ENG56 DriveTrain

Good practice guide for form and diameter measurements for large shafts

Introduction

This report deals with measurement and evaluation strategies for large shafts. By measurement strategy is meant the selection of measurement instrument and decisions made when planning the measurement. If there are requirement for diameter and roundness and both CMM and roundness instrument are available, there is a possibility to check both requirements with the CMM. The result might be quicker measurements but the value of the roundness measured with CMM depends on data point density. A similar example is the measurement of squareness which can be measured with several instruments. For squareness the evaluation of datum is done in many ways in industry (least squares, minimum zone) although recent standards require simulation of contact.

In GPS terminology requirements are called specification and measurement together with evaluation are called verification. In theory in the GPS philosophy specification and verification are linked together by the duality principle described in
ISO 8015 and ISO 17450.

"The Duality principle states that the specification operator defines the requirement on the drawing. The specification operator on the drawing is defined independently of any measuring procedure or measuring equipment. If the verification operator (measuring procedure) is a theoretically perfect implementation of the specification operator, the measurement result is without measurement uncertainty. The deviation of the verification operator from the specification operator indicated on the drawing is a contribution to the measurement uncertainty." [1]

Requirements

The designer writes geometrical specifications into a technical drawing according to functionality of a part. In most of the world the symbol language of GPS developed by ISO is used (in US they have ASME Y14.5). In almost every technical drawing specifications according to standards:

- ISO 1101 - Geometrical Tolerances
- ISO 5459 - Datums
- ISO 14405-1 - Size
- ISO 1302 - Surface Finish

are written. These standards contain only rules for the symbol language; the designer has to choose the right requirement according to his understanding of functionality. The designer can surely work without knowing every ISO-GPS standard but still a lot is needed. For example ISO 1302 tells only how the indication for surface texture is written. To understand the meaning of a parameter ISO 4287 must be read together with ISO 4288 and ISO 11562 etc.

On the drawing board the part is ideal. So mathematically a feature such as shaft diameter is clear. For any real part we get into trouble if the requirement for diameter has a small tolerance (but still typical) such as for example 0.05 mm or lower. The reason is that every manufactured part is non ideal and our shaft contains a wide range of different diameters depending on how and where the diameter is measured. It is the responsibility of the designer to minimize this risk by choosing effective specifications, still not too expensive to manufacture.

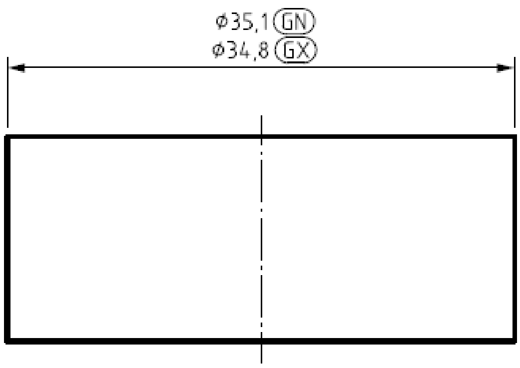
Measurement and evaluation strategies in general

The measurement strategy is the decision which measurement instrument to use and how to use it. For diameter measurement of shafts the number of points to be measured is a critical decision. The evaluation strategy is how to analyse these points. One example would be to measure diameter by taking 36 points (circle divided by 10 degrees) and calculate the least square diameter. Naturally it would be almost difficult, for an industrial measurement technician, to get least square diameter using a micrometer.

The standard ISO 14405-1:2010 gives definition of 14 different diameters that can be imagined on a shaft or hole (table 1). It is the responsibility of the designer to select a definition according to the functional requirements. In figure 1, also taken from ISO 14405-1:2010, an example of a diameter requirement is shown.

Table 1. The standard ISO 14405-1:2010 gives definition of 14 different diameters.

Type of size characteristic	**Subtype**	**Additional definition**	**Associated modifiers**
Local size	Two-point size		LP
	Spherical size		LS
	Section size	With least-squares association criteria	GG ACS
		With maximum inscribed association criteria	GX ACS
		With minimum circumscribed association criteria	GN ACS
		Calculated size with circumference diameter	CC
		Calculated size with area diameter	CA
		Rank-order size of spherical size or two-point size	Example: LSACS SA
	Portion size of length *L*	With least-squares association criteria	Example: GG/20
		With maximum inscribed association criteria	Example: GX/15
		With minimum circumscribed association criteria	Example: GN/30
		Calculated size with volume diameter	Example: CV/10
		Rank-order size of section size or spherical size or two-point size	Example: LS/20SX
Global size	Direct global size	With least-squares association criteria	GG
		With maximum inscribed size	GX
		With minimum circumscribed size	GN
	Calculated global size	Calculated size with volume diameter	CV
	Indirect global size	Rank-order size based on a local size	Example: LSSN
Local and global size	Envelope requirement	Combination of LP and GX or GN	E



NOTE The specification operators indicated are "minimum circumscribed" which applies to the upper limit of size and "maximum inscribed" which applies to the lower limit of size.

Figure 1. Example of a diameter requirement [picture from 4].

Measurement instruments

For shafts the following measurement instruments are commonly used:

- Coordinate measuring machines (CNC controlled) a)
- Micrometer for two point measurement of diameter b) and c)
- Dial indicator for run-out measurements d)
- Roundness and cylindricity instruments e)
- Manual coordinate measuring machine f) and articulated arm CMM g)
- Form and surface texture instruments h)

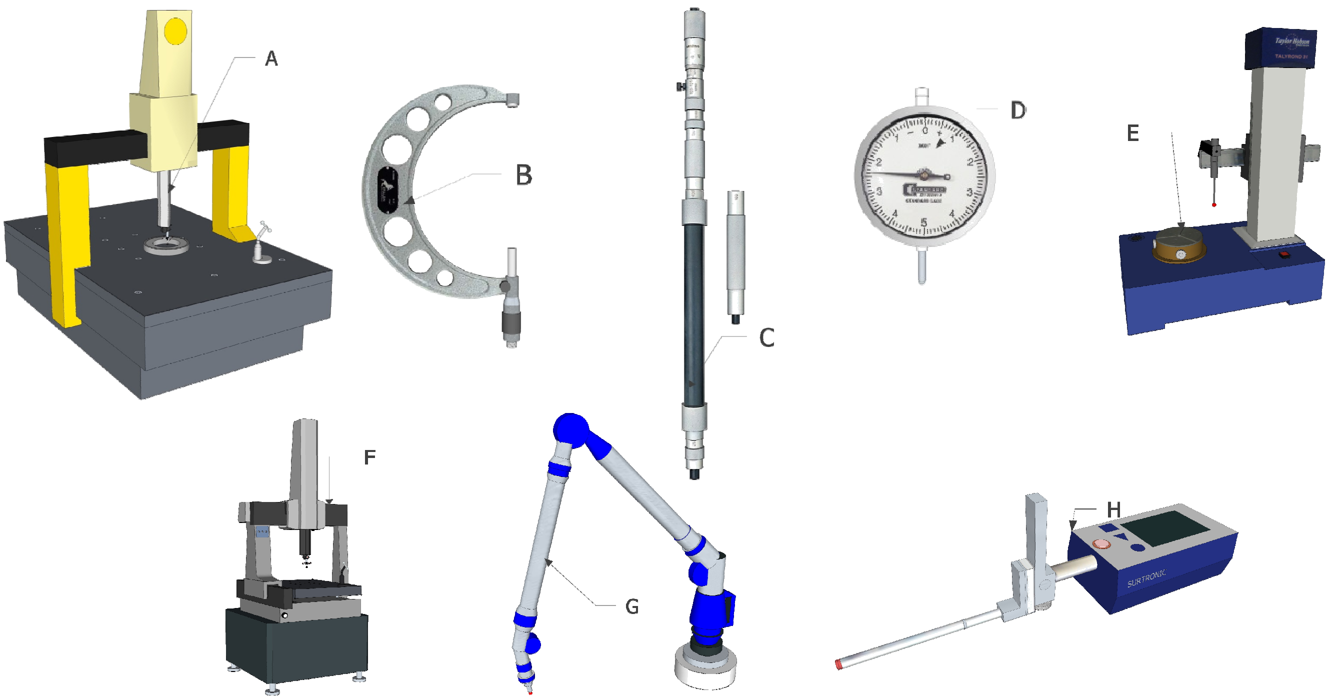


Figure 2. Typical measurement instruments. See list above for instrument type.

The first two instruments in the list are cheap and found in every workshop and the two last instruments in the list are increasingly used in workshops. An issue with large CMM's is the price of about 300 000 € and above.

Naturally size of the object to be measured is an issue. When the part is as big as in figure 4 the alignment of handheld instrument is difficult. There are examples of really large traditional CMM's which are used to measure objects weighing several tons but again the price becomes an issue together with handling and moving or transport of the part to be measured.

Figure 3. Measurement of diameter [3].

If diameter, straightness and roundness is to be measured of a large shaft a large CMM is the only practical solution. A drawback with the CMM compared to other instruments is that the operator has to decide where to take the measurement points and how many. Briefly this is the measurement strategy. The evaluation strategy is how to analyse these points. These issues are discussed in the next chapter.

Measurement and evaluation strategies when a CMM is used

According to the Measurement Good Practice Guide No. 41 “CMM Measurement Strategies” published by NPL the general measurement strategy can be subdivided into a number of parts:

1. Selection of the features on the workpiece to be measured.
2. Definition the workpiece datum(s) to be used within the co-ordinate system.
3. Selection of the workpiece orientation.
4. Selection of the workpiece holding method.
5. Qualification of the probe
6. Definition of the probing strategy.
7. Programming of the CMM.
8. Assessment information record

From the point of the authors of this guide the first thing is to check how close the dimensions and weight of the workpiece is to the measurement volume and weight permissible for the CMM. Then it should be examined what the effects of gravity and clamping forces might be. If the workpiece is small compared to measurement volume of the CMM the workpiece orientation is selected to minimize changes of probe and probe orientation. For example a long shaft will probably be in a horizontal orientation. When the shaft is horizontal it’s easy to make 2-point diameter measurements from both sides with a probe in the same vertical position. However, as discussed in previous section a single twopoint diameter result might be misleading and more points give indication of form error. To get more measured points with the CMM is not impossible but require more planning for probe change and clamping if we want to reach with our probe under the shaft.

The selection of the number of points is a difficult question. Figure 7 gives an example where six points is not enough. The number of points should ideally be so large that the result is robust. By using terminology of table 1 we can say that a GG diameter is quite robust with 6-12 points, GX- and GN diameter may require 12-24 points to be robust. In the literature very different views can be found and numbers above are just the view of the authors. Every CMM operator should experiment with different numbers of points because the economical selection of points depend on the workpiece and it is impossible to give rules that work for every piece in the world.

The question of the number of points might sound theoretical. However the decision will influence the measurement result. It might be that the result exceeds the specifications so the economic effect is considerable.

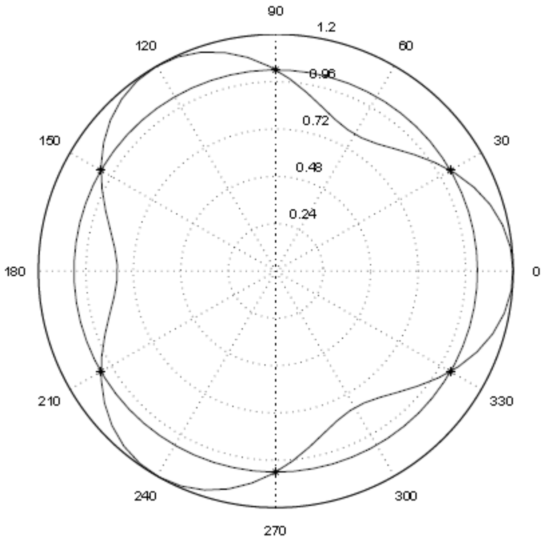


Figure 4. Example of six points equally spaced on a 3 lobed circle which fail to detect the form error (picture and idea from [6]).

Measurement and evaluation strategies when a hand-held two point instrument is used

Two point is the default for diameter according to ISO 14405-1:2010. The shape of the shaft or hole might be ellipse which gives problems for the two point method. The ideal solution is to measure roundness with high point density with another instrument. By combining the roundness plot and the measured diameter in a known orientation all two-point diameters can be constructed. Less ideal but cheaper solution is to make the two point diameter measurement in several angular orientations. The result is a range of two point diameters. It can be argued that there are shapes of roundness errors (figure 6-7) which are difficult for the two point instrument. Still a lot of 2-point diameter measurements are done in the industry. It is important to be aware when the form (roundness) error is considerable to the required accuracy of the measurement task.

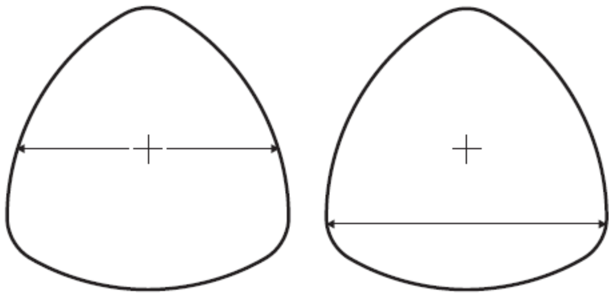


Figure 5. Potential evaluations of two point size (picture and idea from [5])

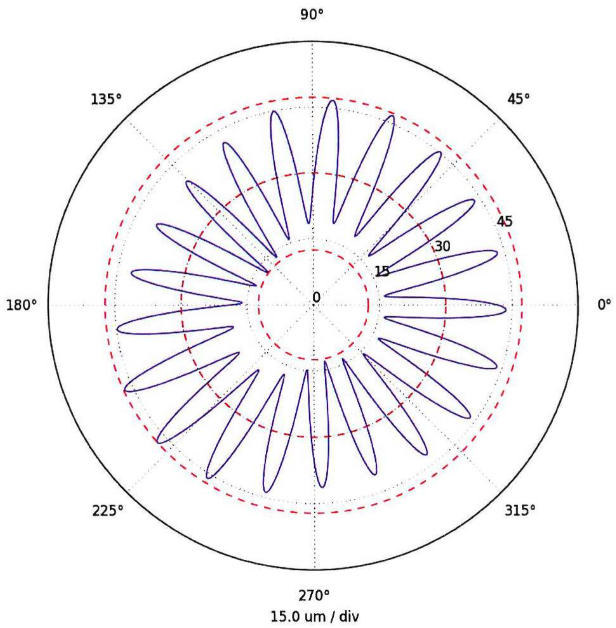


Figure 6. When measuring diameter with a micrometer the user usually tries to measure diameter through center of shaft by searching for largest diameter.

In appendix 1 is given a guide for evaluation of uncertainty of a diameter measurement. The guide is written in finnish and deals with the typical uncertainty contributions when a micrometer is used. In appendix 2 are examples of uncertainty evaluations for diameter measurements arranged at industrial stakeholder. The experience from discussions with industry shows that there is a need for better understanding of measurement uncertainty. Even for the rather simple measurement case shown in appendix 1 the strong message from industry is that uncertainty evaluation should be easier. Here is a challenge for metrology community and future projects.

References

1. The GPS Pocketbook: Turning Ideas Into Reality : Geometrical Product Specifications Per Bennich, Henrik Nielsen, HN Metrology Consulting Incorporated, 2005

2. Lu, W. L., Jiang, X., Liu, X. J., & Xu, Z. G. (2008). Compliance uncertainty of diameter characteristic in the next-generation geometrical product specifications and verification. Measurement Science and Technology, 19, 105103. doi:10.1088/0957-0233/19/10/105103

3. Häkkisen Konepaja, brochure. Raisio 2014.

4. ISO 14405-1:2010 Geometrical product specifications (GPS) -- Dimensional tolerancing -- Part 1: Linear sizes. ISO 2010.

5. E. Morse, Y. Peng, V. Srinivasan, and C. Shakarji, “Metrological challenges introduced by new tolerancing standards,” Meas. Sci. Technol., vol. 25, no. 6, p. 064001, 2014.

6. Flack, Measurement Good Practice Guide No. 41, May 2014, ISSN:1368-6550 ISBN:NPL Doc. Ref:PDB: 2771. NPL

Uncertainty evaluation for diameter of shaft

In this appendix is a guide for evaluation of uncertainty of a diameter measurement.

The guide contains a description of a typical two point diameter measurement and gives examples of relevant uncertainty contributions. As input data is lower and upper tolerance, several temperatures and thermal expansion coefficient.

The contains a measurement model and the user may put the input values in an excel sheet which calculates both results and uncertainties. Finally the result is evaluated according to principles of ISO/DIS 14253-1.

Diameter Measurement using Excel template

Diameter measurement with a standard measuring instrument has a number of uncertainties that are not usually taken into account in the final measurement result. Sometimes these uncertainties are only taken into account as an increasing total uncertainty of the measurement. Although the measurement is done in the right direction and position, many uncertainties remain in the measurement. Such errors comes from temperature of the measuring instrument, environmental factors, temperatures which affect the measurement and what is the repeatability of the measurement method.

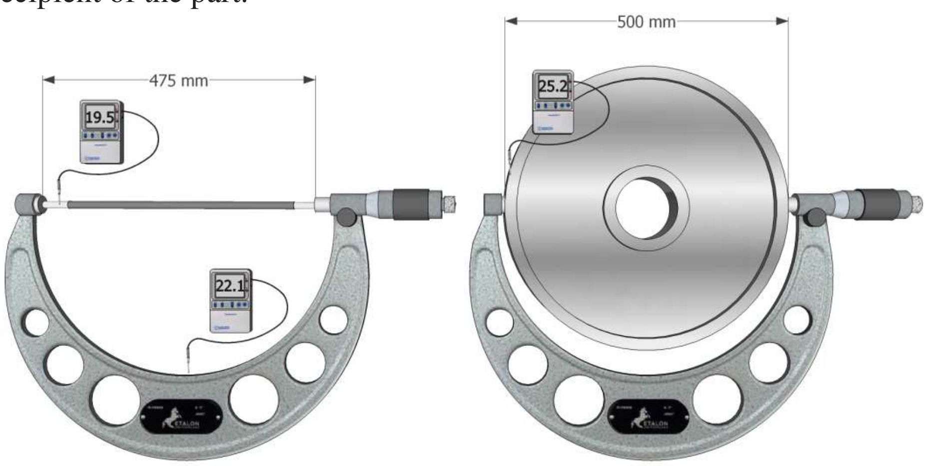
If the known uncertainty factors of the measurement are obtained and compensated, the accuracy of the result is greatly improved and the measurement uncertainty decreases.

Making accurate corrections to the measurement results by hand is laborious and selecting the right signs for correction is sometimes difficult. Finally, it should be possible to quickly determine whether the part can be approved.

The following example uses the Excel program to make corrections to measurement results in a diameter measurement. The program takes into account the temperatures of the object, measuring instrument, and used reference either by temperature measurements or by measuring their magnitude based on experience. In addition, thermal factors and uncertainties of the measuring instrument and zeroing normal are known or evaluated.

The program also asks for the largest error of the measuring instrument used and the uncertainty of the calibration of the measuring instrument. In addition, the zeroing normal measurement and the calibration uncertainty of the normal are used (they can be found in calibration certificates). Additionally, the template asks to do 20 repetitions and calculates the standard deviation of repeatability.

The template is independent of the magnitude of the diameter and whether it is an outer or an inner diameter. By changing the values of the various components in the program, it is possible to obtain a picture of the significance of different factors for the measurement. The program can also evaluate and report on the measurement result on the user's behalf, as well as tell whether the measuring object is to be accepted or rejected. For this classification, the program needs to know what the required tolerance is. According to ISO / DIS 14253-1, the approval of a part depends on whether the measurer is manufacturer of the part or the recipient of the part.



	A	B	C	D	E	F
1	**Diameter measurement and uncertainty calculation**					
2	**Measurement of Diameter**	Measure /mm		Basic Measure /µm		Tol. position
3	Diameter in drawing /mm	500				
4	Measuring device	Micrometer				
5	**Target information**	Knowledge/estimate/measure		An estimate of uncertainty		
6	Drawing number	ABC				
7	Nominal diameter	503.25	mm			
8	Diameter at upper tolerance limit /mm	503.260	mm			
9	Diameter at lover tolerance limit /mm	503.240	mm			
10	Material thermal coefficient /x10^{-6}K^{-1}	11.7	x10^{-6}K^{-1}	±	1	x10^{-6}K^{-1}
11						
12	**Environment info**					
13	Air temperature /°C	20.00	C°			
14	Part temperature/°C	20.40	C°	±	0.1	°C
15	Measurement instrument temperature/°C	20.70	°C	±	0.1	°C
16	Zeroing normal temperature/°C	20.75	C°	±	0.2	°C
17						
18	**Measurement info**					
19	Date	18.5.2017				
20	Measurer	NN				
21	Identif. of the meas. object number/material	Disk A				
22						
23	**Measurement instrument info**					
24	Measurement instrument info	RH2/08				
25	Zeroing normal id.	70666784				
26	Total error for instrument/µm	4	µm			
27	Instrument calibration uncertainty /µm	5	µm			
28	Measurement instrument thermal coefficient/x10^{-6}K^{-1}	11.7	x10^{-6}K^{-1}	±	0.5	x10^{-6}K^{-1}
29	Zeroing normal thermal coeff /x10^{-6}K^{-1}	11.6	x10^{-6}K^{-1}	±	0.3	x10^{-6}K^{-1}
30	Zeroing normal length after certificate/mm	500.002	mm			
31	Zeroing normal calibration uncertainty/µm	2	µm			
32						
33		Direction 0°				
34	**Measurement results /mm**	Meas. 1	Meas. 2	Meas. 3	Meas 4	Average
35	Diameter/mm	503.255	503.257	503.253	503.258	503.256
36						
37	Zeroing normal/mm	499.995	499.995			
38						

(orange)	=The item may also be empty
(yellow)	= The point must be filled
(blue)	= result

This information is obtained from the drawin

This information is detected during the measu

This information is recorded during the measurement

These data are obtained from calibration cert

Repeat measurements	
503.255	
503.257	
503.253	
503.258	
503.255	
503.258	
503.260	
503.260	
503.255	
503.258	
	0.0023

The most common thermal coefficients	
Steel	11,6x10^{-6}K^{-1}
Aluminium	24x10^{-6}K^{-1}
Stainless steel	16x10^{-6}K^{-1}
Cast iron	10x10^{-6}K^{-1}
Glass	9x10^{-6}K^{-1}
Copper	18x10^{-6}K^{-1}
Hard alloy	5x10^{-6}K^{-1}
Ceramic	10x10^{-6}K^{-1}

Corrected measurement results	Direction 0° mes .1 & mes.	Direction 0° mes .3 & mes. 4		Uncertainty µm
Diameter in section 1	503.265	503.265		
average	503.265	mm	±	7.68
Measuring result from zeroing normal	499.995			

Standard uncertainty for the measurement result $\mathbf{l_{ix}}$	(=Standard deviation from repeated measurements)
Standard uncertainty for correction due to the measuring instrument $\boldsymbol{\delta l_m}$	
Standard deviation for correction due to zero reset $\boldsymbol{\delta l_n}$	
Standard uncertainty for workpiece temperature correction $\boldsymbol{\delta l_{ty}}$	
Uncertainty of the thermal coefficient of the material $\boldsymbol{\delta l_{ty}(\alpha)}$	
Standard uncertainty for correction due to the temperature of the measuring device for a full ride $\boldsymbol{\delta l_{ml}}$	
Uncertainty of the thermal coefficient of measurement of the measurement device $\boldsymbol{\delta l_{ml}}$	
Standard uncertainty resets from normal temperature due to correction $\boldsymbol{\delta l_{nl}}$	
Uncertainty of the thermal coefficient of reset of reset normal $\boldsymbol{\delta l_{nl}}$	

R	S	T	U	V	W	X	Y	Z	AA
Quantity X_i	Estimate x_i		Correction to the result x_i [µm]	Standard uncertainty $u(x_i)$		Probability distribution	sensitivity coefficient c_i		Uncertainty $u_i(y)$ [µm]
l_i	503	mm	0.000	2.33	µm	Normal	1		2.33
δl_m	0	µm	0.000	2.75	µm	yhdistetty	1		2.75
l_n	500.002	µm	0.000	1.00	µm	Normal	1		1.00
$\delta l_{ty,}$ T	20.4	C°	-0.002	0.06	C°	Rectangular	5.89	µm/C°	0.34
α_{ty}	11.7	$x10^{-6}K^{-1}$	0.000	0.578	$x10^{-6}K^{-1}$	Rectangular	0.20	µm	0.12
$\delta l_{ml,}$T	20.7	°C	0.000	0.06	°C	Rectangular	5.89	µm/C°	0.34
α_{ml}	11.7	$x10^{-6}K^{-1}$	0.000	0.289	$x10^{-6}K^{-1}$	Rectangular	0.35	µm	0.10
$\delta l_{nl,}$T	20.75	°C	0.004	0.116	/C°	Rectangular	5.84	µm/C°	0.67
α_{ln}	11.6	$x10^{-6}K^{-1}$	0.000	0.173	$x10^{-6}K^{-1}$	Rectangular	0.38	µm	0.07
E_x	503.258 mm		0.002						3.84
						Extended uncertainty when k=2			**7.68**