	u_e^4 / v_e
y	70.83773938		
u_{rep}	0.596923169	16	0.000317405
u_{geo}	0.320896952	3	0.000220913
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

		Degree of freedom
E_{Lprop}	0.007556675	
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	70.837210414
standard uncertainty	0.311459749
k factor	2.158263401
Extended uncertainty	0.672212177

Effective degree of freedom: 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
3-4	68.446105	69.665606	69.668286	69.054491
3-4	69.057196	70.279337	69.676326	69.057196
3-4	68.487013	69.065266	70.898330	70.276680
3-4	68.446105	71.540642	69.676326	71.509315
3-4	70.287307	69.057155	70.287307	69.057196
y_j	68.94474509	69.92160119	70.04131506	69.79097543
S_j	0.794027674	1.03626461	0.547852829	1.096343105
(S_j)^2	0.630479947	1.073844343	0.300142722	1.201968205
y_j - y	-0.729914102	0.246941997	0.366655864	0.116316242
$(y_j$ - y)^2	0.532774597	0.06098035	0.134436523	0.013529468

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p) 95.45 %

y 69.67465919

E_{Lprop} 0.007556675

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.895326088	16	0.001606442
u_{geo}	0.248616327	3	7.95935E-05
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	69.674130225
standard uncertainty	0.419254443
k factor	2.148852324
Extended uncertainty	0.900915884

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
4-5	72.112573	69.668245	69.676286	70.287308
4-5	70.279337	71.522409	68.443377	69.689684
4-5	71.501521	70.279378	69.057155	68.446105
4-5	70.890429	69.668286	70.890429	70.890429
4-5	70.279378	70.300629	69.057195	70.287307
y_j	71.01264741	70.28778957	69.42488835	69.92016639
S_j	0.796743374	0.756990977	0.928008765	0.926953802
(S_j)^2	0.634800004	0.57303534	0.861200267	0.85924335
y_j - y	0.851274477	0.126416641	-0.736484581	-0.241206537
$(y_j$ - y)^2	0.724668235	0.015981167	0.542409538	0.058180594

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p) 95.45 %

y 70.16137293

E_{Lprop} 0.007556675

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.855610741	16	0.001339815
u_{geo}	0.334320148	3	0.000260261
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	70.160843962
standard uncertainty	0.417560111
k factor	2.148852324
Extended uncertainty	0.897275014

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
5-6	67.835056	70.279337	69.065306	69.665565
5-6	70.276680	69.057155	70.287307	69.668245
5-6	69.057196	69.668245	70.890429	71.509355
5-6	70.300589	70.279337	69.668246	68.446105
5-6	68.454289	69.668246	69.151766	69.689684
y_j	69.18476177	69.79046388	69.81261085	69.7957908
S_j	1.096463125	0.511275428	0.775088501	1.095723267
(S_j)^2	1.202231385	0.261402564	0.600762184	1.200609478
y_j - y	-0.461145056	0.144557055	0.166704023	0.149883977
$(y_j - y)$^2	0.212654762	0.020896742	0.027790231	0.022465207

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

		Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	69.64590682		
u_{rep}	0.903466326	16	0.001665666
u_{geo}	0.153787446	3	1.16531E-05
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

		Degree of freedom
E_{Lprop}	0.007556675	
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	69.645377855
standard uncertainty	0.411294217
k factor	2.158263401
Extended uncertainty	0.887681256

Effective degree of freedom: 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-7	69.66828649	68.4461	70.8983	67.2323
1-7	70.27672084	70.8904	69.0545	69.6897
1-7	67.83505528	70.2793	69.6897	69.7085
1-7	69.05719553	69.6683	69.6682	69.0572
1-7	70.30058865	70.8878	70.8904	69.0545
y_j	69.42756936	70.03439023	70.04021977	68.9484374
S_j	1.026455491	1.02198131	0.820384177	1.011852015
(S_j)^2	1.053610876	1.044445798	0.673030197	1.023844501
y_j - y	-0.185084833	0.421736041	0.427565581	-0.664216789
$(y_j - y)$^2	0.034256395	0.177861288	0.182812326	0.441183943

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

		Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	69.61265419		
u_{rep}	0.97402918	16	0.002250235
u_{geo}	0.263962427	3	0.000101141
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

		Degree of freedom
E_{Lprop}	0.007556675	
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	69.612125225
standard uncertainty	0.455154498
k factor	2.148852324
Extended uncertainty	0.978059801

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
7-13	69.6655654	70.2767	69.0545	70.9825
7-13	69.6762854	70.2767	70.2767	70.2873
7-13	72.10998336	71.5015	70.2794	69.7325
7-13	70.27933675	70.8983	69.6683	70.8983
7-13	69.68972437	70.3006	68.4543	70.2873
y_i	70.28417906	70.65075195	69.54663298	70.43759993
S_i	1.053467931	0.544864156	0.793751111	0.512711648
(S_i)^2	1.109794682	0.296876949	0.630040826	0.262873234
y_i - y	0.054388079	0.420960974	-0.683158003	0.20780895
$(y_i$ - y)^2	0.002958063	0.177208141	0.466704856	0.04318456

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.
2	0.04	0.04	0.
3	0.04	0.04	0.

Coverage factor (p)	95.45 %		
y	70.22979098		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.758219244	16	0.000826265
u_{geo}	0.239801241	3	6.88913E-05
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

E_{Lprop}	0.007556675	
$L_{measstd}$	0.04	Degree of freedom
$u_{measstd}$	0	8

Calibrated value	70.229262011
standard uncertainty	0.359660188
k factor	2.148852324
Extended uncertainty	0.772856631

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration\ /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
7-13	71.52240944	70.2793	70.2793	70.2873
7-13	69.05719553	69.6897	70.2873	70.2873
7-13	69.06526558	69.6763	70.8904	69.6763
7-13	70.27933711	70.3006	71.4989	70.8983
7-13	69.06526558	69.0572	70.3192	70.8904
y_i	69.79789465	69.8006345	70.65501583	70.40794804
S_i	1.098620043	0.514675936	0.53773109	0.509320957
(S_i)^2	1.206966	0.264891319	0.289154725	0.259407837
y_i - y	-0.367478609	-0.36473875	0.489642571	0.242574788
$(y_i$ - y)^2	0.135040528	0.133034356	0.239749847	0.058842528

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p)	95.45 %		
y	70.16537326		
		Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.710707373	16	0.000637828
u_{geo}	0.21730686	3	4.64571E-05
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

E_{Lprop}	0.007556675	
$L_{measstd}$	0.04	Degree of freedom
$u_{measstd}$	0	8

Calibrated value	70.164844288
standard uncertainty	0.335896665
k factor	2.148852324
Extended uncertainty	0.72179233

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
ength of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
CG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
9-25	67.90104612	68.4543	70.2793	70.8904
9-25	69.06530633	69.0572	69.6656	69.0653
9-25	69.66828649	69.0977	69.6683	71.4989
9-25	69.05449148	69.6656	69.0653	69.0977
9-25	69.06530705	70.9115	70.3006	69.6656
y_i	68.95088749	69.43725736	69.79581694	70.04356592
S_j	0.642990188	0.92890461	0.513678013	1.098811769
(S_j)^2	0.413436382	0.862863774	0.263865101	1.207387304
y_i - y	-0.605994434	-0.119624573	0.238935011	0.486683995
$(y_i$ - y)^2	0.367229253	0.014310038	0.05708994	0.236861311

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p) 95.45 %

y 69.55688193

E_{Lprop} 0.007556675

		Degree of freedom (ν_c)	u_c^4 / ν_c
u_{rep}	0.82878715	16	0.001179538
u_{geo}	0.237256988	3	6.60138E-05
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

		Degree of freedom
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	69.556352961
standard uncertainty	0.389166231
k factor	2.148852324
Extended uncertainty	0.83626076

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
25-31	71.54068234	70.9299	70.2794	69.6656
25-31	71.49886868	70.2793	69.6683	70.8904
25-31	69.67628612	70.8904	69.0572	69.0788
25-31	69.6655654	70.2793	70.2767	69.6763
25-31	71.49890944	67.8350	69.7085	69.6656
y_i	70.7760624	70.04280082	69.79800353	69.79535808
S_j	1.008998498	1.273932426	0.508549498	0.663408288
(S_j)^2	1.01807797	1.622903826	0.258622592	0.440110556
y_i - y	0.673006189	-0.060255389	-0.305052676	-0.307698124
$(y_i$ - y)^2	0.452937331	0.003630712	0.093057135	0.094678136

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p) 95.45 %

y 70.10305621

E_{Lprop} 0.007556675

		Degree of freedom (ν_c)	u_c^4 / ν_c
u_{rep}	0.913744349	16	0.001742765
u_{geo}	0.231715219	3	6.00588E-05
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

		Degree of freedom
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	70.102527240
standard uncertainty	0.424745501
k factor	2.148852324
Extended uncertainty	0.912715357

Effective degree of freedom 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
1-8	98.52580655	98.9626	98.5371	97.2266
1-8	98.95508297	100.6909	98.0908	97.2266
1-8	98.09845866	100.2654	99.8193	98.0909
1-8	98.52580655	98.1137	97.6616	97.2343
1-8	98.53717711	99.4013	98.5258	97.2266
y_j	98.52846637	99.4867874	98.52693708	97.40101939
S_j	0.302901956	1.027569916	0.807664043	0.385654551
(S_j)^2	0.091749595	1.055899933	0.652321207	0.148729433
y_j - y	0.042663809	1.000984843	0.041134521	-1.084783173
$(y_j$ - y)^2	0.001820201	1.001970657	0.001692049	1.176754532

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p) 95.45 %

y 98.48580256

E_{Lprop} 0.007556675

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.697979256	16	0.000593349
u_{geo}	0.426442399	3	0.00068897
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
$L_{meas std}$	0.04	
$u_{meas std}$	0	8

Calibrated value	98.485273592
standard uncertainty	0.37801891
k factor	2.181165682
Extended uncertainty	0.824521873

Effective degree of freedom 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
8-15	99.39002026	100.2542	100.2542	98.0908
8-15	99.39002026	98.5258	100.6835	100.6835
8-15	100.254206	99.3862	99.8268	98.9551
8-15	100.2541769	99.3862	99.8193	97.6922
8-15	99.40129197	99.3900	98.9551	99.8268
y_j	99.73794307	99.38849448	99.90777737	99.04968848
S_j	0.471290588	0.611074502	0.641048827	1.229272145
(S_j)^2	0.222114818	0.373412046	0.410943598	1.511110006
y_j - y	0.216967221	-0.132481372	0.38680152	-0.47128737
$(y_j$ - y)^2	0.047074775	0.017551314	0.149615416	0.222111785

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p) 95.45 %

y 99.52097585

E_{Lprop} 0.007556675

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
u_{rep}	0.793344261	16	0.000990346
u_{geo}	0.190690257	3	2.75469E-05
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
$L_{meas std}$	0.04	
$u_{meas std}$	0	8

Calibrated value	99.520446883
standard uncertainty	0.36738226
k factor	2.158263401
Extended uncertainty	0.792907685

Effective degree of freedom 17

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
gth of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
31.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
22	98.53717711	97.2266	98.9551	98.9777
22	96.36239729	98.5258	98.5258	98.9777
22	97.2266064	98.5372	98.9626	100.2654
22	96.79743854	97.2343	98.0985	100.2505
22	97.66159342	97.2266	98.9551	98.1137
y_j	97.31704255	97.75011434	98.69940662	99.31698716
S_j	0.836205455	0.713315022	0.384468152	0.928568699
(S_j)^2	0.699239563	0.508818321	0.14781576	0.86223983
y_j - y	-0.953845114	-0.52077333	0.42851895	1.046099494
$(y_j$ - y)^2	0.909820502	0.271204861	0.183628491	1.094324151

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	98.27088767		
u_{rep}	0.744666616	16	0.000768754
u_{geo}	0.452675197	3	0.000874794
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
E_{Lprop}	0.007556675	
$L_{meas std}$	0.04	
$u_{meas std}$	0	8

Calibrated value	98.270358701
standard uncertainty	0.402659149
k factor	2.181165682
Extended uncertainty	0.878266316

Effective degree of freedom: 15

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	(T_M – 20°C) = (T_W – 20°C)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
22-29	99.81929277	96.7974	98.5372	99.8193
22-29	101.1479334	95.5060	97.6922	97.2343
22-29	100.254206	96.7936	96.37017659	98.0985
22-29	99.38999169	99.3900	97.6578	98.0985
22-29	99.40126265	99.8417	98.0908	101.1147
y_j	100.0025373	97.66575132	97.66962971	98.87303936
S_j	0.732391828	1.863277015	1.79057738	1.565717713
(S_j)^2	0.53639779	3.471801233	3.206167352	2.451471956
y_j - y	1.449797871	-0.886988102	-0.883109712	0.320299943
$(y_j$ - y)^2	2.101913866	0.786747892	0.779882764	0.102592054

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

	Value	Degree of freedom (ν_e)	u_e^4 / ν_e
Coverage factor (p)	95.45 %		
y	98.55273942		
u_{rep}	1.554496569	16	0.014598192
u_{geo}	0.560590208	3	0.002057504
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
E_{Lprop}	0.007556675	
$L_{meas std}$	0.04	
$u_{meas std}$	0	8

Calibrated value	98.552210451
standard uncertainty	0.749571391
k factor	2.148852324
Extended uncertainty	1.610718225

Effective degree of freedom: 18

CALCULATION OF LENGTH CALIBRATION

Object of calibration					
Length of measurement [mm]	CTE [K^{-1}]	Uncertainty of CTE ($u_{\alpha W}$) [K^{-1}]	($u^2_{TW} + u^2_{TWS}$) [K^2]	$u_{\alpha M}$	($T_M - 20°C$) = ($T_W - 20°C$)
0.07	2.22E-05	0.00000069	0.003333333	5.7735E-08	0.5

Reference artefact used					
Type	Part number	Nominal length /mm	Calibrated length /mm	$U_{calibration /mm}$	k
ACG1.2 artefact	-	0.04	0.039700	0.0001	2

Calibration measurments: 4 positions, 5 repeatitions each				
Measurement repetition name	Position 1	Position 2	Position 3	Position 4
29-36	97.69217886	99.8641	98.0908	100.2654
29-36	98.09084486	102.0375	100.2654	98.0985
29-36	100.6835025	100.7058	101.1184	98.5220
29-36	98.09845866	101.1295	101.1184	99.3863
29-36	99.81929277	100.2505	101.1147	99.3862
y_j	98.87685552	100.7974749	100.3415299	99.13167051
S_j	1.301857747	0.840620764	1.311138346	0.844688865
$(S_j)^2$	1.694833593	0.706643269	1.719083763	0.713499279
y_j - y	-0.91002718	1.010592188	0.554647184	-0.655212192
$(y_j - y)^2$	0.828149469	1.021296571	0.307633499	0.429303017

Gauge block measurement			
Measurements No.	Position 1	Position 2	Position 3
1	0.04	0.04	0.04
2	0.04	0.04	0.04
3	0.04	0.04	0.04

Coverage factor (p) 95.45 %

y 99.7868827

E_{Lprop} 0.007556675

	Value	Degree of freedom (v_e)	u_e^4 / v_e
u_{rep}	1.099324782	16	0.003651271
u_{geo}	0.464254111	3	0.000967791
E_L	0.000528967		
u_{corr}	8.81612E-05	0	0
u_{temp}	9.29356E-08	∞	0

	Value	Degree of freedom
$L_{measstd}$	0.04	
$u_{measstd}$	0	8

Calibrated value	99.786353735
standard uncertainty	0.543678189
k factor	2.148852324
Extended uncertainty	1.168284139

Effective degree of freedom 18

Appendix (11)

20×

20x

Horizontal	1	2	3	4	5
L	6.99468E-05	0.000141	0.00021	0.000281	0.00035
σ1	0.482818089	0.77828	0.470639	0.00581	0.312163
σ2	0.475215889	0.31146	0.419254	0.41756	0.411294
σ3	0.000818377	0.001647	0.002462	0.003283	0.004098
σ4	8.18377E-05	0.000165	0.000246	0.000328	0.00041
$σ_{total}$	0.67745415	0.838289	0.630303	0.417614	0.516358

Vertical	1	2	3	4	5
L	6.96127E-05	0.00014	0.00021	0.00028	0.00035
σ1	0.177458642	0.179558	0.313841	0.308724	0.894255
σ2	0.455154498	0.35966	0.335897	0.389166	0.424746
σ3	0.000814468	0.001636	0.002457	0.003271	0.004091
σ4	8.14468E-05	0.000164	0.000246	0.000327	0.000409
$σ_{total}$	0.488526209	0.401994	0.459705	0.496761	0.990009

Diagonal	1	2	3	4	5
L	9.84858E-05	0.000198	0.000296	0.000395	0.000495
σ1	0.321891301	0.582289	0.345817	0.593761	0.723216
σ2	0.37801891	0.367382	0.402659	0.749571	0.543678
σ3	0.001152284	0.002317	0.003466	0.00462	0.005787
σ4	0.000115228	0.000232	0.000347	0.000462	0.000579
$σ_{total}$	0.496501407	0.688503	0.530788	0.956259	0.904799

σ1= standard deviation /sqrt(3)
σ2= standard uncertainty calibration of each length
σ3= (L*11.7*1) L=m /$σ_{steel}$=11.7 /ΔT=(21-20 C˚)
σ4= (L*10%*11.7*1)
L= uncertainty calculation of length

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	68.96023276	140.5617	208.8559	279.7736	348.0773
Difference2	69.6043758	142.5393	209.5171	279.7812	349.3979
Difference3	70.96629937	139.2605	207.5548	279.7977	348.8235
Mean	69.84363598	140.7872	208.6426	279.7841	348.7663
SD	0.836265462	1.34802	0.815171	0.010063	0.540682
SD/sqrt(3)	0.482818089	0.77828	0.470639	0.00581	0.312163

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	70.26409381	138.5583	209.476	277.1137	346.0739
Difference2	69.60747316	139.2149	210.1448	276.479	346.0864
Difference3	69.6167644	139.2211	210.8075	277.7886	349.3658
Mean	69.82944379	138.9981	210.1428	277.1271	347.1754
SD	0.307367384	0.311003	0.543588	0.534725	1.548895
SD/sqrt(3)	0.177458642	0.179558	0.313841	0.308724	0.894255

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	98.90958283	197.8192	294.8895	394.7276	492.2388
Difference2	99.36843441	200.1266	295.322	394.2229	492.6758
Difference3	98.02506044	199.7372	296.3199	396.6126	495.0875
Mean	98.76769256	199.2277	295.5104	395.1877	493.334
SD	0.557532088	1.008554	0.598973	1.028425	1.252647
SD/sqrt(3)	0.321891301	0.582289	0.345817	0.593761	0.723216

10×

10x

Horizontal	1	2	3	4	5
L	6.99468E-05	0.000141	0.00021	0.000281	0.00035
σ1	0.618653329	0.398881	0.629795	0.471442	0.396946
σ2	0.475215889	0.31146	0.419254	0.41756	0.411294
σ3	0.000818377	0.001647	0.002462	0.003283	0.004098
σ4	8.18377E-05	0.000165	0.000246	0.000328	0.00041
$σ_{total}$	0.780104326	0.506079	0.756586	0.629781	0.571617

Vertical	1	2	3	4	5
L	0.00006961	0.00014	0.00021	0.0002796	0.0003497
σ1	0.409221393	0.717487	0.8316435	0.6327565	0.8691175
σ2	0.455154498	0.35966	0.3358967	0.3891662	0.4247455
σ3	0.000814468	0.001636	0.0024571	0.0032709	0.0040911
σ4	0.00008145	0.000164	0.0002457	0.0003271	0.0004091
$σ_{total}$	0.61206898	0.802587	0.8969189	0.7428606	0.9673629

Diagonal	1	2	3	4	5
L	9.84858E-05	0.000198	0.000296	0.000395	0.00049
σ1	0.164982479	1.34334	0.733584	0.587132	1.29815
σ2	0.37801891	0.367382	0.402659	0.749571	0.543678
σ3	0.001152284	0.002317	0.003466	0.00462	0.005787
σ4	0.000115228	0.000232	0.000347	0.000462	0.000579
$σ_{total}$	0.412454671	1.392673	0.836834	0.952157	1.407413

σ1= standard deviation /sqrt(3)
σ2= standard uncertainty calibration of each length
σ3= (L*11.7*1) L=m /$σ_{steel}$=11.7 /ΔT=(21-20 C˚)
σ4= (L*10%*11.7*1)
L= uncertainty calculation of length

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	70.14947979	141.1757	208.7803	283.329	349.9888
Difference2	68.44096592	139.4834	207.8738	281.572	349.1083
Difference3	71.0208	140.3379	210.5038	283.2782	350.7918
Mean	69.87041524	140.3323	209.0527	282.7264	349.963
SD	1.071538998	0.690882	1.090838	0.816561	0.68753
SD/sqrt(3)	0.618653329	0.398881	0.629795	0.471442	0.396946

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	66.65986969	139.4396	208.72895	276.24255	345.53194
Difference2	67.51929327	136.792	206.95796	275.37084	344.66023
Difference3	68.39602028	139.4168	210.48631	278.00561	348.19891
Mean	67.52506108	138.5495	208.72441	276.53966	346.13036
SD	0.708792245	1.242725	1.4404488	1.0959664	1.5053557
SD/sqrt(3)	0.409221393	0.717487	0.8316435	0.6327565	0.8691175

σ1 calculation

	L1	L2	L3	L4	L5
Difference1	97.96646134	198.4127	293.8913	393.7119	492.9105
Difference2	97.35639127	193.473	292.6716	395.0622	487.4929
Difference3	97.95861367	198.4048	295.7612	396.1998	491.0605
Mean	97.76048876	196.7635	294.1081	394.9913	490.4879
SD	0.285758036	2.326733	1.270604	1.016942	2.248461
SD/sqrt(3)	0.164982479	1.34334	0.733584	0.587132	1.29815

Appendix (12) – Zygo data

	X1	X2	X3	X4	X5	Mean	SD	SD/sqrt(5)
1	91.2057	91.2057	88.2072	91.2057	91.2057	36.9310	1.1994	0.536388
2	265.1208	266.6201	262.1223	263.6215	265.1208	107.8188	1.528961	0.683772
3	437.5366	437.5366	436.0373	436.0373	436.0373	177.9732	0.734504	0.32848
4	605.4546	606.9539	603.9553	603.9553	608.4531	246.9055	1.748438	0.781925
5	782.3682	779.3697	779.3697	777.8704	780.869	317.9155	1.528961	0.683772
6	948.787	951.7855	948.787	950.2862	948.787	387.0922	1.199395	0.536386
7	92.705	91.2057	89.7064	89.7064	86.7079	36.6866	1.989013	0.889514
8	263.6215	263.6215	260.623	260.623	259.1237	106.5966	1.799113	0.804588
9	433.0388	437.5366	436.0373	433.0388	434.5381	177.2399	1.748425	0.781919
10	605.4546	605.4546	602.4561	603.9553	603.9553	246.2944	1.121941	0.501747
11	773.3726	776.3712	776.3712	773.3726	771.8734	315.5933	1.799133	0.804597
12	948.787	950.2862	948.787	947.2877	944.2892	386.3589	2.03369	0.909494
13	92.705	88.2072	89.7064	88.2072	91.2057	36.6866	1.748428	0.781921
14	262.1223	259.1237	260.623	262.1223	260.623	106.3522	1.121973	0.501762
15	434.5381	434.5381	433.0388	436.0373	434.5381	177.1177	0.948209	0.424052
16	605.4546	603.9553	603.9553	602.4561	605.4546	246.2944	1.121941	0.501747
17	771.8734	773.3726	771.8734	773.3726	776.3712	315.2267	1.642364	0.734488
18	947.2877	947.2877	947.2877	945.7884	947.2877	385.9922	0.59972	0.268203
19	88.2072	86.7079	86.7079	86.7079	88.2072	35.5866	0.734504	0.32848
20	260.623	260.623	257.6245	257.6245	262.1223	105.8633	1.799113	0.804588
21	433.0388	430.0403	431.5395	434.5381	437.5366	176.6288	2.579435	1.153558
22	602.4561	602.4561	600.9568	602.4561	605.4546	245.6833	1.468971	0.656944
23	771.8734	770.3741	773.3726	770.3741	774.8719	314.7378	1.748425	0.781919
24	945.7884	945.7884	948.787	947.2877	945.7884	385.8700	1.19944	0.536406
25	80.7108	83.7094	85.2086	86.7079	85.2086	34.3644	2.033708	0.909502
26	257.6245	257.6245	259.1237	259.1237	262.1223	105.6188	1.642364	0.734488
27	430.0403	431.5395	434.5381	431.5395	433.0388	176.1400	1.528965	0.683774
28	602.4561	603.9553	600.9568	603.9553	606.9539	246.0500	1.989007	0.889511
29	776.3712	773.3726	773.3726	773.3726	774.8719	315.5933	1.19944	0.536406
30	948.787	948.787	947.2877	947.2877	945.7884	386.2367	1.121973	0.501762
31	86.7079	83.7094	88.2072	86.7079	85.2086	35.0977	1.528961	0.683772
32	256.1252	257.6245	254.6259	259.1237	256.1252	104.6411	1.528961	0.683772
33	431.5395	431.5395	431.5395	433.0388	430.0403	175.8955	0.948209	0.424052
34	600.9568	600.9568	602.4561	602.4561	602.4561	245.3167	0.734504	0.32848
35	776.3712	771.8734	776.3712	776.3712	774.8719	315.9600	1.748432	0.781922
36	950.2862	944.2892	947.2877	945.7884	947.2877	385.9922	1.988986	0.889502

	Y1	Y2	Y3	Y4	Y5	Mean	SD	SD/sqrt(5)
1	94.2042	94.2042	95.7035	95.7035	95.7035	38.7643	0.734504	0.32848
2	91.2057	94.2042	95.7035	94.2042	94.2042	38.2754	1.468971	0.656944
3	95.7035	95.7035	94.2042	97.2028	95.7035	39.0087	0.948241	0.424066
4	97.2028	97.2028	100.2013	98.702	98.702	40.1087	1.121931	0.501743
5	95.7035	98.702	98.702	100.2013	97.2028	39.9865	1.528949	0.683767
6	97.2028	98.702	100.2013	95.7035	94.2042	39.6198	2.120288	0.948222
7	265.1208	266.6201	262.1223	265.1208	268.1193	108.1855	1.988986	0.889502
8	263.6215	265.1208	263.6215	268.1193	269.6186	108.4299	2.436027	1.089425
9	265.1208	269.6186	266.6201	269.6186	266.6201	109.0410	1.799113	0.804588
10	266.6201	266.6201	266.6201	268.1193	266.6201	108.7966	0.59968	0.268185
11	271.1179	271.1179	269.6186	271.1179	271.1179	110.3854	0.59972	0.268203
12	269.6186	271.1179	271.1179	272.6171	272.6171	110.6299	1.121931	0.501743
13	436.0373	437.5366	439.0359	437.5366	439.0359	178.4621	1.121973	0.501762
14	439.0359	439.0359	436.0373	440.5351	439.0359	178.8288	1.468983	0.656949
15	437.5366	439.0359	439.0359	440.5351	440.5351	178.9510	0.948209	0.424052
16	437.5366	436.0373	436.0373	436.0373	434.5381	177.7288	0.948209	0.424052
17	442.0344	440.5351	440.5351	436.0373	440.5351	179.3177	2.033711	0.909503
18	442.0344	443.5337	440.5351	440.5351	445.0329	180.2954	1.748438	0.781925
19	611.4517	606.9539	608.4531	609.9524	608.4531	248.2499	1.528965	0.683774
20	609.9524	611.4517	609.9524	611.4517	609.9524	248.8610	0.734504	0.32848
21	609.9524	612.951	611.4517	611.4517	609.9524	249.1055	1.121973	0.501762
22	611.4517	605.4546	608.4531	609.9524	606.9539	248.0055	2.120288	0.948222
23	612.951	612.951	611.4517	611.4517	614.4502	249.7166	1.121941	0.501747
24	612.951	614.4502	614.4502	612.951	611.4517	249.9610	1.121931	0.501743
25	777.8704	776.3712	779.3697	779.3697	777.8704	317.1822	1.121941	0.501747
26	783.8675	785.3668	780.869	780.869	780.869	318.8933	1.896434	0.848111
27	777.8704	779.3697	780.869	779.3697	779.3697	317.6711	0.948241	0.424066
28	779.3697	780.869	782.3682	780.869	780.869	318.2822	0.948209	0.424052
29	783.8675	785.3668	783.8675	783.8675	782.3682	319.5044	0.948241	0.424066
30	783.8675	786.866	785.3668	785.3668	782.3682	319.8711	1.528965	0.683774
31	953.2848	951.7855	950.2862	950.2862	953.2848	387.9478	1.341015	0.59972
32	953.2848	953.2848	954.784	951.7855	953.2848	388.5589	0.948209	0.424052
33	956.2833	953.2848	957.7826	953.2848	956.2833	389.4144	1.799113	0.804588
34	950.2862	951.7855	954.784	953.2848	956.2833	388.5589	2.120288	0.948222
35	945.7884	953.2848	957.7826	948.787	953.2848	387.9478	4.133212	1.848429
36	948.787	954.784	959.2818	951.7855	956.2833	388.9255	3.623121	1.620309

Alicona data

20x						
	X1	X2	X3	Mean	SD	SD/sqrt(3)
1	70.2123	67.2139	68.7131	30.10	1.224092	0.70673
2	227.6272	226.128	230.6256	99.92	1.869831	1.079547
3	391.0389	392.5381	386.5413	170.84	2.54815	1.471175
4	546.9546	545.4554	542.4571	238.69	1.869786	1.079522
5	708.8671	705.8687	707.3679	309.83	1.224092	0.70673
6	864.7828	864.7828	864.3828	378.72	0.188562	0.108866
7	68.7131	65.7147	65.7147	29.22	1.413459	0.816061
8	227.6272	229.1264	221.6305	99.04	3.238596	1.869804
9	391.0389	392.5381	389.5397	171.28	1.224092	0.70673
10	545.4554	546.9546	543.9562	238.91	1.224092	0.70673
11	704.3695	704.3695	702.8703	308.29	0.70673	0.408031
12	866.282	861.7844	861.7844	378.12	2.120189	1.224092
13	67.2139	67.2139	65.7147	29.22	0.70673	0.408031
14	226.128	224.6288	223.1297	98.39	1.224051	0.706706
15	389.5397	391.0389	389.5397	170.84	0.70673	0.408031
16	543.9562	543.9562	543.8956	238.24	0.028558	0.016488
17	704.3695	704.3695	701.3712	308.08	1.413412	0.816034
18	864.7828	864.7828	864.6828	378.76	0.04714	0.027217
19	67.2139	70.2123	62.7164	29.22	3.08052	1.778539
20	220.1313	221.6305	226.128	97.51	2.548104	1.471149
21	392.5381	389.5397	386.5413	170.62	2.448183	1.413459
22	542.4571	542.4571	543.9562	237.82	0.706683	0.408003
23	702.8703	702.8703	704.3695	308.08	0.70673	0.408031
24	864.7828	866.282	861.7844	378.56	1.869831	1.079547
25	68.7131	67.2139	61.2172	28.78	3.238596	1.869804
26	223.1297	223.1297	221.6305	97.51	0.70673	0.408031
27	386.5413	388.0405	389.5397	169.96	1.224092	0.70673
28	542.4571	543.9562	542.4571	237.82	0.706683	0.408003
29	701.3712	701.3712	705.8687	307.86	2.120142	1.224064
30	.2836 702.8	861.7844	860.2853	377.13	0.74955	0.432753
31	65.7147	68.7131	62.7164	28.78	2.448143	1.413436
32	223.1297	224.6288	220.1313	97.51	1.869795	1.079527
33	388.0405	385.0421	382.0438	168.65	2.448143	1.413436
34	537.9595	540.9579	540.9579	236.50	1.413459	0.816061
35	702.8703	702.8703	699.872	307.42	1.413412	0.816034
36	860.2853	857.2869	860.2853	376.37	1.413459	0.816061

20x						
	Y1	Y2	Y3	Mean	SD	SD/sqrt(3)
1	62.7139	64.2131	61.2147	27.47	1.224092	0.71
2	65.7123	64.2131	67.2115	28.78	1.22	0.71
3	70.2099	70.2099	65.7123	30.10	2.12	1.22
4	71.7091	70.2099	67.2115	30.53	1.87	1.08
5	71.7091	68.7107	70.2099	30.75	1.22	0.71
6	68.7107	65.7123	62.7139	28.78	2.45	1.41
7	223.1272	223.1272	220.1288	97.29	1.41	0.82
8	224.6264	223.1272	224.6264	98.17	0.71	0.41
9	226.1256	224.6264	224.6264	98.61	0.71	0.41
10	229.124	227.6248	226.1256	99.70	1.22	0.71
11	232.1224	232.1224	230.6232	101.45	0.71	0.41
12	232.1224	232.1224	229.124	101.23	1.41	0.82
13	379.0429	382.0413	379.0429	166.46	1.41	0.82
14	383.5405	383.5405	380.5421	167.55	1.41	0.82
15	382.0413	386.5389	385.0397	168.43	1.87	1.08
16	382.0413	379.0429	374.5454	165.80	3.08	1.78
17	382.0413	382.0413	382.0413	167.33	0.00	0.00
18	385.0397	385.0397	388.0381	169.09	1.41	0.82
19	540.9554	543.9538	542.4546	237.60	1.22	0.71
20	539.4562	543.9538	540.9554	237.16	1.87	1.08
21	543.9538	545.453	546.9522	238.91	1.22	0.71
22	542.4546	542.4546	542.4546	237.60	0.00	0.00
23	542.4546	546.9522	543.9538	238.47	1.87	1.08
24	545.453	546.9522	549.9506	239.78	1.87	1.08
25	695.372	695.372	695.372	304.57	0.00	0.00
26	702.8679	705.8663	705.8663	308.73	1.41	0.82
27	704.3671	702.8679	701.3687	307.86	1.22	0.71
28	704.3671	699.8695	711.863	308.95	4.95	2.86
29	705.8663	702.8679	704.3671	308.51	1.22	0.71
30	702.8679	701.3687	708.8647	308.51	3.24	1.87
31	852.7869	854.2861	858.7836	374.62	2.55	1.47
32	864.7804	861.782	864.7804	378.34	1.41	0.82
33	864.7804	864.7804	863.2812	378.55	0.71	0.41
34	863.2812	860.2828	861.782	377.46	1.22	0.71
35	860.2828	867.7788	863.2812	378.34	3.08	1.78
36	861.782	864.7804	867.7788	378.77	2.45	1.41

10x						
	X1	X2	X3	Mean	SD	SD/sqrt(3)
1	37	40	38	33.61	1.247219	0.7200823
2	117	118	119	103.46	0.816497	0.471404521
3	198	199	198	173.90	0.471405	0.272165527
4	275	277	278	242.58	1.247219	0.7200823
5	360	361	361	316.23	0.471405	0.272165527
6	436	438	438	383.45	0.942809	0.544331054
7	39	39	38	33.90	0.471405	0.272165527
8	117	117	118	102.88	0.471405	0.272165527
9	199	200	200	175.07	0.471405	0.272165527
10	276	276	275	241.70	0.471405	0.272165527
11	360	356	356	313.31	1.885618	1.088662108
12	437	436	437	382.87	0.471405	0.272165527
13	38	40	39	34.20	0.816497	0.471404521
14	116	118	118	102.88	0.942809	0.544331054
15	199	196	199	173.61	1.414214	0.816496581
16	275	277	276	242.00	0.816497	0.471404521
17	359	358	356	313.60	1.247219	0.7200823
18	437	437	4387	1537.61	1862.048	1075.053832
19	36	38	36	32.15	0.942809	0.544331054
20	115	116	117	101.71	0.816497	0.471404521
21	197	197	198	173.02	0.471405	0.272165527
22	276	276	2776	972.66	1178.511	680.4138174
23	357	355	358	312.73	1.247219	0.7200823
24	438	436	439	383.75	1.247219	0.7200823
25	36	36	37	31.86	0.471405	0.272165527
26	115	116	116	101.42	0.471405	0.272165527
27	196	197	197	172.44	0.471405	0.272165527
28	276	274	275	241.12	0.816497	0.471404521
29	356	355	357	312.14	0.816497	0.471404521
30	437	435	436	382.28	0.816497	0.471404521
31	38	38	40	33.90	0.942809	0.544331054
32	114	114	115	100.25	0.471405	0.272165527
33	197	197	199	173.31	0.942809	0.544331054
34	273	273	274	239.66	0.471405	0.272165527
35	353	354	354	310.09	0.471405	0.272165527
36	436	432	434	380.53	1.632993	0.942809042

10x						
	Y1	Y2	Y3	Mean	SD	SD/sqrt(3)
1	32.4416	32.4416	30.688	31.86	0.826655	0.477269
2	38	34	35	31.27	1.699673	0.981307
3	37	36	38	32.44	0.816497	0.471405
4	41	36	36	33.03	2.357023	1.360828
5	39	39	36	33.32	1.414214	0.816497
6	37	37	36	32.15	0.471405	0.272166
7	113	114	113	99.37	0.471405	0.272166
8	115	117	114	101.12	1.247219	0.720082
9	115	114	115	100.54	0.471405	0.272166
10	115	114	117	101.12	1.247219	0.720082
11	117	115	117	102.00	0.942809	0.544331
12	118	117	117	102.88	0.471405	0.272166
13	196	193	194	170.39	1.247219	0.720082
14	196	196	194	171.27	0.942809	0.544331
15	195	193	194	170.10	0.816497	0.471405
16	193	193	195	169.81	0.942809	0.544331
17	194	193	195	170.10	0.816497	0.471405
18	194	191	196	169.81	2.054805	1.186342
19	275	273	275	240.54	0.942809	0.544331
20	275	274	274	240.54	0.471405	0.272166
21	274	275	277	241.41	1.247219	0.720082
22	272	273	274	239.37	0.816497	0.471405
23	274	275	275	240.83	0.471405	0.272166
24	272	274	273	239.37	0.816497	0.471405
25	352	351	352	308.34	0.471405	0.272166
26	352	353	353	309.22	0.471405	0.272166
27	357	354	353	310.97	1.699673	0.981307
28	357	357	358	313.31	0.471405	0.272166
29	353	359	355	311.85	2.494438	1.440165
30	350	362	356	312.14	4.898979	2.828427
31	431	430	432	377.90	0.816497	0.471405
32	430	432	430	377.61	0.942809	0.544331
33	429	433	434	378.78	2.160247	1.247219
34	431	433	433	379.07	0.942809	0.544331
35	434	435	433	380.53	0.816497	0.471405
36	433	431	431	378.49	0.942809	0.544331

Appendix (13)

MATLAB code for Resolution (Ch. 7):

```
%======================Processing ZYgo data - as reference ===============
noOfReplication=1;
filePath ='ANAS_Resolution_data\';
filePathFolder=filePath;

matVal = zeros(20e6,3); %NOTES: use pre-allocated memory (like in C/C++)
where rhe variables are declared first.
for j=1:noOfReplication
    filename='zygo5_1'; %'test_alicona';%'test_zygo';
    fullName=[filePathFolder '\' filename '.txt'] %string concatenation,
alternative to strcat()
    fid=fopen(fullName,'r'); %opening the file
    pointCounter=0;
    line_counter=0;

    while (~feof(fid))
        readLine=fgetl(fid);
        if (~ischar(readLine))
            break
        end

        val=regexp(readLine,' ','split'); %Splitting the string with
certain delimiter
        if(size(val,2)>=3)
            if(~isnan(str2double(val(3)))) %check if the z value is not NaN
                pointCounter= pointCounter+1;
                matVal(pointCounter,1)=str2double(val(1));%*delta_x;
                matVal(pointCounter,2)=str2double(val(2));%*delta_y;
                if(strcmp(val(3),'***'))
                    matVal(pointCounter,3)=matVal(pointCounter-1,3) %use
the previous one
                else
                    matVal(pointCounter,3)=str2double(val(3)); %unit in ?
                end
            end
        end

    end %END of while

    fclose(fid);

end %END of the inner for j
matVal(pointCounter+1:end,:) = [];


%%CALCULATING the heigth with respect to lateral distance-------------
nLag=pointCounter;
ZhTotal = zeros(nLag,2*nLag); % column 1=for the value, 2=for the lag index
var = zeros(1,nLag); % column 1=for the value, 2=for the lag index
average_heigth=zeros(1,nLag);
lagIndex=zeros(1,nLag);

lagIndexCounter=0;
ZhColCounter=0;
```

```
for i=1:pointCounter
    for j=1:pointCounter
        lag=sqrt(sum((matVal(i,:)-matVal(j,:)).^2));%Euclidean distance
%abs(matVal(i,1)-matVal(j,1));
        if(j~=i)
            if(i==1)
                lagIndexCounter=lagIndexCounter+1;
                lagIndex(lagIndexCounter)=lag; % record all the possible
lag
                %ZhColCounter=ZhColCounter+1;
                ZhTotal(lagIndexCounter,1)=abs(matVal(i,3)-matVal(j,3));

            else
                counter=1;
                while ((lagIndex(counter)-lag)> 0.05)
%lagIndex(counter)~=lag %if the difference < 0.05 um, they are the same
                    counter=counter+1;
                    if(counter>nLag)
                        counter=counter-1;
                        break;
                    end
                end
                colCounter=1;
                while(ZhTotal(counter,colCounter)~=0)
                    colCounter=colCounter+1;
                    if(colCounter>2*nLag)
                        colCounter=colCounter-1;
                        break;
                    end
                end
                ZhTotal(counter,colCounter)=abs(matVal(i,3)-matVal(j,3));
            end
        end
    end
end
lagIndex;
ZhTotal;

%calculating the average heigth
average_heigth(lagIndexCounter+1:end)=[];
lagIndex(lagIndexCounter+1:end)=[];
for i=1:lagIndexCounter
    average_heigth(i)=0;
    j=1;
    colCounter=1;
    while ZhTotal(i,colCounter)~=0
        average_heigth(i)=average_heigth(i)+ZhTotal(i,colCounter);
        colCounter=colCounter+1;
         if(colCounter>2*nLag)
            colCounter=colCounter-1;
            break;
         end
    end
    average_heigth(i)=average_heigth(i)/colCounter;
end
average_heigth;

%----------------------------------------------------------------------

figure;
```

```
plot(lagIndex,average_heigth,'.');
ylabel('Average height/um');
xlabel('lateral distance/um');
title('Zygo data');

matrix_size=size(matVal);

%WRITING The data to File: lagIndex, avergae_height, ZhTotal
fullName2=[filePathFolder '\' filename '-lagIndex_ZYGO.txt'] %string
concatenation, alternative to strcat()
fid2=fopen(fullName2,'w');
for i=1:length(lagIndex)
    fprintf(fid2,'%f\n',lagIndex(i));
end
fclose(fid2);

fullName2=[filePathFolder '\' filename '-averageHeight_ZYGO.txt'] %string
concatenation, alternative to strcat()
fid2=fopen(fullName2,'w');
for i=1:length(lagIndex)
    fprintf(fid2,'%f\n',average_heigth(i));
end
fclose(fid2);

fullName2=[filePathFolder '\' filename '-zhTotal_ZYGO.txt'] %string
concatenation, alternative to strcat()
fid2=fopen(fullName2,'w');
for i=1:length(lagIndex)
    colCounter=1;
    fprintf(fid2,'%f\t',lagIndex(i));
    while ZhTotal(i,colCounter)~=0
        fprintf(fid2,'%f\t',ZhTotal(i,colCounter));
        colCounter=colCounter+1;
        if(colCounter>2*nLag)
            colCounter=colCounter-1;
            break;
        end
    end
    fprintf(fid2,'\n');
end
fclose(fid2);

%keep all the data
lagIndex_zygo=lagIndex;
average_heigth_zygo=average_heigth;
ZhTotal_zygo=ZhTotal;


%====================== Processing Alicona data ==========================
noOfReplication=1;
filePath ='ANAS_Resolution_data\';
filePathFolder=filePath;

matVal = zeros(20e6,3); %NOTES: use pre-allocated memory (like in C/C++)
where rhe variables are declared first.
for j=1:noOfReplication
    filename='alicona5_1';
    fullName=[filePathFolder '\' filename '.txt'] %string concatenation,
alternative to strcat()
    fid=fopen(fullName,'r'); %opening the file
```

```
    pointCounter=0;
    line_counter=0;

    while (~feof(fid))
        readLine=fgetl(fid);
        if (~ischar(readLine))
            break
        end

        val=regexp(readLine,' ','split'); %Splitting the string with
certain delimiter
        if(size(val,2)>=3)
            if(~isnan(str2double(val(3)))) %check if the z value is not NaN
                pointCounter= pointCounter+1;
                matVal(pointCounter,1)=str2double(val(1));%*delta_x;
                matVal(pointCounter,2)=str2double(val(2));%*delta_y;
                matVal(pointCounter,3)=str2double(val(3)); %unit in ?
            end
        end

    end %END of while

    fclose(fid);

end %END of the inner for j
matVal(pointCounter+1:end,:) = [];


%%CALCULATING the heigth with respect to lateral distance-------------
nLag=pointCounter;
ZhTotal = zeros(nLag,2*nLag); % column 1=for the value, 2=for the lag index
var = zeros(1,nLag); % column 1=for the value, 2=for the lag index
average_heigth=zeros(1,nLag);
lagIndex=zeros(1,nLag);

lagIndexCounter=0;
ZhColCounter=0;

for i=1:pointCounter
    for j=1:pointCounter
        lag=sqrt(sum((matVal(i,:)-matVal(j,:)).^2));%Euclidean distance
%abs(matVal(i,1)-matVal(j,1));
        if(j~=i)
            if(i==1)
                lagIndexCounter=lagIndexCounter+1;
                lagIndex(lagIndexCounter)=lag; % record all the possible
lag
                %ZhColCounter=ZhColCounter+1;
                ZhTotal(lagIndexCounter,1)=abs(matVal(i,3)-matVal(j,3));

            else
                counter=1;
                while ((lagIndex(counter)-lag)> 0.05)
%lagIndex(counter)~=lag %if the difference < 0.05 um, they are the same
                    counter=counter+1;
                    if(counter>nLag)
                        counter=counter-1;
                        break;
                    end
```

```
                end
                colCounter=1;
                while(ZhTotal(counter,colCounter)~=0)
                    colCounter=colCounter+1;
                    if(colCounter>2*nLag)
                        colCounter=colCounter-1;
                        break;
                    end
                end
                ZhTotal(counter,colCounter)=abs(matVal(i,3)-matVal(j,3));
            end
        end
    end
end
lagIndex;
ZhTotal;

%calculating the average heigth
average_heigth(lagIndexCounter+1:end)=[];
lagIndex(lagIndexCounter+1:end)=[];
for i=1:lagIndexCounter
    average_heigth(i)=0;
    j=1;
    colCounter=1;
    while ZhTotal(i,colCounter)~=0
        average_heigth(i)=average_heigth(i)+ZhTotal(i,colCounter);
        colCounter=colCounter+1;
         if(colCounter>2*nLag)
            colCounter=colCounter-1;
            break;
         end
    end
    average_heigth(i)=average_heigth(i)/colCounter;
end
average_heigth;

%----------------------------------------------------------------------

figure;
plot(lagIndex,average_heigth,'.');
ylabel('Average height/um');
xlabel('lateral distance/um');
title('Alicona data');

matrix_size=size(matVal);

%WRITING The data to File: lagIndex, avergae_height, ZhTotal
fullName2=[filePathFolder '\' filename '-lagIndex_ALICONA.txt'] %string
concatenation, alternative to strcat()
fid2=fopen(fullName2,'w');
for i=1:length(lagIndex)
    fprintf(fid2,'%f\n',lagIndex(i));
end
fclose(fid2);

fullName2=[filePathFolder '\' filename '-averageHeight_ALICONA.txt']
%string concatenation, alternative to strcat()
fid2=fopen(fullName2,'w');
for i=1:length(lagIndex)
    fprintf(fid2,'%f\n',average_heigth(i));
```

```
end
fclose(fid2);

fullName2=[filePathFolder '\' filename '-zhTotal_ALICONA.txt'] %string
concatenation, alternative to strcat()
fid2=fopen(fullName2,'w');
for i=1:length(lagIndex)
    colCounter=1;
    fprintf(fid2,'%f\t',lagIndex(i));
    while ZhTotal(i,colCounter)~=0
        fprintf(fid2,'%f\t',ZhTotal(i,colCounter));
        colCounter=colCounter+1;
        if(colCounter>2*nLag)
            colCounter=colCounter-1;
            break;
        end
    end
    fprintf(fid2,'\n');
end
fclose(fid2);

%keep all the data
lagIndex_alicona=lagIndex;
average_heigth_alicona=average_heigth;
ZhTotal_alicona=ZhTotal;


%====================== plot ======================
height_transmission=zeros(length(lagIndex_alicona),2)
for i=1:length(lagIndex_alicona)

    for j=1:length(lagIndex_zygo)
        %if(lagIndex_alicona(i)==lagIndex_zygo(j))
        threshold=0.05;
        if(abs(lagIndex_alicona(i)-lagIndex_zygo(j))<threshold)
            height_transmission(i,1)=lagIndex_alicona(i);
            height_transmission(i,2)=100-(100*(abs(average_heigth_zygo(j)-
average_heigth_alicona(i))/average_heigth_zygo(j))); %in percentage
            break
        end
    end
end

figure;
plot(height_transmission(:,1),height_transmission(:,2),'.');
xlabel('Lateral distance/um');
ylabel('Transmitted height/%');
title('Transmission curve');


fullName2=[filePathFolder '\' filename '-Transmission curve.txt'] %string
concatenation, alternative to strcat()
fid2=fopen(fullName2,'w');
for i=1:length(lagIndex)
    fprintf(fid2,'%f\n',height_transmission(i));
end
fclose(fid2);

CPUTime=toc
```