# Guide to Dimensional Measurement Equipment

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# Contents

# 1 Preface

Inspection and measurement processes play a significant part in any production system and are crucial to demonstrate the conformance of manufactured product. The data gathered can be used to calculate Right First Time (RFT), throughput, quality, scrap rates, production times and other business metrics. Furthermore, robust measurement processes are critical in situations of quality improvement and new part introduction.

This guide aims to supplement the general measurement knowledgebase by providing guidance on common issues encountered within the measurement and inspection field. This guide has been created with the support of experienced Measurement Specialists, Manufacturing Engineers, Inspectors, Operators and other users who have experience working with measurement equipment.

This document provides guidance on suitable equipment and methods to meet the intent of the local quality system. It is not a list of requirements, and neither is it prescriptive or mandatory.

The capability charts provided in this document provide a guideline of measurement system capability in order to aid initial measurement systems selection. Validation of measurement systems must always be performed in line with the local quality system and customer requirements.

The images accompanying the capability charts are for **illustrative purposes only**, the chart shows the capability for a generic device not the exact model depicted.

# 2 User Guide

## 2.1 How can this guide help me?

This guide can be helpful to anyone within a manufacturing or design environment undertaking tasks such as:

- Creating the inspection plans for newly introduced parts. The capability charts and descriptions can be used to select a suitable inspection method for each feature, prior to validating the measurement system with techniques such as Gauge R&R.
- Identifying high-risk measurement processes and prioritising them for improvement.
- Specifying a tolerance on a particular feature; this guide can be used to evaluate if the feature is practical to measure

## 2.2 How does the Capability Chart work?

A capability chart shows the likelihood that acceptable Gauge R&R results may be produced by a particular gauge in a typical application. These capability charts are based on data from an extensive set of practical gauge studies. As such, they indicate the likely capability for a gauge used to measure a particular size and tolerance. However, product and application specific factors can degrade the indicated performance, and it is the responsibility of each business area to assess whether they need to conduct additional measurement capability studies to validate a gauge for use in their situation.

- Systems in the green zone may be used without further validation where there are no factors which may reduce the capability for the system considered e.g. poor access to the feature, flexible component or rough irregular surface.
- Systems in the amber zone have the potential to achieve acceptable capability, but require further testing to validate the system.
- Systems in the red zone are unlikely to achieve acceptable capability and therefore should be avoided.

Figure 1 shows a typical capability chart. To read the chart, find the closest value to the Feature Size on the vertical axis and read it across to the closest value to the Specified Tolerance. Interpret the colour of the corresponding cell according to the key shown below the chart.

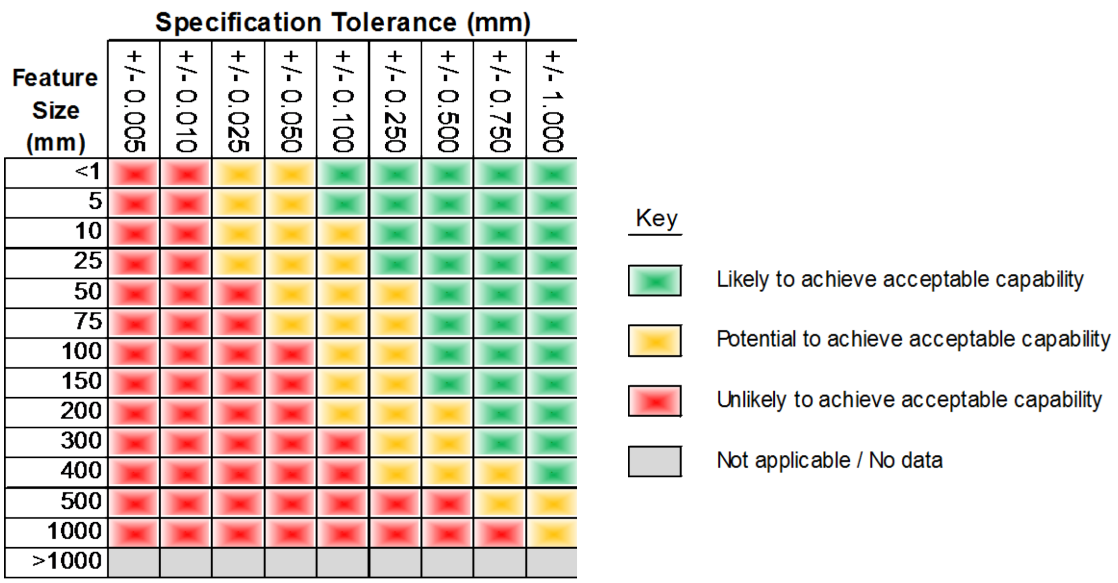


**Figure 1 - Typical Gauge Capability Chart**

A part requiring measurement can be grouped according to the strength of its characteristics:

### 2.2.1 Strong Characteristics:

- A solid, prismatic component with a good surface finish
- A straightforward measurement (e.g. the diameter of a hole or length of a cylinder)
- There are no accessibility issues associated with the measurement
- The component is manufactured using a consistent machining process

A measurement system for a feature with strong characteristics has a **higher** likelihood of achieving an acceptable Gauge R&R result. Consequently the amber zone in Figure 1 could shift left as tighter tolerances might be measureable.

### 2.2.2 Weak Characteristics:

- A complex component with an irregular shape and/or poor surface finish
- A complicated measurement needs to be made (e.g. concentricity)
- The user faces accessibility issues in making the measurement
- The component is manufactured using a highly variable process, with significant differences between components

A measurement system for a feature with weak characteristics has a **lower** likelihood of achieving an acceptable Gauge R&R result. In this case the amber zone in Figure 1 may shift right as the system becomes less capable.

### 2.2.3 Equipment resolution

Equipment resolution should also be considered in addition to the capability charts. In general a 1:10 ratio, or better, of resolution to product tolerance is recommended. Where this is not achievable, capability tables cannot be relied on and measurement system capability should be demonstrated. Poor resolution to tolerance means an insufficient number of measurement intervals across the product tolerance.

# 3 General Measurement Guidelines

## 3.1 Equipment Selection

### 3.1.1 Feature Selection

| Equipment Selection | | Length | | | Step Height | | | Wall Thickness | | | Oustide Diameter | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S | M | L | S | M | L | S | M | L | S | M | L |
| Micrometers | External | X | | | | | | X | X | | X | X | |
| | Internal | | | | | | | | | | | | |
| Callipers | | X | | | X | | | X | X | | X | X | |
| Depth Gauges | | | | | X | X | | | | | | | |
| Height Gauges | | X | X | | X | X | | | | | | | |
| Bore Gauges | Micrometers | | | | | | | | | | | | |
| | Indictator | | | | | | | | | | | | |
| | Spider Gauge | | | | | | | | | | | | |
| | Air Gauge | | | | | | | | | | | | |
| | Countersink Gauge | | | | | | | | | | | | |
| Thickness Gauges | Snap Gauges | X | X | | | | | | X | X | | X | X |
| | Ultrasonic | | | | X | | | | X | | | | |
| Beam Comparators | Bowers | | X | | | | | | | | | X | |
| | Omnigage | | X | | | | | | | | | X | |
| Indicators (Dial & Digital) | Lever | | | | X | | | | | | | | |
| | Plunger | | | | X | | | | | | | | |
| GO / NO GO Gauges | Plug Gauges | | | | | | | | | | | | |
| | Slip Gauges | | | | X | X | | | | | | | |
| | Snap Gauges | | | | | | | | | | X | X | |
| Visual Comparators | Radius | | | | | | | | | | | | |
| | Thread | | | | | | | | | | | | |
| Surface Texture | Portable Probe | | | | | | | | | | | | |
| | Desktop Machine | | | | | | | | | | | | |
| Roundness & Form Machines | | | | | | | | | | | | X | X |
| Profile Projectors | | | | | | | | | | | | | |
| Hand-held Laser Scanners | | X | X | | | | | | | | | | |
| 3D Structured Light Scanning | | X | X | X | | | | | | | X | X | X |
| Coordinate Measurement Machine | | X | X | X | X | X | X | | | | X | X | X |
| Laser Trackers | | | | X | | | | | | | | | |

| Inside Diameter | | | Hole Depth | | | Hole Diameter | | | Radius | | | Thread Pitch | | | Runout | Finish | | | Profile | Round-ness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S | M | L | S | M | L | S | M | L | S | M | L | S | M | L | | S | M | L | | |
| | | | | | | | | | | | | | | | | | | | | |
| | | X | | | | | | | | | | | | | | | | | | |
| | | | X | X | | | | | | | | | | | | | | | | |
| | | | X | X | X | | | | | | | | | | | | | | | |
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| X | X | | | | | X | X | | | | | | | | | | | | | |
| X | X | | | | | X | X | | | | | | | | | | | | | |
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| | | | | | | | | | X | | | | | | | | | | X | |
| X | X | X | | | | | | | | | X | | | | X | | | | | |
| | X | X | X | X | | | X | X | | X | X | | | | X | | | | | X |
| | | | | | | | | | | | | | | | | | | | | |

**Figure 2 - Feature Selection Chart**

## 3.2 Validation of Measurement Systems

Before a measurement system is used to inspect a part it must be validated to ensure that it is capable and fit for purpose. A measurement system should have a small repeatability, reproducibility and bias relative to the tolerance band being measured. A Gauge R&R study is normally used to assess repeatability and reproducibility whilst bias is assessed with a comparison to an independent system. Depending on the type of measurement system and resources available a choice must be made between several methods of measurement system validation.

Table 1 summarises these methods:

| Method | Typical Application | Acceptance Criteria | Notes |
|---|---|---|---|
| **Gauge R&R** | Micrometer, Height Gauge, Bore Micrometer, CMM. | Total Gauge R&R (number of standard deviations for study variation set to 6) ≤ 20% of tolerance | Gauge R&R with an assessment of bias should be used in most circumstances where multiple parts and operators are available. |
| **Bias Study** | To support tests of variation | Bias ≤ 10% of tolerance | A bias study is used in support of tests of variation, such as Gauge R&R or Type 1 to give an assessment against a known reference to give bias. |
| **Type 1 Study** | Where time or resource limitations prohibit a full study | Cgk ≥ 1.00 evaluated at 20% of total tolerance | Type 1 studies are useful to quickly assess the repeatability and bias of a gauge but do not assess reproducibility. These should be used where full Gauge R&R is not practical or possible. |
| **Attribute Agreement Analysis** | Go-No Go gauges, Plug gauge | K >0.75 | Attribute studies test the level of agreement between multiple operators and measurements. These are useful for measurement systems which give a pass or fail result and not an actual measured value. |
| **Measurement Uncertainty** | Complex measurement systems where normal methods can't be applied. | Expanded uncertainty 'U', with a coverage factor k=3, should be less than or equal to 10% of tolerance | Measurement uncertainty is a complex technique which can assess all aspects of a measurement system. Practical tests and theoretical calculations can be combined to understand the overall uncertainty in a measurement. This technique is useful when it is difficult or impossible to use techniques such as Gauge R&R. |

**Table 1 - Validation Methods**

Many reference guides exist on carrying out these studies, some of which are listed in the Standards, Training and Further Reading section.

### 3.2.1 Bias and Reference Measurements

Techniques such as Gauge R&R are good at assessing the repeatability and reproducibility of a measurement system. However, it is possible to be repeatable and reproducibly wrong! The measurement system could give very stable results over a range of repeats and operators but could be consistently reading small or large. This error is called bias. Calibration will help to minimise bias however an element of bias can come from the application itself.

In order to assess bias it is important to get data from an independent measurement system. By taking the average of several results (5-10 typically) from the independent measurement system and comparing this to the Gauge R&R results the bias can be assessed.

The difference between the two systems should be no more than 10% of feature tolerance.

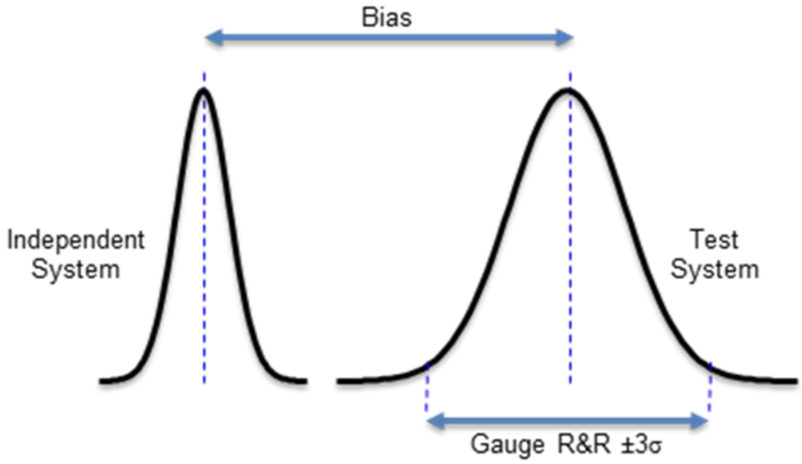



**Figure 3 - Gauge R&R and Bias Assessment**

### 3.2.2 Gauge R&R

When performing a Gauge R&R study it is important to ensure a practically achievable and statistically significant sample is taken. Table 2 shows the minimum number of repeats which should be used for a given number of parts and operators.

| | | No. of Parts / Features | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| No. of Operators | 2 | 21 | 11 | 8 | 6 | 5 | 5 | 4 | 4 | 4 | 3 | 3 |
| | 3 | 11 | 6 | 5 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | 4 | 8 | 5 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | 5 | 6 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | 6 | 5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

**Table 2 - Minimum numbers of repeats for operator and part combinations**

### 3.2.3 Validation - Frequently Asked Questions

**Q1: "We only have 2 operators using this gauge, shall I take part in the study to increase the number of operators?"**

A1: "Not unless you are trained to use the gauge and familiar with the component being measured. Having an untrained operator may result in the failure of the study due to the stability and/or reproducibility of the measurements due to the untrained operator. It would be far better to compromise on the amount of measurement readings than to perform a study that is not representative of the way the process works."

**Q2: "We cannot get access to 10 parts, will 5 do?"**

A2: "Lowering the sample size will affect the reliability of the test. However there are times when this may be required. In difficult situations, a compromise may be required but the analyst should be mindful when interpreting the data. For example if a Gauge R&R returns 29% against tolerance with only 5 parts there is a reasonable case for either acquiring further parts for study or asking the operators to repeat the measurements 4 or 5 times rather than the usual 3."

**Q3: "We can't get parts that represent the full process variation as the only ones we have are from the same batch. What should we do?"**

A3: "Testing with a small subset of the possible input conditions is possible but will result in lower confidence in the results and any conclusions. Consider alternative ways of expanding the variation in input condition and consult someone experienced in measurement systems analysis for advice on experimental design, analysis and conclusions."

**Q4: "We have very low volumes, only a couple of parts are available. What can we do?"**

A4: "In this situation you could measure multiple features on the same part. As the variation within part may not be representative of the full process spread, it is key, as in all situations, to assess the Total R&R as a fraction of the tolerance whilst considering the potential impact of a limited subset of process spread." See A3 regarding input condition variation and advice.

**Q5: "Our gauge measures hundreds of features, do I have to run a Gauge R&R study on each of them?"**

A5: "No, in most situations this should not be required. It is however important to select the features which are subject to Gauge R&R giving consideration to tight tolerance features and features that may be, for instance, difficult to access."

**Q6: "The gauge is automated (there is no operator influence)! What do I do?"**

A6: "First, be sure that there really is not any operator influence - for instance if there is a setup process which is manual then this may lead to reproducibility problems. If the gauge is completely automated then a study can be performed with only 1 operator. The Gauge R&R study will report only on the repeatability element of the Gauge R&R."

**Q7: “I have a surface finish gauge, and it keeps failing Gauge R&R. What do I do?”**

A7: ”Some gauges are notoriously difficult to perform Gauge R&R on. If this method is not appropriate for your application a specialist should be contacted for guidance.”

**Q8: “Under what circumstances should I repeat the Gauge R&R?”**

A8: ”A Gauge R&R should be repeated whenever the process (either measurement process or manufacturing process) significantly changes. If the part tolerance is changed it might be necessary to repeat a gauge study as the change in tolerance can impact on the manufacturing process which in turn can affect the capability of the measurement process.”

**Q9: “My Gauge R&R against tolerance is very good but I only get 1 distinct category. Is my measurement process good or not?”**

A9: ” It is likely that the parts selected for the study are not representative of the total process variation. This will affect the % R&R against study, the number of distinct categories and the X bar chart. If the parts are representative then the measurement process is not adequate for the application of SPC analysis as the majority of the variation seen will be from the measurement system and not the underlying process.” See A3 regarding input condition variation and advice.

## 3.3 Regular Monitoring of Capability

It is important to monitor the capability of a measurement system over time to ensure it still performs as initially validated. Many factors can change over time which will influence the performance of the system, for example:

- Wear or accumulation of dirt / debris due to improper asset care
- Damage to the system resulting from user error (bending, scratching, dropping etc.)
- Environmental changes in temperature, humidity, vibration etc.
- New inspectors or operators

Regular calibration ensures that the measuring equipment retains its capability and traceability and the periodicity of the calibration should be based upon the usage (wear) or deterioration.  Often calibration intervals are based upon time which can vary from a few weeks to several months. If a gauge was accidentally dropped and damaged without the knowledge of the user then the gauge may give the wrong results. Consequently it is essential that a regular check of the performance of the measurement system is carried out. There are two straightforward, quick methods for achieving this which should be carried out on a frequent basis, typically daily:

- **Artefact Check**
  A set of known reference artefacts can be checked on a regular basis. Typical artefacts can be gauge blocks, ring gauges, spheres or length bars. For more complex measurement systems such as CMM's then a combination of these can be used. The Zeiss CMM Check pictured below is an example of this type of artefact.

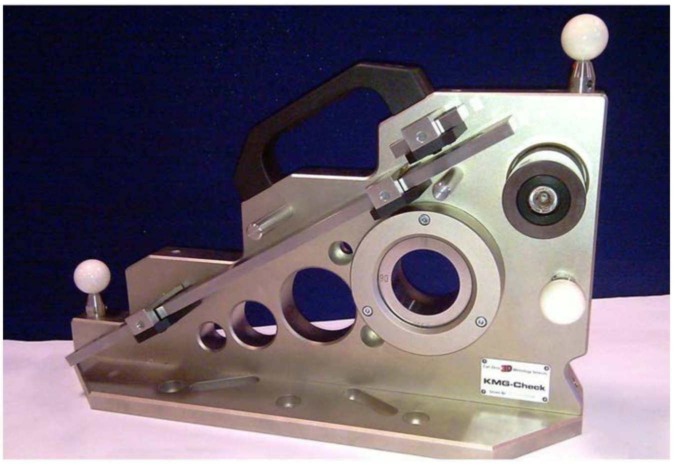



**Figure 4 - Zeiss Artefact**

- **Gold-Standard Part**
  Whilst an artefact is very simple and quick to achieve it does not test all elements of a measurement system. On complex systems such as CMM's or vision measurement machines other elements of the system such as component fixturing, programs and probe angles can have a big impact on performance. In these cases it is better to have a scrap part which is kept to one side. The part can be measured on a regular basis and the results compared to the original measured results for the part.

Any change in the measurement results from either the artefact or the gold-standard part will indicate a change in the systems performance and an investigation is required.
Figure 5 shows the measured result over a 4 week period from the measurement of a 10mm bore.

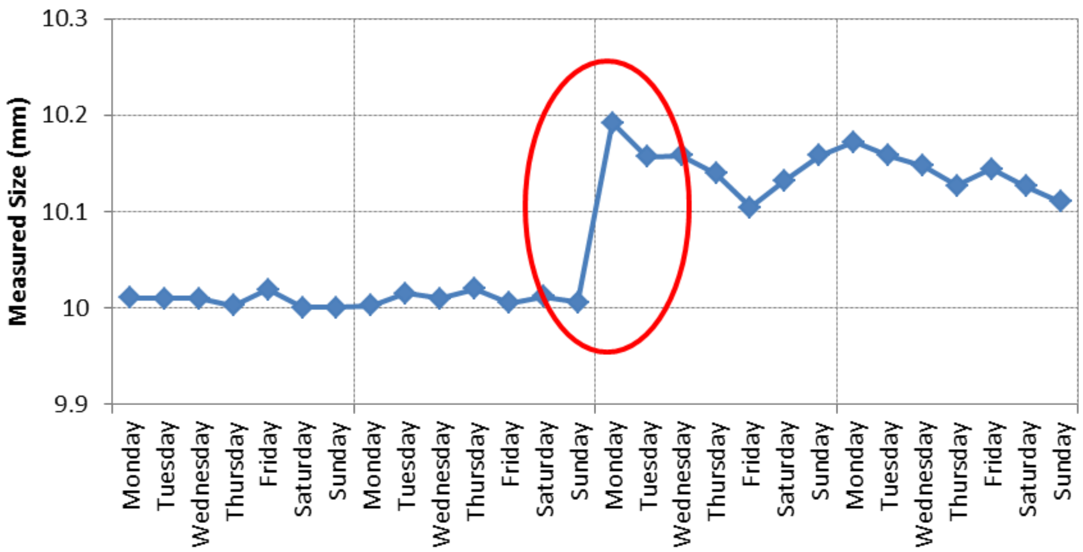



**Figure 5 - Validation Check Results**

After 2 weeks of stability the result shifts and the repeatability drops significantly. By monitoring these results on a regular basis it is possible to identify measurement system issues early and rectify the problem before downstream problems occur.

## 3.4 Asset Care

Gauge condition is a key factor in equipment capability and it is important that gauges are maintained accordingly. The guidelines in this section outline practices that should be followed for common equipment types. Additional device specific guidance can be found in the measurement equipment guidelines.

### 3.4.1 General Environmental Requirements

- Measurement environments should be clean, tidy and free from dust, dirt, noise or vibration which could affect the measurement result.
- Thermal effects must always be considered, especially if measuring features with tight tolerances. Temperature change will cause the part and gauge to change size but not necessarily at the same rate or in the same way. As a result the temperature difference between the part, gauge and the ambient temperature should be minimised wherever possible. For precision measurement a temperature-controlled environment is a pre-requisite and temperature soak is usually required (see Section 3.5.1).
- Wherever possible measurement should be done at 20°C. Features are defined, measurement systems are validated and gauges are calibrated at this standard temperature. Parts will have differing thermal expansion coefficients and may not expand linearly; this is a common source of measurement uncertainty if temperature cannot be precisely controlled.
- If it is not possible to minimise differences in temperature then an assessment should be made to understand to what extent temperature variation is likely to influence the measurement result. The amount of thermal expansion depends primarily on three factors:
    - Temperature difference
    - Component size and shape
    - Component material type

  Part temperature should be monitored throughout the measurement process to allow meaningful temperature corrections to be made.
  A maximum permissible temperature variation can be calculated:

$$\Delta T = \frac{tol \times Y}{L \times \alpha}$$

$\Delta T$= maximum permissible temperature range (°C)
tol = feature total tolerance (m)
Y = allowable % of feature tolerance (non-dimensional)
L = feature nominal size at 20°C (m)
$\alpha$= coefficient of thermal expansion (CTE) for the material (m/m/°C)

- Often gloves or insulation should be used to minimise heat transfer from the user's hands to the frame of the gauge or part.
- The gauge should not be subject to draughts, sources of radiant heat or direct sunlight. These can cause temperature differences causing potentially large errors.
- Lighting and humidity are also important to measurement capability; 700-1000 lux is recommended and a relative humidity of less than 55% will help to prevent rusting of ferrous parts.
- An appropriate measuring surface or table should be used; larger devices (such as height gauges) may require heavy granite tables.

### 3.4.2 General Storage Requirements

- Storage areas for measurement equipment should be kept clean and free from dust, dirt and grease. If using open storage, such as shadow boards, in shop-floor environments, steps should be taken to prevent build-up of contamination.
- The gauges themselves should be stored clean and free from contaminants. When storing equipment which is rarely used, corrosion preventive oil should be applied to steel surfaces, for additional protection the equipment can be wrapped in an oil-soaked paper or cloth before replacing in its case.
- The equipment should be stored in an environment similar to the measurement environment to reduce temperature soak times required.
- Equipment should not be stored in close proximity to areas where large temperature variation is expected (e.g. near heaters, air-conditioning units, machinery or in direct sunlight). This will reduce the time required for the gauge to reach ambient temperature and prevent damage.
- Gauges should be kept in an appropriate case, usually provided by the supplier.


**Figure 6 - Good gauge storage practice**

- Where possible the gauge's measuring faces should be slightly separated before storage.
- Wherever possible gauges should be stored with their corresponding setting rings, measuring rods and other ancillaries.
- Care should be taken when storing gauges to ensure they are not under any load which could cause bending or other damage.
- All comparative gauges should be clearly identified with their calibrated size.

### 3.4.3 General Usage Guidance

- The measuring faces, gauge body and parts should be free from scratches, chips, burrs, discolouration, peeling, rust, swarf and other debris. Even if this does not affect the measurement it could scratch the part or gauge and make them unusable.
- After being used the gauge should be wiped clean with a dry cloth removing any oil, cutting fluid, fingerprints etc. If left for a period of time, these may cause the gauge to corrode.
- Great care should be taken to ensure gauges are not bent or damaged. If measurement equipment is damaged or worn it must be replaced or sent for calibration immediately.
- Care should be taken to ensure that the gauge is correctly aligned with the feature.
- Figure 7 shows the importance of both position and perpendicularity when measuring a diameter.

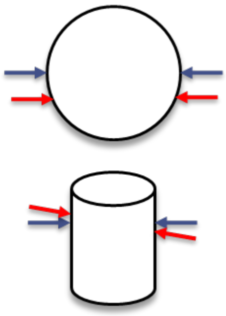


**Figure 7 - Position and Perpendicularity**

- Gradations can vary greatly between similar gauges and care should be taken not to misread scales. Even if the scale is correctly interpreted parallax error and Abbe error can cause inaccuracies. The scale should be read from a viewpoint perpendicular to the scale's axis and the jaws or anvils should never be over tightened to avoid this.
- Gauges should be handled with care to minimise heat transfer and prevent damage. Heat transferred from operators' hands to measurement surfaces can cause measurement errors and touching probes or automated devices can cause serious damage.
- Gauges and fixtures should be checked for excessive play prior to use.
- Wherever possible, measurement equipment should be cleaned in accordance with the manufacturer's recommendations.

Table 3 lists the typical cleaning processes for different components and a suggested frequency.

| Item | Equipment | Frequency |
|---|---|---|
| **CMM Granite** | Proprietary granite cleaning solution, available from metrology suppliers | Daily in high-contamination areas, weekly in measurement rooms. |
| **CMM bearing guideways** | Lint-free wipes, isopropyl alcohol | Daily in high-contamination areas, weekly in measurement rooms. |
| **CMM scales open** | Manufacturer recommended | 6 or 12 month maintenance schedule. Avoid over-cleaning scales as this may damage the scale. |
| **CMM probe joints, kinematic couplings etc** | Manufacturers cleaning equipment, e.g. Renishaw “Yellow-tac” | Visual check and clean as necessary on a weekly basis. |
| **Gauges, micrometers, slips etc** | Lint-free wipes, isopropyl alcohol. | Visual check before use and clean as required. |
| **Optics** | Proprietary optical wipes as recommended by manufacturer. Care must be taken to select correct wipes to protect sensitive optical coatings on lenses. | Visual check and clean as necessary on a weekly basis. |

**Table 3 - Typical Cleaning Methods**

## 3.5 Part Preparation

Parts should be at a stable temperature and clean prior to making any measurements.

### 3.5.1 Temperature Soak

For precise measurement it is important that the part and measurement equipment are at the same temperature. This is achieved by soaking the part in an environment with the same temperature as the measurement environment. This process is known as temperature soak:

- The surface and core temperature of the part should be stable and at the ambient temperature, ideally 20°C. Where this is not possible the effects of differences in temperature should be fully understood. Even small differences in temperature can have a significant effect on measurement results.
- The part should be soaked in a clean location where the ambient temperature is the same as the temperature in the measurement area. This area may be in the measurement area or elsewhere in the facility.
- The time required for temperature soak should be accounted for in a measurement plan.
- Many factors including material, size, shape, mass and temperature difference can affect soak times.
- Ambient temperature may vary depending on time of day/year, which will potentially change soak times. It is therefore important that the temperature of the part is monitored to ensure the soak time is appropriate.

### 3.5.2 Part Cleaning

Poor cleaning and preparation of parts can result in inaccurate measurement. If the wrong cleaning procedures are used it can even have a detrimental effect on the part; causing corrosion or inhibiting a further stage in the manufacturing process.

- There should be a dedicated process to clean the part prior to soak and wipe down.
- The cleaning process should be suitable for the level of contamination in the facility and the tolerance of the part. If the part has very tight tolerances then dust and other airborne contaminants can have a significant effect on the measurement result.
- Some cleaning products and processes can chemically interact with the surface of the component or any coating. It is therefore critical to ensure that the relevant technical authority approves any cleaning product.
- Typical cleaning products for general use could include:
    - Dust & Swarf - Tack Cloth
    - Grease & Coolant - Isopropyl alcohol & Lint Free Cloths or Degreasing Wet Wipes
- Features and gauging intended for measurement should be wiped down in the measurement area immediately prior to measurement. This ensures any fine dust or particulates are removed before measurement.
- Air duster cans or air lines can blow dust around the measurement area, so should be avoided where possible.

## 3.6 Calibration

The purpose of the calibration process is to ensure that measuring equipment complies with its specification and that any measurements taken with the equipment are traceable to National and International standards. The measuring instrument or process is compared with a standard in order to provide traceability to internationally agreed standards.

A wide variety of measuring equipment is used during manufacturing and assembly. Every piece of measurement equipment needs to be calibrated. A calibration is not valid indefinitely; it will expire and have to be repeated.

All gauges must have a valid calibration before being used. If the gauge does not have a valid calibration it must NOT be used. **It is the responsibility of the user to ensure the equipment is within calibration.**

### 3.6.1 Calibration Standards

All measurements must be traceable through calibration to National and International standards. The following is a list of the most common organisations that issue standards. Specific documents are referenced in each of the gauge guidelines.

The following organisations issue national or international standards for different gauges:

- International Organisation for Standardisation → ISO
- British Standards → BS
- Japanese Standards Association → JIS
- American Society of Mechanical Engineers → ASME
- German Institution for Standardisation / Deutsches Institut für Normung → DIN

## 3.7 Standards, Training & Further Reading

The following standards, training courses and publications are available for more information on dimensional measurement and measurement systems. Specific documents are referenced in each of the gauge guidelines.

### 3.7.1 NPL Dimensional Measurement Training

The National Physical Laboratory (NPL) Level 1 & 2 dimensional measurement training courses are available for anyone to attend. The courses cover dimensional measurement, CMM measurement, geometric dimensioning and tolerancing and various measurement instruments. Details of these courses are available from the NPL website (www.npl.co.uk).

### 3.7.2 Books & Guides

#### 3.7.2.1 NPL Good Practice Guides

These are Good Practice Guides written by the NPL that are available for download from the NPL website. There are over 100 guides available for download covering a wide range of measurement subjects. The guides that cover dimensional measurement include:

- GPG(011): A Beginner's Guide to Uncertainty of Measurement
- GPG(037): The Measurement of Surface Texture using Stylus Instruments
- GPG(039): Dimensional Measurement using Vision Systems
- GPG(040): Callipers and Micrometers
- GPG(041): CMM Measurement Strategies
- GPG(042): CMM Verification
- GPG(043): CMM Probing
- GPG(079): interpretation of engineering drawings for measurement
- GPG(080): Fundamental Good Practice in Dimensional Metrology

#### 3.7.2.2 International Vocabulary in Metrology (VIM)

The VIM defines the terms used within metrology. (Available as a free download from www.bipm.org; Product Code: JCGM 200:2012)

#### 3.7.2.3 Metrology Handbook - The Science of Measurement

This handbook is used as reading material for trainees at the Mitutoyo Institute of Metrology. It provides information about the fundamentals of metrology and illustrates the use of dimensional measurement tools. (Available to purchase from www.mitutoyo.co.uk; ISBN-13:978- 0955613302)

#### 3.7.2.4 Measurement Systems Analysis (MSA) by AIAG

This is a reference guide useful for the validation of measurement systems. The book is written and used by the Automotive Industry Action Group (AIAG) and covers statistical approaches to the validation of measurement systems such as Gauge R&R. (Available to purchase from www.aiag.org; Product Code: MSA-4)

#### 3.7.2.5 Measurement System Capability: Reference Manual v2.1

This reference guide was developed by leading members of the European automotive industry such as Audi, BMW, Volkswagen, and Opel as a "uniform reference manual for the determination of measurement systems capability in the automotive industry and its supplier base." It contains clear guidance on a detailed process for the verification of a measurement system as fit for purpose. (Available as a free download from www.qdas.com)

# 4 Measurement Equipment Guidelines

## 4.1 Micrometers

Micrometers have been in use for many years. More sensitive measuring instruments have been developed in recent years to satisfy the requirements for higher accuracy, and have replaced the use of micrometers in many applications. However, most of these newer instruments are of the comparator type and require a setting master and have a small measuring range. Micrometers have a definite advantage over these gauges as they can measure actual, absolute lengths over a much larger range. Smaller micrometers are very versatile and are used widely but larger micrometers and analogue micrometers are generally being replaced for applications with tight tolerances. They are also relatively cheap and operators require very little training, especially if using digital micrometers. Digital micrometers are more reliable than analogue micrometers as they eliminate parallax error and are easier to read. Internal (inside) micrometers use the same scale and mechanism but are used to measure large bores.

### 4.1.1 Environmental Requirements

- Heat from hands can warm the frame of a micrometer; this can cause significant measurement errors on large micrometers. Gloves or insulation on the frame can be used if required to minimise any heat transferred from hands to the frame.
- There should be adequate lighting for the user to read analogue scales accurately, typically a minimum of 700 lux is appropriate.


**Figure 8 - Typical Micrometer Storage (Mahr)**

### 4.1.2 Usage Guidance

- The user should be conscious of any changes that indicate possible errors with the gauge.
    - The thimble should run evenly and not stick.
    - The ratchet should turn smoothly.
    - The zero line on the spindle should align with the index line on the sleeve.
    - The end of the thimble should be aligned with a graduation line on the sleeve and should not cover it.
- If the micrometer has been dropped or damaged in any way, the previously mentioned checks should be carried out. The parallelism between measuring faces and flatness of the micrometer can also be checked if an optical parallel is available. If there is any doubt over the condition of the micrometer DO NOT use it.


**Figure 9 - Two Methods of Checking Parallelism (Mitutoyo UK Ltd)**

- Before using an analogue micrometer, all the scales should be checked for clearly marked graduations.
- Different types of anvils can be used to measure different types of features. Some examples of common anvils are pin, ball or disc anvils.
- Internal micrometers (also known as inside micrometers) can be used on large diameters when feature tolerance does not justify using a more accurate comparative gauge.


**Figure 10 - Ball Micrometer and Disc Micrometer (Mitutoyo UK Ltd)**

- The micrometers should be periodically checked for zero error. For micrometers that do not start at 0, e.g. 25-50mm or 75-100mm, a calibrated length bar should be used to zero the scale.
- The accuracy of the measurement in analogue micrometers relies on the lead of the screw. The error in the screw is cumulative, which means the error increases with the length of travel. For this reason a micrometer with the closest possible range to the nominal dimension should be used. For example when measuring a 30mm dimension a 25-50mm micrometer should provide greater accuracy than a 0-50mm micrometer. This is particularly applicable to analogue micrometers.
- The zero point of micrometers should be checked regularly. It is possible on a digital micrometer to re-zero the scale. Continued re-zeroing may mask any significant changes in the scale so should be avoided.

### 4.1.3 Common Pitfalls

- Misuse of the ratchet system resulting in over or under tightening.

### 4.1.4 Calibration

#### 4.1.4.1 External

- BS EN ISO 3611 - External Micrometers
- ASME B89.1.13 - Micrometers
- DIN 863-1, 863-3 - External Micrometers
- ISO 3611 – Micrometers for External Measurement
- JIS B 7502 – Micrometers and Callipers
- BS 959 – Internal Micrometers

### 4.1.5 Standards, Training and Further Reading

- NPL Guide - Micrometers & Callipers

### 4.1.6 Capability Chart

#### 4.1.6.1 Digital Micrometer

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Yellow | Yellow | Green | Green | Green | Green | Green |
| 5 | Red | Red | Yellow | Yellow | Green | Green | Green | Green | Green |
| 10 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 25 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 50 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 75 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 200 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green |
| 300 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 400 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 500 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |
| 1000 | Red | Red | Red | Red | Red | Red | Red | Red | Yellow |
| >1000 | Red | Red | Red | Red | Red | Red | Red | Red | Red |

**Table 4 - Digital Micrometer Capability Chart**


**Figure 11 - Digital Micrometer**

#### 4.1.6.2 Analogue Micrometer

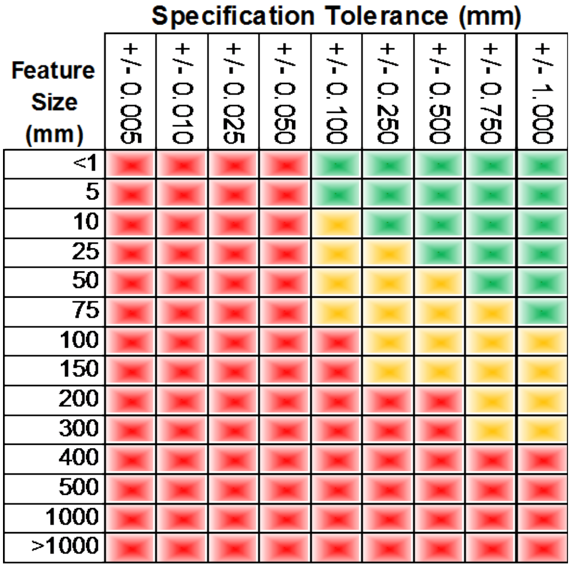



Table 5 - Analogue Micrometer Capability Chart


Figure 12 - Analogue Micrometer (Mitutoyo UK Ltd)

### 4.1.6.3 Internal Micrometer

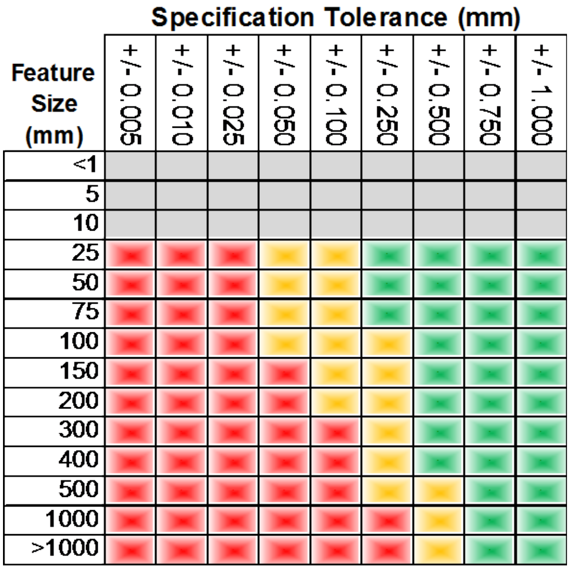



Table 6 - Internal Micrometer Capability Chart

Figure 13 - Internal (Stick) Micrometer (Bowers)

## 4.2 Callipers (Digital, Dial & Vernier)


**Figure 14 - Digital Calliper**

Callipers can be used to make multiple measurements using the inside jaws, outside jaws and sliding bar. Furthermore the depth bar at the end of small callipers (typically 150mm) can be used to measure depths making it a very versatile tool on the shop floor. The diagrams below show the different measurements possible with a calliper (digital shown).

The readings give an absolute measurement, in other words they can give a direct reading of the distance measured. Digital and dial callipers also allow the user to zero at any point, allowing for differential measurements to be taken if required.

The device does not comply with Abbe's principle as the measurement scale is not in direct line with the measurement axis. As a result bending of the calliper beam and scale, and straightness and parallelism of the measuring jaws all affect the capability of the device.

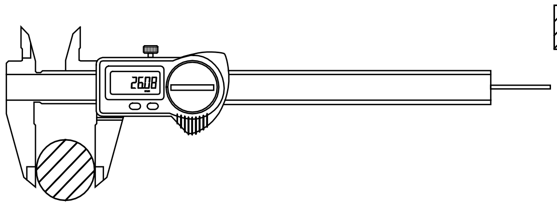


**Figure 15 - Outside Measurement (Mahr)**

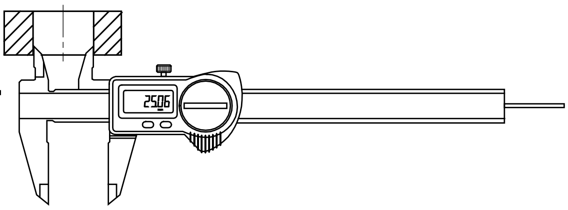


**Figure 16 - Inside Measurement (Mahr)**

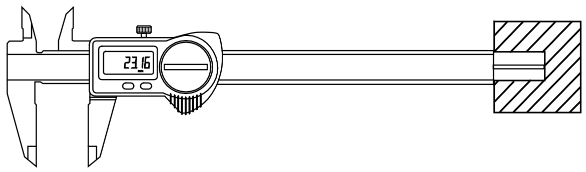


**Figure 17 - Depth Measurement (Mahr)**

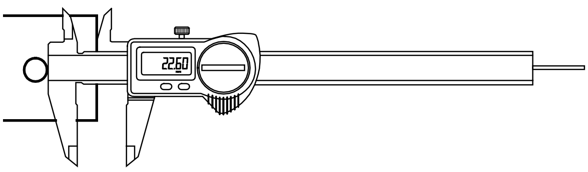


**Figure 18 - Step/Distance Measurement (Mahr)**

### 4.2.1 Environmental Requirements

- Callipers are typically used on the shop floor and some callipers may have a rating indicating a level of resistance to dust and water. However, care must be taken to ensure that callipers are not left during use in places where they may get hotter than ambient temperature, for example on a machine gearbox, or in direct sunlight.

### 4.2.2 Usage Guidance

- Always select the most suitable calliper for the application, noting the measuring range, and that it is in calibration.
- When measuring, place the fixed jaw in contact with the object to be measured, which should be as close as possible to the main scale. Slowly move the sliding jaw to contact the other face ensuring that it moves smoothly. Do not apply excessive measuring force.
- To set a digital calliper, turn the display on and bring the external jaws together until they touch. The ‘zero’ button should be pressed. The digital calliper can then be used as appropriate. This procedure should be repeated before using the gauge each session.

The calliper accuracy should be regularly checked by measuring calibrated gauge blocks. Ideally select a gauge block that is roughly the same size as the dimension to be measured. The reading on the calliper should match the size of the gauge block. See
Figure 19.


**Figure 19 - Checking Anvils with Gauge Block**


**Figure 20 - Checking Anvils with Setting Ring (Mitutoyo UK Ltd)**

When using digital callipers, check that the zero is still valid after making the measurement by closing the jaws fully. If it is not zero then reset the calliper and make the measurement again.

### 4.2.3 Common Pitfalls

- Vernier callipers can be difficult to read, and can be even more difficult if the measurements are made at awkward angles (resulting in parallax error).
- Callipers can be prone to inaccuracy as they are subject to Abbe error because the measurement scale is not in direct line with the measurement axis. Applying excessive measuring force further decreases accuracy.

### 4.2.4 Calibration

#### 4.2.4.1 External

- BS EN ISO 13385-1 - Precision Vernier Callipers
- ISO 3599 - Vernier Callipers, reading to 0.1 and 0.05mm
- DIN 862 - Vernier Callipers
- JIS B 7507 - Vernier, Dial and Digital Callipers

### 4.2.5 Standards, Training and Further Reading

- NPL Measurement Good Practice Guide No. 40 - Micrometers and Callipers

### 4.2.6 Capability Chart

#### 4.2.6.1 Digital Calliper

| Feature Size (mm) | Specification Tolerance (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
| <1 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 5 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 10 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 25 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 50 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 75 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 200 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 300 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 400 | Red | Red | Red | Red | Red | Red | Yellow | Yellow | Green |
| 500 | Red | Red | Red | Red | Red | Red | Red | Red | Yellow |
| 1000 | Red | Red | Red | Red | Red | Red | Red | Red | Red |
| >1000 | Red | Red | Red | Red | Red | Red | Red | Red | Red |

**Table 7 - Digital Calliper Capability Chart**


**Figure 21 - Digital Calliper**

### 4.2.6.2 Dial Calliper

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 5 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 10 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 25 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 50 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 75 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 200 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 300 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 400 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 500 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| >1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |

**Table 8 - Dial Calliper Capability Chart**

**Figure 22 - Dial Calliper (Bowers)**

### 4.2.6.3 Vernier Calliper

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 5 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 10 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 25 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 50 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 75 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 150 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 200 | Red | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow |
| 300 | Red | Red | Red | Red | Red | Red | Red | Red | Yellow |
| 400 | Red | Red | Red | Red | Red | Red | Red | Red | Red |
| 500 | Red | Red | Red | Red | Red | Red | Red | Red | Red |
| 1000 | Red | Red | Red | Red | Red | Red | Red | Red | Red |
| >1000 | Red | Red | Red | Red | Red | Red | Red | Red | Red |

**Table 9 - Vernier Calliper Capability Chart**


**Figure 23 - Vernier Calliper (Mahr)**

## 4.3 Depth Gauges

The depth gauge is a popular variation of a micrometer or calliper specifically designed to measure depths and steps. Depth micrometers are more accurate than depth callipers. Micrometers can have a resolution under 10 microns, whereas callipers are limited to around 20 microns. Callipers are less reliable because the force applied by the user is not repeatable producing different readings. Depth micrometers usually come in a set with interchangeable rods so different depths can be measured with just one measuring head. Readings of up to approx. 300mm are capable with depth micrometers whilst depth callipers can measure up to approx. 500mm.

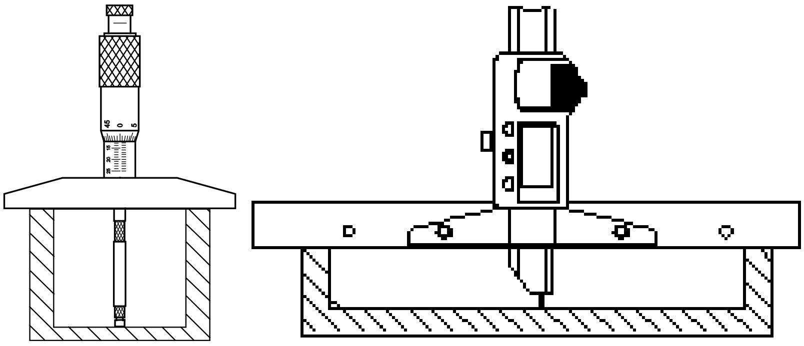


**Figure 24 - Depth Micrometer and Depth Calliper (Mahr)**

### 4.3.1 Usage Guidance

- The user should regularly check that the cap on the depth micrometer is tight. A loose cap will not hold the measuring rod securely, resulting in an unstable zero point.

**Figure 25 - Depth Micrometer Cap (Mitutoyo UK Ltd)**

- When changing rods on a depth micrometer the user should check the rods are thoroughly clean.
- Care should be taken to ensure that the measuring rods remain straight and are not damaged.


**Figure 26 - Depth Micrometer and Measuring Rods (Mitutoyo UK Ltd)**

- When measuring using depth callipers, the user should try to apply the same force during every measurement.
- Periodically, the minimum or maximum measuring point of a depth micrometer should be checked with a gauge block. A gauge block should be placed under each side of the depth micrometer and pushed down. The value shown on the micrometer should be compared to the gauge block size.

**Figure 27 - Checking Depth Micrometer with Gauge Block (Mitutoyo UK Ltd)**

### 4.3.2 Common Pitfalls

- Misuse of the ratchet system resulting in over or under tightening.
- Excessive force applied when using a depth calliper.
- Measuring different or incorrect positions within a hole which is not flat.

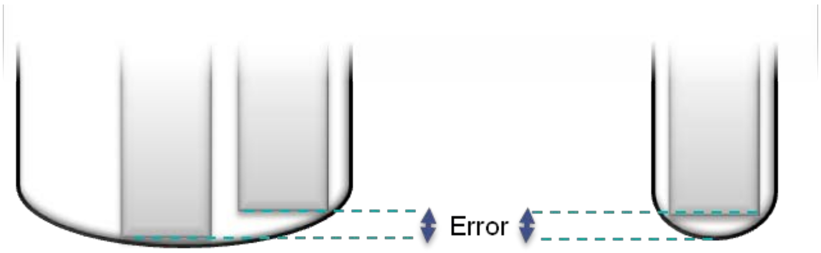



**Figure 28 - Error in Bore Depth Measurement**

### 4.3.3 Calibration

#### 4.3.3.1 External

- BS 6468 - Depth Micrometers
- BS 6365 - Precision Vernier Depth Gauges

### 4.3.4 Standards, Training and Further Reading

- MXG001 - Best practice guidelines for the use of micrometers and callipers
- NPL Guide - Micrometers and Callipers

### 4.3.5 Capability Chart

#### 4.3.5.1 Depth Micrometer

| Feature Size (mm) | Specification Tolerance (mm) +/-0.005 | +/-0.010 | +/-0.025 | +/-0.050 | +/-0.100 | +/-0.250 | +/-0.500 | +/-0.750 | +/-1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 5 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 10 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 25 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 50 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 75 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green |
| 100 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green |
| 150 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 200 | Red | Red | Red | Red | Red | Red | Red | Yellow | Green |
| 300 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |
| 400 | Red | Red | Red | Red | Red | Red | Red | Red | Yellow |
| 500 | Red | Red | Red | Red | Red | Red | Red | Red | Red |
| 1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| >1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |

**Table 10 - Depth Micrometer Capability Chart**


**Figure 29 - Depth Micrometer (Mitutoyo UK Ltd)**

#### 4.3.5.2 Depth Calliper

| Feature Size (mm) | Specification Tolerance (mm) +/-0.005 | +/-0.010 | +/-0.025 | +/-0.050 | +/-0.100 | +/-0.250 | +/-0.500 | +/-0.750 | +/-1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 5 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 10 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 25 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 50 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 75 | Red | Red | Red | Red | Red | Red | Yellow | Green | Green |
| 100 | Red | Red | Red | Red | Red | Red | Yellow | Green | Green |
| 150 | Red | Red | Red | Red | Red | Red | Yellow | Green | Green |
| 200 | Red | Red | Red | Red | Red | Red | Yellow | Yellow | Green |
| 300 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |
| 400 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |
| 500 | Red | Red | Red | Red | Red | Red | Red | Red | Yellow |
| 1000 | Red | Red | Red | Red | Red | Red | Red | Red | Red |
| >1000 | Red | Red | Red | Red | Red | Red | Red | Red | Red |

**Table 11 - Depth Calliper Capability Chart**


**Figure 30 - Depth Calliper (Mahr)**

## 4.4 Height Gauges

Height gauges come in a variety of configurations. Models range from manual gauges with analogue scales to highly accurate digital touch probes. Motorised automatic versions are also available. Both gauges use a vertical axis to measure distances using a probe. This may mean that the part needs to be orientated in a particular direction for the feature being measured. The automated height gauge has a touch trigger probe that can measure lengths as well as various other functions e.g. finding the centre of a hole, the distance between 2 holes etc. Most of the programs for these functions are built into the gauge. Automated gauges can come with additional accessories such as touch screens and extra holders to measure multiple distances at once.

**Figure 31 - Automated Height Gauge in Operation (Mahr)**

### 4.4.1 Environmental Requirements

- Height gauges are capable of measuring large dimensions. This means that they can be more exposed to the thermal expansion of large parts. Care should be taken to ensure that this effect is minimised whenever possible.
- The height gauge uses the table it sits on as part of the measurement system. Consequently the cleanliness and finish of the table is crucial. Ideally, a granite or steel surface plate should be used. They are manufactured to different grades - Grade AA is the most accurate and has a flatness limit of 1 µm - 18 µm, depending on the size of the plate. Grade A’s flatness limit is twice that of an AA plate and Grade B twice that of Grade A plate.


**Figure 32 - Digital Height Gauge on a Granite Table**

### 4.4.2 Usage Guidance

- The accuracy of the height gauge can be verified by measuring standardised gauge blocks. This check can be repeated periodically, using a range of heights.
- The gauge should be held and touched only where it is intended to be. There are usually handles provided to move and adjust the gauge. Heat transferred from the hands can affect the accuracy of the gauge.
- When using a manual height gauge, care should be taken to ensure the same force is applied during every measurement.

### 4.4.3 Common Pitfalls

- The surface plate is dirty or of an insufficient flatness and reduces capability.

### 4.4.4 Calibration

#### 4.4.4.1 External

- BS 1643 - Vernier Height Gauges

## 4.4.5 Capability Chart

### 4.4.5.1 Digital Height Gauge

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 5 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 10 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 25 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 50 | Red | Red | Red | Red | Yellow | Yellow | Green | Green | Green |
| 75 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 200 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 300 | Red | Red | Red | Red | Red | Red | Yellow | Green | Green |
| 400 | Red | Red | Red | Red | Red | Red | Yellow | Yellow | Green |
| 500 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |
| 1000 | Red | Red | Red | Red | Red | Red | Red | Red | Yellow |
| >1000 | Red | Red | Red | Red | Red | Red | Red | Red | Yellow |

**Table 12 - Digital Height Gauge Capability Chart**

**Figure 33 - Digital Height Gauge (Mahr)**

### 4.4.5.2 Automatic Height Gauge

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Yellow | Green | Green | Green | Green | Green | Green |
| 5 | Red | Red | Yellow | Green | Green | Green | Green | Green | Green |
| 10 | Red | Red | Yellow | Green | Green | Green | Green | Green | Green |
| 25 | Red | Red | Yellow | Green | Green | Green | Green | Green | Green |
| 50 | Red | Red | Yellow | Yellow | Green | Green | Green | Green | Green |
| 75 | Red | Red | Yellow | Yellow | Green | Green | Green | Green | Green |
| 100 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 150 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 200 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 300 | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Green | Green |
| 400 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 500 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 1000 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| >1000 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |

**Table 13 - Automated Height Gauge Capability Chart**


**Figure 34 - Automated Height Gauge (Bowers)**

## 4.5 Contact Bore Gauges

Contact bore gauges are used to measure bore diameters. They are available both as comparators (bore indicators) and absolute gauges (2 & 3 point bore micrometers).

Bore micrometers produce high quality measurements but are subject to the effects of bore geometry. The 3 point bore micrometer has good reproducibility due to the self-aligning nature of the gauge. If a bore is 3-lobed, a 3 point bore micrometer can detect this by measuring at various angular positions. This reduces the chances of incorrect measurement. Similarly a 2 point bore micrometer should measure a 2-lobed bore. 3 point bore micrometers are easier to use than 2 point bore micrometers because of the extra contact point. The point makes it quicker and easier to operate and also provides a better measure of average diameter.

Bore Indicators are usually set against a known master ring and then used to measure to difference between the bore in question and the master ring. Bore Indicators can take hole measurements more than 2m deep if fitted with the right extensions. They are more accurate than bore micrometers but being comparators they have a very small range. Bore micrometers are more appropriate when many different parts must be measured.

**Figure 35 - Gauge with Setting Ring**

Countersink gauges measure the major diameter of countersunk bores. The capability of a countersink gauge largely depends on the application it is used in, often the gauges are used at awkward angles or in confined spaces. Capability also depends on the angle of the countersink; a gauge designed to measure the diameter of a 90° countersink will give poor results if the actual angle is 91°. A full, detailed Gauge R&R study should be carried out to see if the capability of the gauge is acceptable.

### 4.5.1 Usage Guidance

- Setting rings are classed depending on their tolerance. Class XXX indicates the tightest tolerance, XX, X and Y are intermediate grades and Z is the lowest grade.
- As a general rule a setting ring should have a tolerance of 10% or less than the feature tolerance. For example a bore with tolerance +/- 0.30mm should be measured with a bore comparator which has been calibrated with a setting ring of tolerance +/- 0.03mm or lower.
- Usually a stop, shoulder or collar is required to ensure that the measurement is taken perpendicular to the bore at a consistent depth.

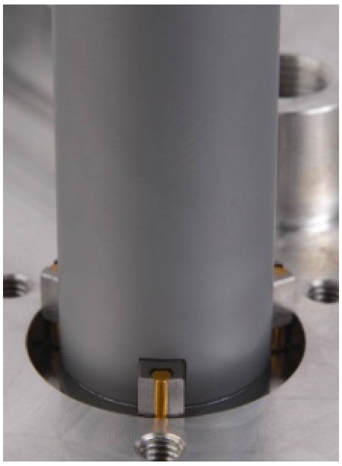


**Figure 36 - 3 Point Bore Micrometer self-aligning in hole (Mitutoyo UK Ltd)**

- The capability of most bore gauge measurements can be increased easily by customising the measurement process e.g. including fixtures, depth stops and collars. These help to ensure measurements are taken from the same point in the bore each time.
- The shape of the bore (ovality, lobes etc.) being machined should be taken into consideration when deciding what type of bore gauge to use. Measurements can be taken at different angular positions to check for variation of diameter.
- When using two point bore gauges, rocking the gauge to find the minimum reading will improve accuracy, ensuring the gauge is perpendicular to the bore.
- The diameter of the bore should be checked at two different heights to determine if there is a taper being produced from the machining process.
- The angle of countersink gauge plunger should be as close as possible to angle of the countersink feature to achieve a reliable measurement.

### 4.5.2 Common Pitfalls

- The measurements are taken from different heights in the hole.
- The lobing of hole is not taken into consideration.
- The dial gauge may spin around twice when taking a measurement but may not be accounted for by the user when reading the scale.

### 4.5.3 Calibration

#### 4.5.3.1 External

- BS 959 - Internal Micrometers

### 4.5.4 Capability Chart

### 4.5.4.1 Countersink Gauges

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 5 | Red | Red | Yellow | Yellow | Green | Green | Green | Green | Green |
| 10 | Red | Red | Red | Yellow | Green | Green | Green | Green | Green |
| 25 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 50 | Red | Red | Red | Red | Yellow | Green | Green | Green | Green |
| 75 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Red | Red | Red | Yellow | Green | Green |
| 200 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 300 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |

Table 14 - Countersink Gauge Capability Chart


Figure 37 - Countersink Gauge (Bowers

### Bore Micrometer (3 point)

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 5 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 10 | Red | Red | Yellow | Green | Green | Green | Green | Green | Green |
| 25 | Red | Red | Yellow | Green | Green | Green | Green | Green | Green |
| 50 | Red | Red | Yellow | Yellow | Green | Green | Green | Green | Green |
| 75 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 100 | Red | Red | Yellow | Yellow | Yellow | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Red | Red | Yellow | Green | Green | Green |
| 200 | Red | Red | Red | Red | Red | Yellow | Yellow | Green | Green |
| 300 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 400 | Red | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow |
| 500 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| >1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |

Table 15 - 3 Point Bore Micrometer Capability Chart

Figure 38 - 3 Point Bore Micrometer (Mitutoyo UK Ltd)

### 4.5.4.2 Bore Micrometer (2 point)

| Feature Size (mm) | Specification Tolerance (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
| <1 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 5 | Red | Yellow | Green | Green | Green | Green | Green | Green | Green |
| 10 | Red | Yellow | Green | Green | Green | Green | Green | Green | Green |
| 25 | Red | Yellow | Yellow | Green | Green | Green | Green | Green | Green |
| 50 | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green | Green |
| 75 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 100 | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Green | Green |
| 150 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Green |
| 200 | Red | Red | Red | Red | Red | Red | Yellow | Yellow | Green |
| 300 | Red | Red | Red | Red | Red | Red | Yellow | Yellow | Green |
| 400 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 500 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| >1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |

**Table 16 - 2 Point Bore Micrometer Capability Chart**


**Figure 39 - 2 Point Bore Micrometer (Mahr)**

### 4.5.4.3 Bore Indicators (2 point)

| Feature Size (mm) | Specification Tolerance (mm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
| <1 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 5 | Yellow | Yellow | Green | Green | Green | Green | Green | Green | Green |
| 10 | Yellow | Yellow | Green | Green | Green | Green | Green | Green | Green |
| 25 | Yellow | Yellow | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 50 | Yellow | Yellow | Yellow | Yellow | Yellow | Yellow | Green | Green | Green |
| 75 | Red | Yellow | Yellow | Yellow | Yellow | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Green | Green |
| 150 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Yellow |
| 200 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |
| 300 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |
| 400 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |
| 500 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| 1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |
| >1000 | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey | Grey |

**Table 17 - 2 Point Bore Indicator Capability Chart**

**Figure 40 - Bore Indicators (Bowers)**

## 4.6 Air Gauges

Air Gauging is a non-contact measurement method, making it useful to check soft, polished or thin walls. When used in the correct conditions, it can achieve a very high level of capability. The diameter of the bore is calculated using the correlation between the air pressure and the distance between the nozzle and internal wall of the work piece. Air gauges are typically effective on surfaces with a surface finish of less than 32 µm $R_a$.


**Figure 41 - Air Gauge Probe and Setting Ring**

### 4.6.1 Equipment Applications (Features)

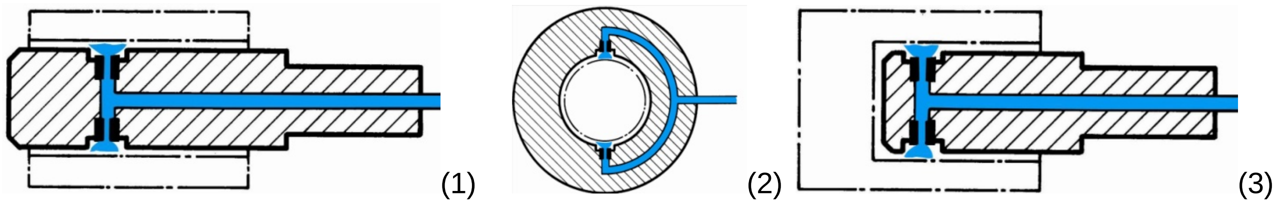



**Figure 42 - Examples of Air Gauging Applications (Mahr)**

(1) - Diameter measurement of cylindrical through bores with air plug gauge
(2) - Diameter measurement of cylindrical shafts with air ring gauge
(3) - Diameter measurement of cylindrical blind bores with air plug gauge

### 4.6.2 Environmental Requirements

- The operating range for air gauges is 0-50°C. However, the measurements will be more reliable when the operating condition is closer to standard operating temperature.
- Ensure a clean, dry, air supply is used for air gauges.
- The air supply for an air gauge should not be connected using in-line oilers; any oil released will affect the measurement.
- The air supply must have a constant temperature and pressure.

### 4.6.3 Usage Guidance

- Care should be taken to avoid twisting or trampling the hose during operation.
- Much of the guidance regarding setting rings and bore form contained in the contact bore gauge section also applies to air gauges.

### 4.6.4 Capability Chart

#### 4.6.4.1 Air Gauges

It is difficult to create a capability chart for Air Gauges since they are designed specifically for the particular application required. The great advantage of air gauging is that they can be used on the shop floor, provide a rapid measurement system for volume parts and so long as the environmental temperatures are reasonably stable provide a robust measurement system. Air gauges capable of measuring tolerances in the range 0.2 – 0.01 mm are readily available and should prove capable. Below 0.01 mm and for difficult measurement tasks air gauges must be carefully designed and assessed. Many configurations of air gauges are available as they are specific to the features and characteristics being inspected. Careful inspection planning is required so the air gauge measurements are representative of the product requirements. For example, 3 and 4 jet air gauges provide an averaging of the diameter, therefore, use of these may need to be justified through a measurement limitation approval. The surface roughness of the parts is also important with air gauging. Air gauges can also be used for match gauging of parts prior to assembly processes to ensure the required fine limit clearance or interferences are achieved. Air gauges may not be appropriate at tolerances above +/-0.050mm as less expensive alternative solutions may be available. Depending on manufacturer, minimum and maximum masters may be required to establish the linearity of the device. A detailed Gauge R&R Study should still be carried out to verify the capability of the system.


**Figure 43 - Air Gauge (Mahr)**

## 4.7 Large Bore Gauges - 'Spider' Gauges

A 'spider' gauge can be used when measuring large internal diameters when the capability of an internal micrometer is insufficient. Similarly to bore indicators, these gauges have a very small range but very good capability.

**Figure 44 - 'Spider' Gauges**

The gauge is a large two part device, it consists of a split-pin configuration with a shroud, sleeve and handle arrangement attached to a digital indicator. This gauge is capable of giving readings to 0.001mm, over a range of +/-0.250mm, although this constraint can be increased.

### 4.7.1 Common Pitfalls

- Due to 'spider' design, can't be used where there is an obstruction within the bore. Alternative ring-variants have been produced which eliminate this issue.

### 4.7.2 Capability Chart

The capability of this type of gauge depends heavily on the application but experience has shown that on tolerances of +/- 25µm a Gauge R&R of less than 20% can be easily achieved on diameters of approximately 300mm. Typically the bias when compared to a CMM can be of the order of 2.5µm or less.

## 4.8 Adjustable Snap Gauges

Snap gauges can be used to make rapid measurements on cylindrical features. The gauge is set using a calibrated master and all measurements are compared to this reference. A digital or dial display shows the variation between the master and the work piece.

Despite being quick and easy to use snap gauges can still give reliable, accurate results. They are versatile and can be used in a wide variety of applications but a calibrated master is required for every type of measurement being made. The gauge can be modified for use in different applications (e.g. pointed or ball anvils).

In some cases the supplier can customise the gauge according to its size and application and older Go/No Go snap gauges can easily be retrofitted with digital display. Snap gauges are very useful tools on the shop floor as they are flexible and robust.

**Figure 45 - Carbon Fibre Snap Gauge (Bowers)**

### 4.8.1 Usage Guidance

- The entire measuring surface of the snap gauge should be in contact with the feature being measured to avoid uneven anvil wear. If this cannot be achieved then the part should be located in different positions on the anvil. Repeated use of one part of the anvil will cause uneven wear. (Figure 46 shows a narrow part which will wear a groove in the anvils and a sufficiently large part which will wear the anvils evenly).

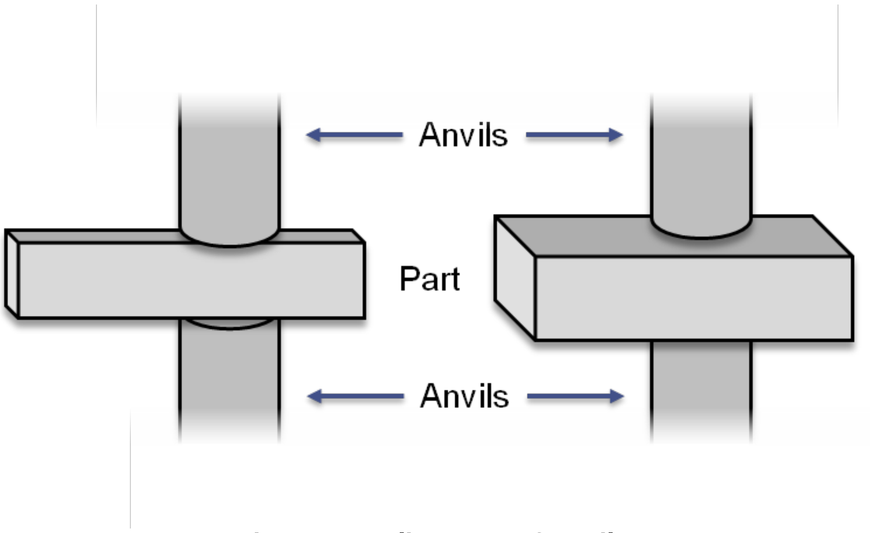



**Figure 46 - Alignment of Anvils**

- Periodic checks should be made to verify that the anvils are parallel. To check for parallelism, a precision wire or steel ball should be placed at the front, back, left and right edges of the anvils, comparing the indicator readings at each stage.
- Parallelism should be checked every time the anvils are removed or replaced from the snap gauge or if the gauge has been dropped.
- For large production runs it is better to set the gauge using a calibrated master of the required size. For smaller runs a set of gauge blocks can be used.
- If snap gauge is going to be used for a particular part regularly, the gauge and anvils can be modified as appropriate to achieve better, more capable results.

### 4.8.2 Capability Chart

#### 4.8.2.1 Snap Gauges

While using snap gauges there is potential for operator variability. The gauges are also application specific. This means that it is difficult to create a generic capability chart that can be used for all snap gauge applications. A full, detailed Gauge R&R study should be carried out to check if the gauge achieves an acceptable result.

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 5 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 10 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 25 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 50 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 75 | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green | Green |
| 100 | Red | Red | Yellow | Yellow | Yellow | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 200 | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Green | Green |
| 300 | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Yellow | Green |
| 400 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 500 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |
| 1000 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |
| >1000 | Red | Red | Red | Red | Red | Red | Red | Yellow | Yellow |

**Table 18 - Snap Gauge Capability**


**Figure 47 - Snap Gauge (Mahr)**

## 4.9 Ultrasonic Gauges

Ultrasonic gauging is most typically a form of non-destructive testing (NDT) for sub surface flaw detection, however it also has application as a dimensional measurement tool. Ultrasonic thickness gauges work by measuring the time it takes for a sound pulse to travel through the material and be reflected back. The time and the speed of sound through the material are used to calculate the thickness. The speed of sound through the material is determined during the set up procedure, which will include setting the instrument with a standard reference block made of the same material as that being measured.

Ultrasonic gauges are most useful when only one side of the part is accessible. Typical applications are measuring wall thickness of pipes and tanks. The measurement is heavily dependent on the material, the temperature of the test piece and the material used to couple the transducer to the work piece (called the couplant). The frequency is automatically pre-set depending on the material and an appropriate couplant is normally specified by the manufacturer.

Ultrasonic gauges can potentially be accurate, capable gauges but need to be operated very carefully. It can be difficult to get a positive Gauge R&R value due to operator variations in transducer tip alignment.


**Figure 48 - Ultrasonic Measurement Kit**

### 4.9.1 Environmental Requirements

- Contact transducers can be used up to around 50°C. However, results are more reliable when the operating temperature is closer to the standard operating conditions.
- A dust and dirt free environment is crucial as the transducer must couple precisely with the surface.

### 4.9.2 Usage Guidance

- The probes or transducer tips can easily wear out resulting in rounded edges. This will have a negative effect on the repeatability of the instrument. Transducer tips should be treated as consumables and regularly replaced. The setup procedure after a transducer is changed should:
  - use calibrated reference masters of the same material and surface conditions as of the component to be measured.
  - use at least two points, one for the maximum and one for the minimum range values. It is also recommended to check the readings on reference masters between the ranges.
  - be carried out at the same temperature as the measuring environment.
  - be performed whenever the test material or the transducer is changed.
- If the surface of the part being measured is curved, a smaller sized transducer should be used. Generally the tighter curvature of the surface, the smaller the transducer should be.

### 4.9.3 Common Pitfalls

- Attempting to measure very thin sections with typical ultrasonic gauging can be problematic. **Below 0.4mm in thickness results can be unreliable and it should be demonstrated that the gauge is fit for purpose**.
- Dirt, coolant or swarf on the surface of the part. This does not allow the couplant to interact with the part as required.
- User not aligning the measurements to exactly the same point.
- Inadequate quantity of couplant gel so the probe does not make good contact

**Figure 49 - Operator Taking Measurement**

### 4.9.4 Capability Chart

It is difficult to produce a generic capability chart for ultrasonic gauges. This is because the results of ultrasonic gauge measurements depend on a huge variety of specific factors such as:

- Material Factors
  - Acoustic properties
  - Sound scattering
  - Sound absorption
  - Velocity variation
  - Phase reversal/ distortion
  - Physical properties
  - Surface roughness
  - Curvature

- Equipment Factors
  - Gauge properties
  - Transducer properties
  - Setup
  - Couplant

- Operator Factors
  - Calibration
  - Beam alignment
  - Coupling technique


**Figure 50 - Ultrasonic Gauge (Bowers)**

Typically ultrasonic gauges are at their limit of capability on tolerances of +/- 0.1mm on thin sections (<5mm) and potentially worse for thicker sections. On sections less than 0.4mm they become unreliable and should not be used without specialist advice.

## 4.10 Beam Comparators

Beam comparators are very versatile length gauges. They have poor capability on lengths less than around 250mm and consequently are mainly used on larger workpieces. The gauges are available in modular form or as all-in-one gauges.

Modular beam comparators can be configured and adapted to nearly any measurement task. Further optional accessories can be purchased for use in special measurement applications.

All-in-one gauges are typically more compact and simpler to set up. They can often be reversed allowing both internal in external measurements to be made. Despite this reversibility they are not as versatile or capable as the modular gauges.

**Figure 51 - A Modular Comparator on a Stand (Bowers)**

### 4.10.1 Usage Guidance

- After changing parts of the gauge, the gauge should be checked by measuring calibrated masters, slip gauges or gauge blocks.
- The quality of the calibrated master is important. A master made of similar material as the component can help compensate for temperature differences.

### 4.10.2 Common Pitfalls

- Measuring small dimensions can be problematic giving poor results.
- Incorrectly assembled modular comparators can be prone to backlash error.

## 4.10.3 Capability Chart

### 4.10.3.1 Modular Beam Comparators

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Red | Yellow | Green | Green | Green | Green | Green |
| 5 | Red | Red | Red | Yellow | Green | Green | Green | Green | Green |
| 10 | Red | Red | Red | Yellow | Green | Green | Green | Green | Green |
| 25 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 50 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 75 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 100 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 200 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 300 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 400 | Red | Red | Red | Yellow | Yellow | Yellow | Yellow | Yellow | Green |
| 500 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |
| 1000 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |
| >1000 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |

**Table 19 - Modular Beam Comparator Capability Chart**

**Figure 52 - Modular Beam Comparator (Bowers)**

### 4.10.3.2 Omnigauge Comparators

| Feature Size (mm) | Specification Tolerance (mm) +/- 0.005 | +/- 0.010 | +/- 0.025 | +/- 0.050 | +/- 0.100 | +/- 0.250 | +/- 0.500 | +/- 0.750 | +/- 1.000 |
|---|---|---|---|---|---|---|---|---|---|
| <1 | Red | Red | Red | Yellow | Green | Green | Green | Green | Green |
| 5 | Red | Red | Red | Yellow | Green | Green | Green | Green | Green |
| 10 | Red | Red | Red | Yellow | Green | Green | Green | Green | Green |
| 25 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 50 | Red | Red | Red | Yellow | Yellow | Green | Green | Green | Green |
| 75 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 100 | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green | Green |
| 150 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green |
| 200 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green |
| 300 | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green | Green |
| 400 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Green |
| 500 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |
| 1000 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |
| >1000 | Red | Red | Red | Red | Red | Yellow | Yellow | Yellow | Yellow |

**Table 20 - Omnigauge Comparator Capability Chart**

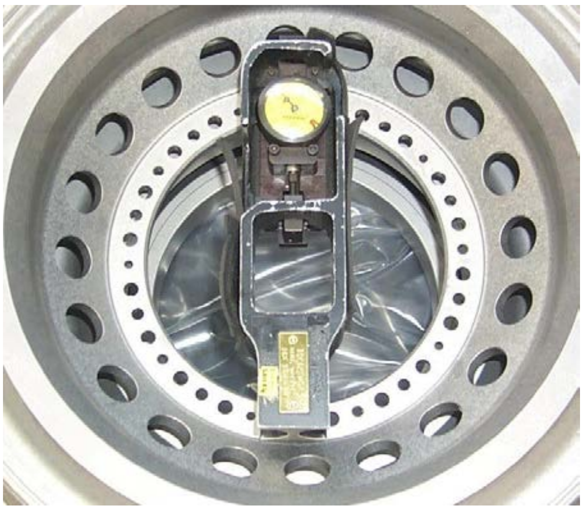


**Figure 53 - Onmigauge Measuring a Disk Bore**

## 4.11 Indicators

Indicators are often referred to as; Dial/Digital Test Indicators (DTI), Lever Arm Test Indicators or Finger Indicators. There are two main types - lever and plunger. Indicators are used for a variety of tasks such as measuring runout and flatness and also for making comparative measurements. They are also used to set up work pieces on machine tools. Indicators primarily make small measurements, from less than 1mm to up to about 200mm with graduations of max 0.01mm.

**Figure 54 - Digital Indicator (plunger type)**

**Figure 55 - Analogue Indicators (lever & plunger type) (Mitutoyo)**

Digital indicators have significant advantages over dial indicators, primarily they are easier to operate and have a much clearer scale. However, the reference point is lost when the gauge is turned off which can be unhelpful.

Lever indicators have a tilting arm and can measure displacement at an angle perpendicular to the axis of the indicator. The arm can be interchanged for where different lengths or contact points are required.

### 4.11.1 Usage Guidance

- Indicators are usually mechanical devices with a number of gears and racks to convert linear motion to angular motion, so they are prone to backlash as they wear. This error can be avoided by always taking measurements in the same direction.
- The lever arm should be adjusted so that the movement of the tilt is as close as possible to being perpendicular to the measured surface to avoid cosine error.
- For lever indicators - When changing contact points, only points of the same length should be interchanged. A change in the length of the contact point changes the magnification of the indicator. Points with different tip diameters can be interchanged as required.
- For lever indicators - The centreline of the contact point should be parallel to the surface of the work piece i.e. the contact point should be at $90^{\circ}$ to the direction of measurement. If this cannot be achieved, the angle should be determined and a correction factor applied.

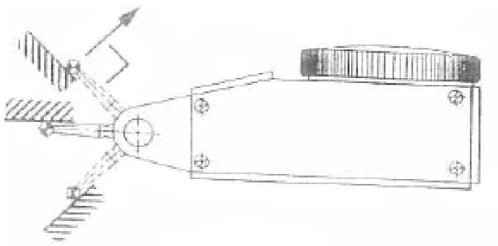


Figure 56 - Angle of Measurement (Brown & Sharpe)

### 4.11.2 Common Pitfalls

- Incorrect indicator tip length used with lever indicators.
- Lever Indicators measure angular displacement and not linear displacement. This causes a cosine error. The error is negligible when the angle is small, typically less than 10º.

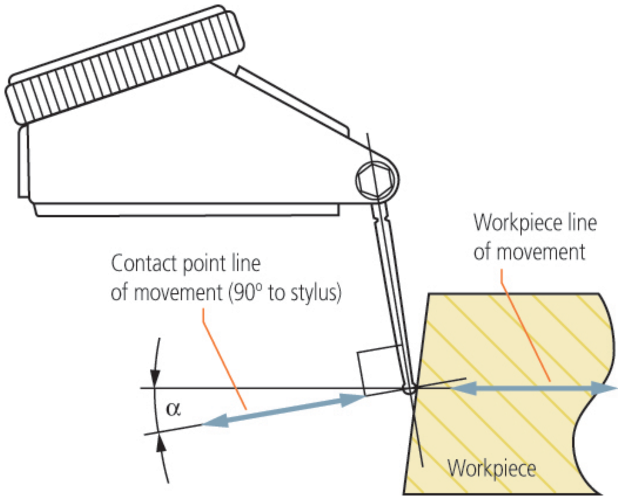



Figure 57 - Cosine Error (Mitutoyo UK Ltd)

- Hysteresis error due to the small delay between the physical action of the gauge and it registering on the display. The error is extremely small but is cumulative, so still needs to be kept in mind when making measurements.

### 4.11.3 Calibration

#### 4.11.3.1 External

- BS 907 Dial Gauges for Linear Measurement
- BS 2795 Dial Test Indicators (lever type) for Linear Measurement

### 4.11.4 Standards, Training and Further Reading

- The Mitutoyo Metrology Handbook has a good section on indicators

### 4.11.5 Capability Chart

#### 4.11.5.1 Indicators

The capability chart shown is the ideal scenario and only includes the capability of the Indicator. The other uncertainties in the setup of the measurement process have to be taken into account. These uncertainties are cumulative and can play a major factor in the capability of the measurement process. The best way to validate a system is to conduct a full, detailed Gauge R&R study.

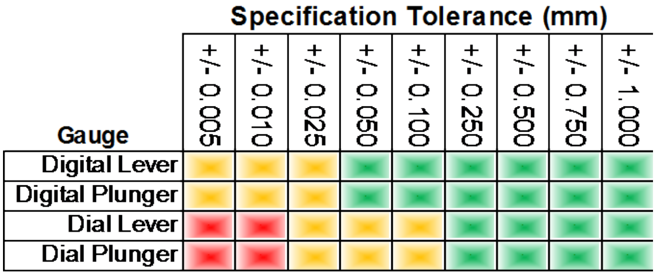



**Table 21 - Indicators Capability Chart**

## 4.12 Attribute Gauges

GO/NO GO gauges are attribute gauges. Hence they can only determine whether a feature is within tolerance, not the actual dimension. Both plug and snap GO/NO GO gauges are available.

The plug (go/no go) gauge has two ends - the GO end which is the size of the LSL and the NO GO side which is the fractionally larger than the USL. For example, for a hole to pass inspection the GO end should pass through the hole and the NO GO end should not pass through the hole.

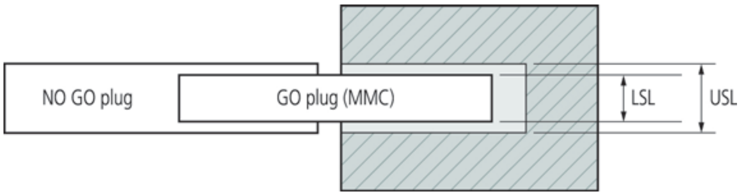



**Figure 58 - GO/NO GO Principle**

GO/NO GO snap gauges are used to measure outside diameters. The first set of jaws on the gauge is built to the upper tolerance and the second set of jaws is built to the lower tolerance. A correctly machined part will pass through the first set of jaws and stop at the second set. This allows the part to be checked quickly in one action. The gauge is usually built to specification so has good accuracy.

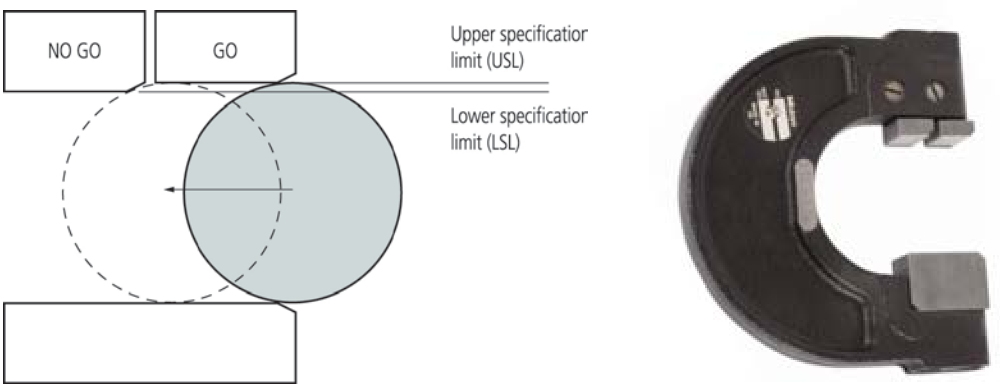



**Figure 59 - GO/NO GO Snap Gauge (Mitutoyo UK Ltd)**

As well as plug and snap gauges used for GO/NO GO attribute measurements there are a number of pieces of equipment that can be used for an attribute check or to provide a measurement at distinct intervals. These include plug and pin gauges for holes as well as slip and feeler gauges for gaps and flushes.

Plug gauges are usually custom manufactured at the required sizes and are highly accurate. Alternatively, master plug gauge sets can be used to put together an appropriate sized gauge. Plug gauges are a quick, cheap and effective method of measuring bore diameters. They are particularly useful when measuring large quantities of parts. Feeler gauges are generally used for checking small gaps in component assemblies, where tolerance requirements are not too tight. This can be to verify maximum or minimum gaps. Feeler gauges maintain a good level of capability down to 0.125 mm; however measurement capability is dependent on each individual application as there is a high degree of operator influence.

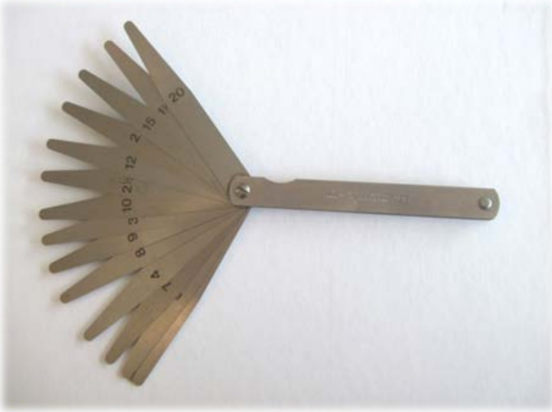


**Figure 60 - Feeler Gauges** **Figure 61 - Slip Gauges**

Slip gauges, also known as Gauge Blocks are reference measurement standards. There are several grades of gauge blocks available dependent upon the required application. The lower grade standard (workshop) can be used for measurement of an attribute on gaps, slots or steps. These blocks are often used in conjunction with another piece of equipment such as a dial test indicator. More accurate measurements are made using laboratory grade gauge blocks in calibration rooms or in high precision measurement rooms. However these gauge blocks are more expensive and should therefore not be used on the shop floor. Pin Gauges are designed to measure small holes (<2mm) and provide an attribute check on whether a hole is conforming. They can also be used to provide measurements of small holes with the resolution of measurement dependent on intervals between pin sizes. Great care should be taken as these gauges, especially those with a smaller diameter, can be damaged very easily.


**Figure 62 - Plug Gauges (Mitutoyo UK Ltd)**

Larger plug gauges can be used in a similar way to pin gauges to provide a measurement of hole size, with the resolution limited to the intervals between the plug size in the set used.
For measurements or attribute checks made with these gauges capability is highly dependent on the specific application, therefore a capability study should always be undertaken using actual parts where possible.

### 4.12.1 Storage Requirements

The following points should be considered in addition to the general storage requirements:

- These gauges are master gauges and may be used in calibration hence extra care should be taken to prevent any damage to them.
- All gauges should be clearly identified with their calibrated size.

### 4.12.2 Usage Guidance

- It is commonly thought that GO/NO GO gauging has only two possible outcomes - pass or fail. There are actually three possible results - pass, feature is oversized or feature is undersized. Depending on the feature (outside diameter or hole diameter), it is possible to rework it and inspect again.

**Figure 63 - Using the Plug Gauge (Mitutoyo UK Ltd)**

- Measurement should be carried out in bare hands so the user can get the best ‘feel’.
- Gauges are usually marked with a ‘+’ or ‘-‘. A ‘+’ means the gauge is oversized by the manufacturing tolerance and a ‘-‘ means the gauge is undersized by the manufacturing tolerance.
- Gauges should be clearly marked to prevent any confusion. For example:
    - Mark GO gauges in green and NO GO gauges in red
    - Place stickers to differentiate between + and - gauges
- Plug and snap gauge tolerances should be manufactured to a much smaller tolerance than the feature. Generally, +/- 10% of the feature tolerance split evenly between the GO and NO GO gauges.
- Gauges are manufactured to an appropriate grade with respect to the manufacturing tolerances. The selection of the correct grade is important in achieving a capable measurement process. The cost of the gauges increase as the tolerance becomes tighter.
- The approximate tolerance grades in increasing accuracy are given below. These are subject to change depending on the manufacturer and size of the master:
    - ZZ - 0.005mm Z - 0.0025mm X - 0.001mm XX - 0.0005mm

### 4.12.3 Common Pitfalls

- Incorrect classification due to varied operator ‘feel’. An operator may pass a part another might fail.
- Failure to detect feature form / profile. For example, a bore may be tapered with an increasing diameter but can still pass a plug gauge inspection as long as the initial bore diameter is correct.

### 4.12.4 Calibration

#### 4.12.4.1 External

- TDS 206 Plug Limit Gauges
- BS 969 Limits and Tolerances on Plain Limit Gauges

### 4.12.5 Capability Chart

Attribute gauges cannot be assessed with a normal Gauge R&R. An attribute agreement analysis should be carried out to verify the capability of the system.

## 4.13 Visual Comparators

Visual comparators such as thread and radius gauges function by the user pressing the thread against one of the gauge blades and checking the ‘fit’. The gauge largely depends on the operators’ feel, hence the variability. This needs to be kept in mind when considering the use of visual comparators for any measurement application.

Radius gauges are used in a similar manner to thread gauges. The feature is pressed against the gauge to check the ‘fit’. They can be used to measure internal and external radii profiles. Again, this is not very accurate as there is large operator variability.

**Figure 64 - Radius Gauge (Bowers)**

### 4.13.1 Environmental Requirements

- The edges on radius and thread gauges should be checked for any chips, burrs or debris that may affect the measurement.

### 4.13.2 Usage Guidance

- A light source should be placed behind the feature being measured. The gauge should be placed against the feature to check there is no light leakage between the feature and edge of the gauge.
- Gauges are manufactured to an appropriate grade with respect to the manufacturing tolerances. The selection of the correct grade is important in achieving a capable measurement process. The cost of the gauges increase as the tolerance becomes tighter. The tolerance grades are:
    - ZZ - 0.005mm
    - Z - 0.0025mm
    - X - 0.001mm
    - XX - 0.0005mm

### 4.13.3 Common Pitfalls

- Incorrect classification due to varied operator ‘feel’. An operator may pass a part another might fail.

### 4.13.4 Capability Chart

#### 4.13.4.1 Radius & Thread Gauges

The operator variability of thread and radius gauges makes it difficult to assess their generic capability. A study done using radius gauges suggests that minimum tolerance when using radius gauges should be approximately +/- 1.500mm or greater. This depends on the application and the type of radius being measured. A full, detailed attribute Gauge R&R study should be carried out to check the capability of the measurement system.

## 4.14 Surface Finish Instruments

Surface texture affects the functional performance as well as the mechanical properties of materials. It is believed that 90% of all engineering component failures are surface initiated through mechanisms such as fatigue cracking, stress corrosion cracking, fretting or abrasive wear. The functional performance requirements for surfaces vary hugely; those of vehicle brake disks are clearly different to those of bearing surfaces.

Surface texture characteristics are generated by a combination of the machining process, feed rate, tool speed, tool geometry and also the environmental conditions. It is important to understand how the manufacturing process modifies the surface when planning measurement. Both the process specifics (e.g. the direction of lay (machining marks)) and the level of control (e.g. a regular repeatable cylindrical grinding process vs. a hand polishing process) should be considered.

The surface texture may be assessed comparative or direct measurement. Comparative methods assess the surface texture by observation or the feel of the surface. The technique involves dragging the finger nail over the surface to be measured and comparing to the reference standards. This was amongst the first methods for surface texture measurement and is still popular today.

**Figure 65 - Comparative Surface Texture Standards**

Direct measurement of the surface is usually carried out with a tactile measuring instrument with a diamond tipped stylus. These instruments can measure vertical movements down to nanometre values and due to the effects of vibration and shock are normally only used in laboratories. The contact pressure applied at the stylus tip is very small in order to ensure it does not plough the surface giving false readings.

**Figure 66 - A Surface Texture Machine with Tactile Probe**

There are two types of stylus instrument in general use, those in which a skid supports the stylus and those without. In the skidded instrument, the stylus is supported by a curved, metal skid that rests on the work piece surface and acts as a reference. The current ISO standards do not recommend skidded instruments but these are still in general use in workshops as they also more robust and provide additional filtering to the data.

**Figure 67 & 68 - Skidless (left) and Skidded (right) Surface Texture Probes (Mitutoyo UK Ltd)**

There are many other non-contact or optical measuring instruments which can measure surface texture more quickly. However, non-contact methods depend upon reflections from the surface and these varies with different materials, depth and characteristic of the surface. As a result the only measurements traceable to National or International standards are currently made by tactile stylus instruments.

The surfaces to be measured can incorporate waviness or curvature which if not removed from the measurement will affect the final result. Filtering can remove these effects, it can be done automatically by modern digital equipment or by using skidded or larger styli. A stylus with a larger 5µm tip radius will filter out troughs into which it cannot reach and a skidded probe will filter out long wavelength waviness as the skid acts as the reference level.

Analysis of the surface requires magnifying the vertical displacement of the styli compared with the horizontal travel. This is known as the aspect ratio which is typically 400:1. The most common sampling length is 0.8mm (cut off length) with the evaluation length being the average 5 such lengths over 4.0mm.

Surface finish is typically measured using $R_a$ (Roughness Average, also known as: Centre Line Average [CLA], Arithmetic Average [AA]). This is defined as the average height from a mean line of all coordinates of the surface over the length of assessment. This is the oldest and most common texture parameter but today many new parameters have been derived with similar functionality.

Typical Industry standard uses a 2D line profile to define the characteristics of a surface. On its own, $R_a$ does not fully define the properties of a surface as can be seen in the following illustration where different machining processes have the same $R_a$, but the shape of the surfaces are quite different.

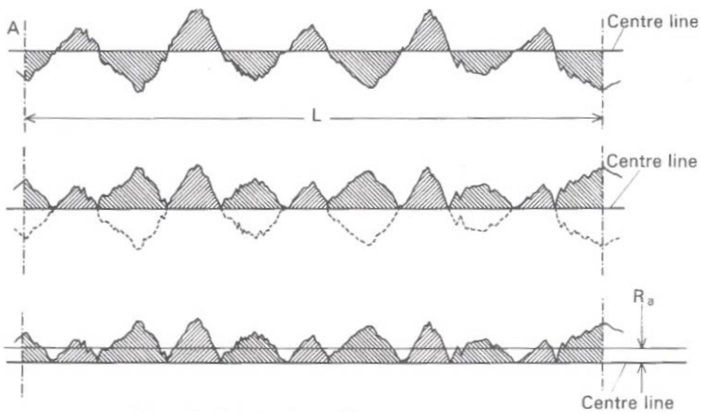



**Figure 69 - Graphical Derivation of $R_a$**

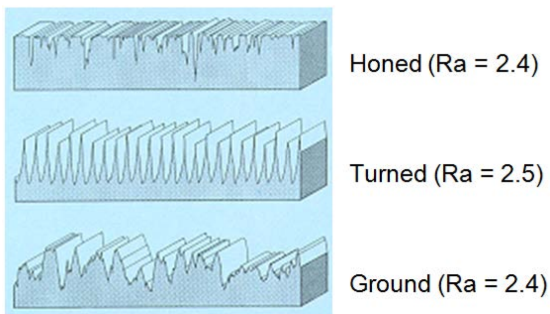



**Figure 70 - $R_a$ values for different finishes**

The most commonly used 2D measurement parameters are as follows:

- $R_a$: Arithmetic mean of the absolute peak height and valley depth values.
- $R_q$: Root Mean Square (RMS)
- $R_v$: Maximum valley depth

- $R_p$: maximum peak height
- $R_t$: Maximum height of the profile ($R_t = R_p - R_v$) within evaluation length
- Rz: Ten point height parameter
- Rsk: Skewness - a measure of whether the bulk of the material is above or below the mean line.
- Rku: Kurtosis - measure of the sharpness of the surface Surface

### 4.14.1 Environmental & Storage Requirements

Surface texture measurement is done at the sub-micron level therefore extra care should be taken to:

- Control the environment. Temperature variation, draughts and vibration will have a more noticeable effect on results taken at the sub-micron level.

- Keep the part, fixture, probe and other parts of the measurement system clean. Dust, dirt, coolant and other contaminants will have a big impact on the measurement capability.

- To protect the styli from damage. Damaged styli will cause measurement errors as shown in Figure 71.

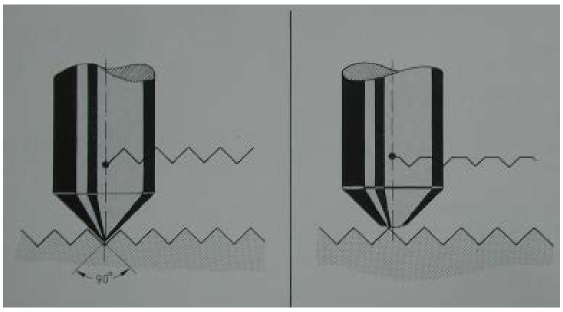


**Figure 71 - The Effect of a Damaged Probe**

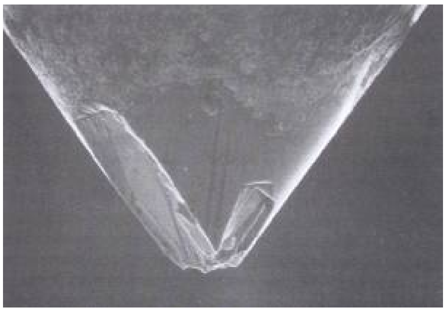


**Figure 72 - A Damaged Diamond Tip**

### 4.14.2 Usage Guidance

- It is important that if comparative methods are used, it must be with surfaces produced by similar techniques. Comparison standards for different machining processes are available from Rubert and Co, Manchester.
- Dedicated fixtures will improve measurement repeatability. When carrying out repeatability measurements, it is important to measure the same surface as close to the original position as possible. This is because the surface will vary over the part and 2D measurement is only over a very small length, typically 0.8mm.  Fixturing will also help prevent misalignment of the stylus.
- The measurement device should be placed level to the measurement surface. Some measurement devices can be affected when both the device and measurement surface is tilted. If such as situation cannot be avoided, the effects of measuring at the required angle will need to be assessed.

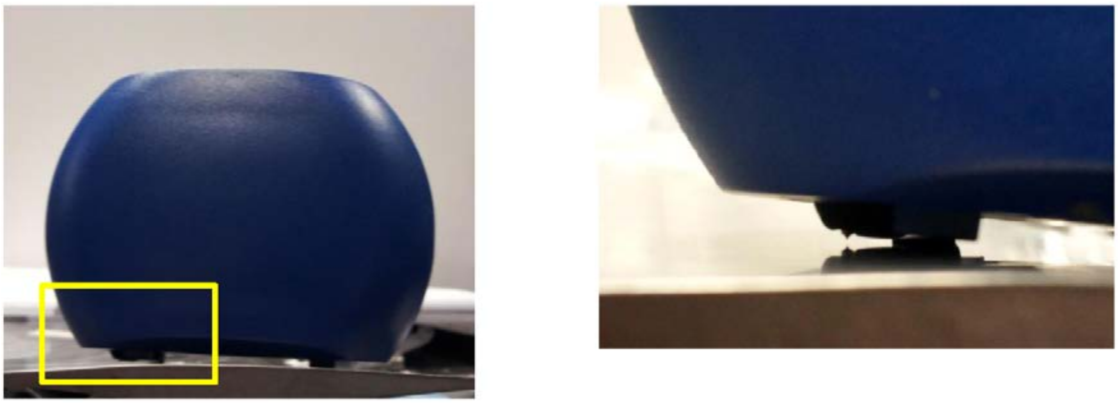


**Figure 73 - Curvature causing stylus to leave surface**

- Care must be taken when selecting instruments to measure curved surfaces, such as aerofoil surfaces. With portable skidded devices the supporting skids or “feet” have been found to prevent full contact of the styli with the curved surface (below). With skidless instruments, the range of movement in the vertical direction can also limit the curvature of the surface that can be measured.
- Inexpensive hand-held gauges are generally not suitable for measurement of complex free form surfaces such as curved aerofoils.
- Any styli should be inspected regularly for signs of wear and it should be checked that the stylus/probe can reach the required surface without causing damage to the probe or surface.
- The instrument calibration should be checked regularly using the glass surface roughness standards and the instrument itself should be serviced and calibrated by the instrument OEM.

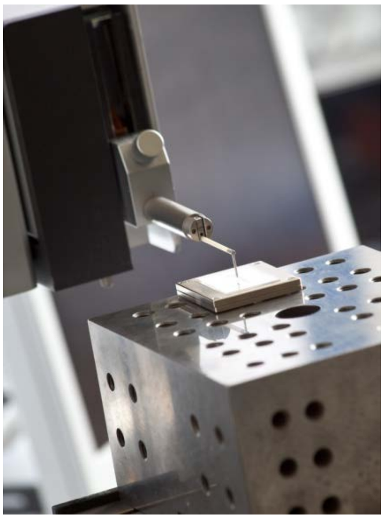


**Figure 74 - Skidless Probe Measuring a Glass Artefact**

- The instrument should first be checked on a surface roughness standard similar to the measurement roughness to be evaluated. The Ra value measured should correspond with the roughness standard. If the desired value is not as expected, then the instrument should be quarantined and the problem investigated.
- After turning the machine on, time should be given for the machine to stabilise. The minimum time is usually given in the manufacturer’s instructions.
- The stylus shape shall be a cone with either 60° or 90° inclusive angle. Tip radii should be 2µm or 5µm.
- Suitable sampling lengths and required filters are defined in RRES 90036.

- The 16% rule on acceptance of surfaces is as follows when a surface roughness value is specified in the product definition:- A surface is considered acceptable if less than 16% of the measured values (over the measured length) are over/under the limit specified.
- Max Rule: When a maximum value is specified, none of the measured values (over the measured length) can exceed the specified value.
- The measurement direction should traverse perpendicular to the direction of the lay unless otherwise indicated. For aerofoil surfaces the measurement should be taken in the direction of the gas flow.

### 4.14.3 Common Pitfalls

- Smaller tip sizes tend to report larger values of Ra, so care should be taken choosing tip size.
- In the case of a skidless probe the stylus tip should be the ONLY part of the probe touching the part.
- Although surface roughness measuring instruments apply very little pressure to the surface, a 0.002mm stylus radius can plough a small track in the material if the surface is not very hard. This will give false readings
- The use of the correct filter and correct sample length is very important as misapplication can lead to wildly incorrect interpretation of surface parameters.
- Results of surface roughness measurements using Stylus instruments are the only true traceable devices to the national standards.

### 4.14.4 Standards, Training and Further Reading

- ISO:BS 3274 Surface Texture
- ISO 4287 Geometric product specifications (GPS) Surface Texture- Profile method, terms definitions, parameters
- ISO 4288 Geometric product specifications (GPS) Rules and procedures for assessment of surface texture
- ISO 5436-1,2 Surface Texture - profile and software standards
- Surface Texture NPL Guide 37 - Measurement of Surface Texture Using Stylus instruments
- Exploring Surface Texture - A fundamental guide to measurement of surface finish - Taylor Hobson publication.
- MXG 003 - Validation of Surface Finish Measurement

### 4.14.5 Capability Chart

Surface texture machines are very sensitive pieces of equipment but there are many sources of error that can affect a machine's capability. It has been found very difficult to test the repeatability of these measurements primarily because the surface finish varies over the surface and with 2D measurements only a small sampling length is measured. It is also impossible to precisely reposition the measurement surface in exactly the same place each time and even if it was possible, the first measurement is likely to have slightly modified the surface.

As a result, the applicability of using Gauge R&R to assess surface roughness instruments is not recommended.

## 4.15 Roundness & Form Machines

The measurement of straightness, roundness and cylindricity are different types of form measurement. The instruments detailed in this section have capability at the nanometer scale, typically in the order of 0.05µm, or 50nm. They are used to measure features such as roundness, concentricity and runout on components like bearings and shafts.

A measurement transducer is used to follow the work piece as it revolves on a rotary table and the transducer can record any changes in roundness, flatness, concentricity etc. Figure 75 shows a Talyrond with rotating table, but they can also consist of a revolving spindle which is used to measure the roundness bores or diameters in fixed components. These instruments are considered the reference methods for roundness as they sample many thousands of points in a full revolution (around 36,000 points) with measurement uncertainties many times better than any co-ordinate measuring machine. On some more recent roundness measuring machines it is now possible to measure surface roughness and roundness simultaneously whilst some other models can measure both but require change of styli.

Straightness and form measuring machines measure the deviation in the component with reference to a straightness standard integrated into the machine. The measurement length is limited to the length of the straightness standard of the machine and this is typically of the order 120mm. Some of these machines have a motorised y-axis so that 3D graphical plots can be produced of the surface.

Machines are available in a variety of sizes, from desktop to full measuring stations and some recent machines include CNC programming capability.


**Figure 75 - Talyrond Roundness Tester**

**Figure 76 - Talysurf Form & Surface Finish Tester (Taylor Hobson)**

### 4.15.1 Environmental Requirements

Form measurement is done at the sub-micron level and as a result extra care should be taken to:

- Control the environment. Temperature variation, draughts and vibration will have a more noticeable effect on results taken at the sub-micron level.
- Keep the part, fixture, probe and other parts of the measurement system clean. Dust, dirt, coolant and other contaminants will have a big impact on the measurement capability.
- To protect the very delicate styli from damage. They should always be kept in their protective cases.

### 4.15.2 Usage Guidance

- Care should be taken not to damage the probes while moving parts on the machine. The probes are very delicate, using a damaged probed can severely affect the measurement result.
- Newer machines have a function that allows them to protect themselves from running into the part. Even though this would happen only in the case of incorrect programming, it is important that this does not happen as the damage to the part and machine can be extensive.
- The measurement transducers travel must not be exceeded and the straightness column on they should not be moved without the machine being re-calibrated.

### 4.15.3 Common Pitfalls

- The part must not move during the measuring operation and therefore the holding or clamping methods are particularly important.
- Use of the correct filters and proper alignment of the part on the measuring instrument is key.
- Incorrect programming and operation of the machine.

### 4.15.4 Standards, Training and Further Reading

- ISO 1101:2004-(GPS) Geometric tolerancing of form, orientation, location and runout
- ISO/TS 12180-(GPS) Part 1 & 2 - Cylindricity
- ISO/TS 12181-(GPS) Part 1 & 2 - Vocabulary and parameters of roundness
- BS ISO 1132-2 2001 - Rolling bearing tolerances - measuring and gauging principles
- ISO/TS 12780 Part 1 & 2 (GPS) - Straightness
- ISO/TS 12781 Part 1 & 2 (GPS) - Flatness
- Exploring Roundness - Fundamental guide to measurement of cylindrical form - Taylor Hobson publication

### 4.15.5 Capability Chart

#### 4.15.5.1 Form Machines

The Surface Form Machines are highly accurate and measure to tight tolerances. However, there are many sources of error present that affect the machine’s capability. The environment, probe angle, fixturing and alignment all influence the machines capability. There is no way to assess and generalise all these error sources to create a generic capability chart. The best way to validate the measurement system is to run a full, detailed Gauge R&R Study.

## 4.16 Profile Projectors

Profile Projectors use a light source to optically check the profile and contour features of a part. The image of the part is magnified onto a large screen and with equipment the shape and dimensions of the part can be measured. Traditionally, this method of measurement was fairly inaccurate but new developments have considerably improved its accuracy. New edge-sensing technology is available to reduce the operator variability.

**Figure 77 - Magnified Part on Screen**

Using a profile projector and a protractor is one of the easiest ways to measure an angle accurately. Radii are also commonly measured using profile projectors. Overlays can be placed on the projection to measure the dimension accurately. Similar overlays can be created to measure commonly used parts with complex features such as thread profiles or gear tooth charts.

Profile projectors, used with a radius overlay chart, can be used for a quick check to see if a part is round. This is gives an immediate answer with a resolution of 10-15 microns.

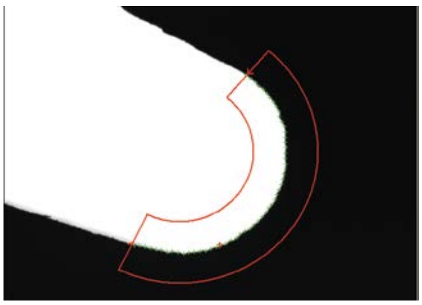


**Figure 78 - Part with radius overlay chart (Mitutoyo UK Ltd)**

### 4.16.1 Environmental Requirements

- Appropriate lighting levels should be used so the image on the screen can be seen clearly.

### 4.16.2 Usage Guidance

- Edge-sensing technology has helped eliminate errors and bias between users. The addition of this technology to any projector would greatly improve its capability.
- 10X to 20X magnification projectors are selected most often because they produce good, clear, bright images on the screen. A higher magnification would produce a larger image but the brightness of the screen would decrease. Edges are harder to find accurately at higher magnifications.
- Customised overlays can be made for use on parts with unique features. GO/NO GO type overlays can be made to check features quickly. Overlays are also available to measure thread profiles.

### 4.16.3 Common Pitfalls

- Choosing incorrect magnification level.
- Failing to correctly locate and edge.

### 4.16.4 Capability Chart

Profile Projectors capability depends largely on operator variability and the machine setup. Generally, use should be avoided for medium and tight tolerances. A full, detailed Gauge R&R Study should be carried out to understand the capability of the system.

## 4.17 Hand-Held Laser Scanners

Hand-held laser scanners use the principle of optical triangulation to take individual section measurements. They are traditionally used by the automotive industry for panel gap and flush measurement but it can be also used for measurement of chamfers and radii on edges. Other applications include mismatch and large scratch measurement. These devices are usually used with a standoff. This is typically a small piece of fixturing which locates the scanner head relative to the feature being measured. Generic standoffs are used however custom application-specific standoffs are often required to achieve acceptable capability.

**Figure 79 - GapGun Scanning** a Radius

**Figure 80 - GapGun with Display**

### 4.17.1 Environmental Requirements

- All standoffs and fixtures should be clean and visually free from wear and damage.
- A regular verification regime must be in place to ensure any drift in capability is captured.
- The temperature of the laser head should be monitored. If at any time during use the temperature exceeds the operating range then stop using it, record the temperature and report the situation for action.

### 4.17.2 Storage Requirements

- The scanner and all its peripherals such as standoffs, verification artefacts and calibration artefacts should be stored in protected cases accompanied with clear labels indicating each parts application.

### 4.17.3 Usage Guidance

- The laser and camera lenses should only be cleaned using materials approved by the OEM.
- All parts should be firmly attached together with no play or backlash.
- All electrical connections and cables should be secure with no undue bends and free from damage.
- Verification should be carried out at least once every shift.
- Inspection tools should be locked down through the use of checkplans, to avoid the use of wrong tools by the operator.
- Detailed local operating procedures (can be in the form of inspection plans or operator manuals) must be created for each instance.
- A GapGun administrator role and person should be defined and all GapGun operators and administrators must complete the relevant OEM training.
- Regular checks in accordance to the GapGun Mandatory Basics must be carried out and a Log should be maintained.

### 4.17.4 Common Pitfalls

- As hand-held laser scanners produces discrete scans or sections of a part edge, the form of the part must be consistent. If for example, hand-dressed features with inherent large form errors are to be measured then information from single sections is not enough to assess the full part geometry. Depending upon the FVRA risk scoring of each individual feature other measurement solutions may need to be considered.
- Prior to starting a project it is important to confirm suitability of a hand-held laser scanner for all the proposed application features. Please contact the core Measurement Excellence team to carry out a "Project Sanity Check" before proceeding to any trials.

### 4.17.5 Standards, Training and Further Reading

- MXS021 - GapGun Mandatory Basics
- GapGun Starter Pack - Obtainable from the core measurement excellence team

### 4.17.6 Capability Chart

As the capability is generally application specific, a full Gauge R&R study in accordance to MXS001 must be carried out prior to its use in production.

In general, the GapGun FOV7 head (10 micron resolution) is suitable for tolerances above +/-0.200mm for use with custom standoffs or above +/-0.400mm when used with generic "freehand" standoffs as its orientation angle can affect its capability.

More recently robot-mounted applications of GapGun have been evaluated offering improved capability compared to human operation. For more details please contact the core Measurement Excellence team.

### 4.18 3D Structured Light scanning systems

3D structured light scanning systems are devices for the measurement of a 3 dimensional object using projected and structured light and high resolution cameras. They typically project a coded series of light and dark fringes of different intensities onto the surface of the object. Observations of the fringe under a known triangulation angle indicate the 3D contour along the fringe.

Typical applications include:

- Scanning of blisks to determine extent and location of service damage prior to repair.
- Scanning of turbine & compressor aerofoils to determine dimensional conformance.
- Reverse engineering of legacy parts.
- In-process inspection of wax assembly prior to turbine aerofoil casting.
- Adaptive Manufacturing and Adaptive Repair

**Figure 81 - Robot Mounted ATOS Triple Scan (GOM)**

#### 4.18.1 Environmental Requirements

- As this is a high precision non-contact measurement system the cleanliness of the part and sensor are crucial. A dust free environment will improve measurement capability. Also suitable temperature controls should be considered for the measurement of parts or features with challenging tolerances.

#### 4.18.2 Storage Requirements

- 3D structured light systems are capable of making very accurate measurements if used correctly. Accurate calibration of the device is essential and the artefacts and any reference frames should be stored in accordance with the sensor manufacturers guidelines.

#### 4.18.3 Usage Guidance

- Ensure lenses, lens filters and dust filters are cleaned only using materials and procedures approved by the measurement machine supplier.
- Follow the manufacturers recommended maintenance routine. In some cases it may be appropriate to return the sensor to the manufacturer for a professional service, maintenance and test.
- All threads, mechanical interfaces, camera mounts, robots and FOBA studio stand mounts should be clean and visually free from wear or damage detrimental to performance. All assemblies should be firmly screwed together.
- An indicator that the reference frame may require re-measuring is the reference point and preview mesh residuals. For each measurement project, the maximum transformation error should be reviewed. Re-measure the reference frame if the maximum error exceeds the previously determined threshold.
- The correct calibration cross or plate should be clean and free from wear or damage.
- Photogrammetry frames (where used) should be checked for structural damage as well as damaged reference points. Measurement frames are not mechanically stable and change can occur over time and with handling.
- Run all required measurement volume calibration procedures, ensuring that the calibration artefact is at ambient temperature. Record temperature of the artifact and supply to the sensor software to compensate nominal values. Check the results against acceptance criteria provided by the supplier and take appropriate action if outside required limits.
- Repeatability and reproducibility should be analysed using Polyworks Inspector Multi Data Variability. This allows the creation of trend and run charts to support understanding of variation/consistency in the measuring process across the whole point cloud/polygon model. Many properties can be represented in a false colour map from basic statistics (average error etc) to more sophisticated process capability data.
- Should surface preparation of the component be required, then only approved products may be used to prepare the surface. The repeatability and the consistency (thickness / thinness) of the coating must be understood. The part should be cleaned with a lint free cloth prior to coating and dust etc must be avoided. The coating must be given adequate time to dry prior to measurement.
- As with all measurement systems, it is critical to maintain traceability. Care must be taken to ensure that each element in the overall measurement system is traceable; this includes, but is not limited to, reference frames, scale bars, VDI/VDE 2634 artefacts, calibration plates and crosses and any other transfer artefacts.

### 4.18.4 Common Pitfalls

- Mistakes in programming.
- Incorrect choice of measurement volume for the component.
- Over-sizing the reference frame for the component.
- Poor design and maintenance of reference frames.
- Poor photogrammetric measurement of reference frames.
- Poor fixturing/clamping of component leading to movement during the measurement process

### 4.18.5 Standards, Training and Further Reading

#### 4.18.5.1 External

- VDI / VDE 2634 pts I, II, and III. These standards should be used to determine the basic capability of the system:
    - Part I covers Photogrammetry and applies to the testing of optical measurement systems with point-by-point probing.
    - Part II covers Digitising Single View and applies to the testing of the measuring of three dimensional objects in a single view and is used to determine and monitor the capability of the sensor throughout the measurement volume
    - Part III covers Digitising Multiple View and is applicable to area based scanning where the object being measured spans multiple views which must be aligned and stitched together to create a single view.

### 4.18.6 Capability Chart

The measuring technology is usually of very high capability, but the application and environment it is used in can greatly affect the capability. A full, detailed Gauge R&R Study should be carried out to understand the capability of the system.

## 4.19 Coordinate Measurement Machines (CMM)


**Figure 82 - Zeiss Large Bridge CMM**

The Coordinate Measuring Machine (CMM) is often the primary measurement system used for component verification. The CMM is an extremely versatile measurement system that is available in a wide range of configurations, accuracies and costs. In its simplest form the CMM is a manually operated (i.e. non-motorised) 3-axis system with a touch-trigger probe. In this form the operator will move the probe to touch a number of points on the object being measured and the X/Y/Z coordinates will be collected by the CMM software. Although manual CMMs have the advantage of a low purchase price they are expensive to operate as they need a full-time operator. Most CMMs today are motorised, and although they can still be operated manually via a joystick controller, they mainly run automatically.

**Figure 83 - A motorised CMM being driven with a joystick**

CMM's are available in a wide range of sizes, with axis lengths from about 400mm at the bottom end up to several metres at the top end. CMM accuracy depends on a number of factors including the CMM design and construction standard, the probing system accuracy, the probing strategy and the environmental conditions of use. Typical accuracy of a low-cost manual CMM will be of the order of 5µm, a good quality medium sized CMM will be around 2µm, and the best available reference standard CMMs can now measure to 0.5µm. Enhancements to the basic 3-axis CMM include indexable probe heads, single or double axis rotary tables, analogue scanning probes, probe and stylus changing racks, high-speed scanning probes (Revo), video cameras for optical measurements, laser scanners for non-contact measurement and surface finish probes.

**Figure 84 - An indexable probe head**

CMMs are controlled using specialist software, usually supplied by the CMM manufacturer. Unfortunately there are many different programming languages in use, and so CMM programming has become a specialist subject. It should be noted that the cost of writing programs could easily exceed the original cost of the machine.

### 4.19.1 Environmental Requirements

The following point should be considered in addition to the general environmental requirements:

- Most CMM manufacturers specify an operating temperature of 20 +/-2ºC to achieve the stated accuracy, so a temperature controlled environment is usually required. Some CMMs have the capability to compensate for ambient temperature over a wider range than this, but it is difficult to test the validity of these claims before buying the CMM, so seek specialist advice if you are thinking of installing a CMM in a variable temperature environment.

- Perhaps more important than absolute temperature is temperature stability. Thermal gradients in and around the machine can lead to significant deterioration in the accuracy, so the situation of the CMM with regard to doors (cold drafts) and windows (direct sunlight) should be considered carefully.

- Ideally CMMs should be installed in areas that do not have serious atmospheric contamination such as oil, dust or particularly fine grit, as these can have damaging effects on the air-bearings. If the CMM has to operate in this type of environment then there are some mitigations. The first is to make every effort to minimize the effects by siting the machine so that it is not in the direct path of contaminants, and covering it as far as possible. A simple roof is a help, but enclosing it in a box is more effective. There are also some CMMs that are designed specifically for shop-floor use so these should be considered.

### 4.19.2 Storage Requirements

- Due to the size of the machine environmental requirements are more applicable than storage requirements. However, individual parts (e.g. probe heads) should still be stored in accordance with the general storage requirements.

### 4.19.3 Usage Guidance

- As with any machine, keeping everything clean goes a long way to maintaining its performance. In particular ensure that all air-bearing surfaces are kept clean of oil and dust.
- Check that all probe styli are clean and show no signs of wear or damage.
- Check that all probe and stylus module interfaces are clean.
- Carry out regular probe qualification.
- Carry out regular artefact checks to validate the on-going accuracy of the machine. (Refer to the section on Regular Monitoring of Capability).
- The CMM inspection is often the last time that a component is measured before delivery to the customer, so it is vitally important to ensure that the measurement results can be relied on. This is achieved in three stages.
    - CMM calibration: This ensures that the machine's fundamental accuracy is within the manufacturer's specification, this should be done at least annually.
    - Component specific CMM program validation: This checks the CMM gives reliable and repeatable results when running a program on a specific part. Validation is done by carrying out a Gauge R&R study and a bias check as defined in MXS 001 - Validation of Dimensional Measurement Systems.
    - Finally to ensure the continuing accuracy of the CMM and the program through regular checks. These include probe calibration checks and artefact checks.
- MXS002 - Mandatory CMM basics covers most of the fundamental things that affect machine accuracy and capability, and the requirements of this document must be followed.
- If at any time there is doubt about the validity of the CMM results then stop using it immediately and run some artefact tests.
- The probing strategy (e.g. number of probe points, probe point distribution, approach speeds, analysis routines) can have significant effects on the measurement capability. Generic or feature / product / commodity specific standards should be developed and used to ensure the best and most reliable results.
    - NPL Good Practice Guide 41 'CMM Measurement Strategies'
    - NPL Good Practice Guide 43 'CMM Probing'

### 4.19.4 Common Pitfalls

- Using a stylus assembly that is too long or too heavy for the probe, resulting in a serious degradation of the machine accuracy. Always refer to the manufacturer's documentation when building unusual stylus configurations to check that the size or weight limits are not exceeded.
- Mistakes in programming.
- Rotary tables, particularly two-axis tables, can be significant sources of error. Special tests are needed to calibrate and set rotary tables and specialist advice should be sought before specifying or using them.

### 4.19.5 Capability Chart

The basic measuring technology is usually of very high capability, but the application and environment it is used in can greatly affect the capability. Therefore a full, detailed Gauge R&R study should be carried out to understand the capability of the system for each part family. Each new part within a family should then have an Automated Measurement System study to confirm each new programme (ref AS13003)

#### 4.19.5.1 Standard Production CMM

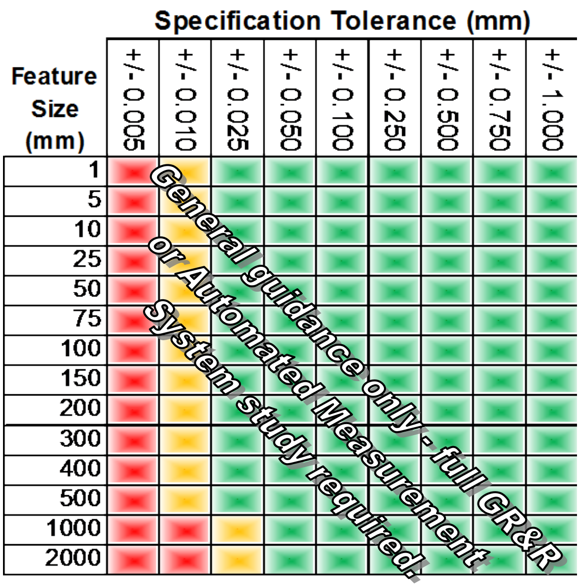



**Table 22 - Standard production CMM with specified Maximum Permissible Error of 2.3 + 0.3L/100 µm**

### 4.19.5.2 High Performance Laboratory CMM

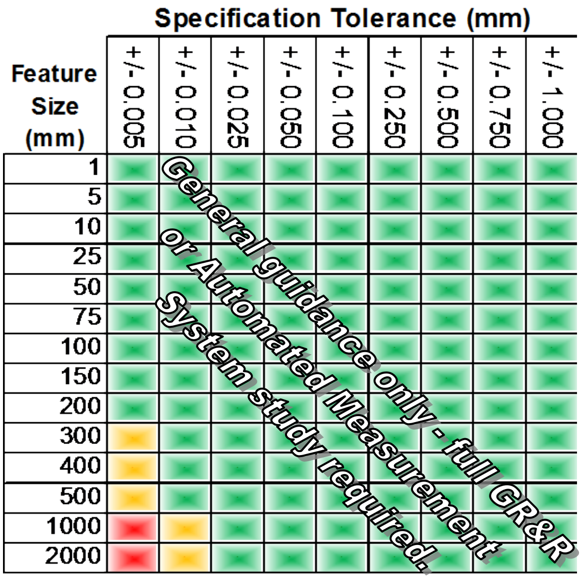



**Table 23 - High performance Measurement Laboratory CMM with MPE of 0.6 + 0.16L/100 µm**

## 4.20 On-machine Probing


**Figure 85 - Renishaw MP700 On-machine Probe**

Most modern machine tools can be fitted with touch probes that can be used to measure the raw material, part finished or finished components. Originally only single point touch-trigger probes were available, but new more sophisticated systems have recently been developed which effectively turns it into a Coodinate Measuring Machine (CMM). However, there are a number of limitations when measuring on-machine compared with on the CMM:

- The first limitation is in the programming of the system. Unlike CMMs, machine controllers do not have the ability to carry out complex geometric programming, only simple surface hits or circle measurements. However, products such as Hexagon's PC-DMIS NC and Renishaw's Productivity Plus, enable more CMM-like programs to be written.
- The second limitation is that the probes do not have interchangeable styli, so the range of measurements that can be made is more limited than a CMM.

Despite these limitations on-machine probing can give significant productivity benefits by checking features and applying corrections before the finished cuts are made; greatly reducing non-conformance. On-machine probing can also enable the machine to find the true position of the raw material and adapt the NC program accordingly. This can reduce the reliance on high-cost tooling to present the part in the right position. It must however be noted that measuring on the machine tool does not account for any clamping loads that have been applied to the component during the machining operation and once removed from the fixture the part form or shape may change. Most machine tools are not calibrated so that traceability to National Standards is not assured. The same machine is used to cut the part and measure so even if it is wrong it will report a good result and there is no independent verification.

Typical applications for on-machine probing are finding the initial position of the raw material and then applying a global program offset, and for measuring a part-machined surface prior to the finishing cut so that an adjustment can be made in order to produce a conforming feature.

### 4.20.1 Environmental Requirements

On-machine probing is done by definition in a workshop environment, so there are no special environmental requirements. However, many of the general environmental requirements still have some relevance. For example, if there is any thermal growth in the machine this may not be noticed by the probing system as this part of the same machine system.

### 4.20.2 Storage Requirements

Due to the varied nature of the system and its potentially large size storage requirements vary enormously from application to application.

### 4.20.3 Usage Guidance

- Check that the probe stylus is clean and shows no signs of wear or damage.
- Carry out regular probe qualification.
- Carry out regular artefact checks to validate the on-going accuracy of the machine.
- The use of on-machine probes is a specialist activity so before carrying out any on-machine probing an expert should be consulted.
- Using a calibrated artefact that is similar to the object being machined can enable corrections to be made to the measurements to improve the accuracy and traceability.

### 4.20.4 Common Pitfalls

- Failing to calibrate the probe.
- Assuming that because the machine says a part is correct it must be correct. Unless the machine has been specifically calibrated for the measurements then all final measurement should be over-checked by a final view inspection.
- Rotary tables, particularly two-axis tables, can be significant sources of error. Special tests are needed to calibrate and set rotary tables and specialist advice should be sought before using them to make measurements.

## 4.21 Laser Trackers

**The text for this section has been provided by staff at the National Physical Laboratory (NPL), and is used here with their kind permission.**

Laser trackers have become popular measuring tools for users needing to make precision measurements of items that are simply too large to be handled by Coordinate Measuring Machines (CMMs) or of items which are non-portable.

A laser tracker is a portable coordinate measuring system that tracks a moving target reflector and measures the position of the target in spherical coordinates. The radial distance or range component is typically measured by an interferometer (IFM) or an absolute distance meter (ADM). The IFM or ADM laser beam is steered to track the moving target, usually a spherically mounted retroreflector (SMR), by a motorised gimbal mechanism. Angle encoders on the mechanism provide azimuth and elevation angles to the target.

Typical models include trackers from manufacturers such as API, Leica and Faro, which incorporate either ADM and/or IFM modes of operation (e.g. API T3/Radian, Leica 901/401, FARO ION).

Typical range of operation is from 30 to above 120 m.


**Figure 86 - Typical Laser Trackers (courtesy of NPL)**

### 4.21.1 Environmental Requirements

Typical values of the environmental parameters are given below:

- Operating Temperature: -10º C to > 45º C (14º F to > 113º F)
- Barometric Pressure: 580 mmHg - 800 mmHg
- Relative Humidity: 10-95% non-condensing

### 4.21.2 Storage Requirements

- Typical Storage Temperature: -10º C to 60º C (14º F to 140º F).
- The tracker should be dismantled from the tripod and the tracker head, together with any controllers, cables, environmental sensors and SMRs, should be packed carefully in suitable padded boxes.

### 4.21.3 Usage Guidance

- The laser tracker should be unpacked carefully and thermal stabilisation should take place for the tracker to reach ambient temperature before being switched on if cold. A period of warming up (one or more hours is also recommended).
- The laser tracker should be mounted carefully on a suitable tripod and care should be taken to lock the tripod in place.
- Before the start of any set of continuous measurements, specific calibration procedures should be followed. These are normally defined by the manufacturer (e.g. birdbath and quick volumetric (QVC) tests defined by API).
- The SMR(s) should be cleaned carefully from any dust particles (This can be done using a low-pressure air gun).
- Check that the environmental sensors (temperature and pressure) are properly connected, updating and the readings are within the typical operating range.
- Make sure that servo motors are switched off before moving the tracker to a new position.

### 4.21.4 Common Pitfalls

- Forgetting to clean the SMR before use.
- Forgetting to lock the tripod in place to prevent it from small movement in range and azimuth during measurements.
- Forgetting to switch to back face mode when doing a two face measurement.
- Forgetting to switch off the servo motors before moving the tracker to a new position.

### 4.21.5 Calibration

As with any metrology tool, a laser tracker needs to undergo periodic calibration and performance verification. The calibration processes include the following:

- Laser wavelength calibration.
- Environmental sensors (temperature, pressure and humidity) calibration.
- Specific manufacturer calibration procedures.
- Laser tracker performance verification.

The most commonly used standard for laser tracker verification is the ASME B89.4.19-2006.
The standard involves several tests that rely on measuring a known reference length (artefact) and comparing the observed error (laser tracker measured length minus reference length) with the specified Maximum Permissible Error (MPE) by the manufacturer. The main artefact (or reference length) is at least 2.3 m long. The tests are designed to exercise the tracker measurement system over a wide range of angles and distances similar to those encountered in real world use.
The NPL service utilises the seven tests prescribed in ASME B89.4.19:

- Horizontal length measurement system test (9 configurations)
- Vertical length measurement system test (8 configurations)
- Right diagonal length measurement system test (8 configurations)
- Left diagonal length measurement system test (8 configurations)
- Two-face system test measurement (12 configurations)
- Ranging tests (IFM and/or ADM) up to 30 metres
- User selected volumetric tests (2 configurations)

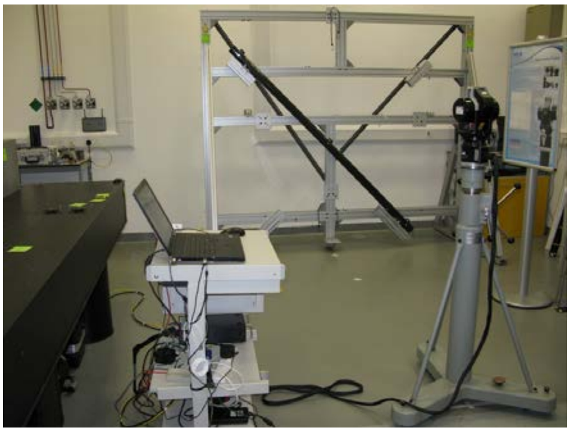


**Figure 87 - ASME B89.4.19 Tracker verification service at NPL showing tracker, rig and laptop used for data acquisition and post processing (courtesy of NPL)**

### 4.21.6 Standards, Training and Further Reading

- The most commonly used standard for laser tracker performance verification is ASME B89.4.19.2006:
    - ASME B89.4.19-2006, "Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems", ASME, November 2006

- Other standards are in different stages of development such as:
    - VDI/VDE 2617 Blatt10 / Part 10:
        - "Genauigkeit von Koordinatenmessgeräten, Kenngrößen und deren Prüfung, Annahme- und Bestätigungsprüfung von Lasertrackern" / Accuracy of coordinate measuring machines, Characteristics and their checking, Acceptance and reverification tests of laser trackers". Verein Deutscher Ingenieure /Verband Der Elektrotechnik Elektronik Informationstechnik, January 2011
    - ISO 10360- Part 10 (draft) : "Geometric Product Specifications (GPS)- Acceptance and reverification tests for coordinate measuring systems (CMS) -Part 10: Laser Trackers for measuring point to point distances, (Draft) May 2010

- A novel network-based laser tracker testing/calibration methodology, demonstrated by NPL has received large interest from the laser tracker manufacturers and industrial community. The method is approximately eight times faster than existing methods in the published standard (ASME B89.4.19-2006) and simple enough to be performed by end users, with no specialist equipment. Furthermore, the network-based test gives detailed quantitative information about the tracker, as well as rigorous uncertainties for the results. The test can be used not only for performance verification, but also for periodic monitoring of tracker sub-systems and drift/wear of mechanics. The uncertainty evaluation can be used to predict task-specific performance of the tracker, enabling users to judge fitness for purpose. B. Hughes, W. Sun, A. Forbes, A. Lewis, D. Veal and K. Nasr, "Laser Tracker Error Determination using a Network Measurement", Measurement Science and Technology, Vol.22, No.4, April 2011
- B. Muralikrishnan, D. Sawyer, C. Blackburn, S. Phillips, B. Borchardt and W. T. Estler, "ASME B89.4.19 Performance Evaluation Tests and Geometric Misalignments in Laser Trackers", Journal of Research of the National Institute

# 5 Glossary

This section defines common terms used in dimensional measurement. Terms such as bias and accuracy are often misinterpreted hence a standard reference is required.

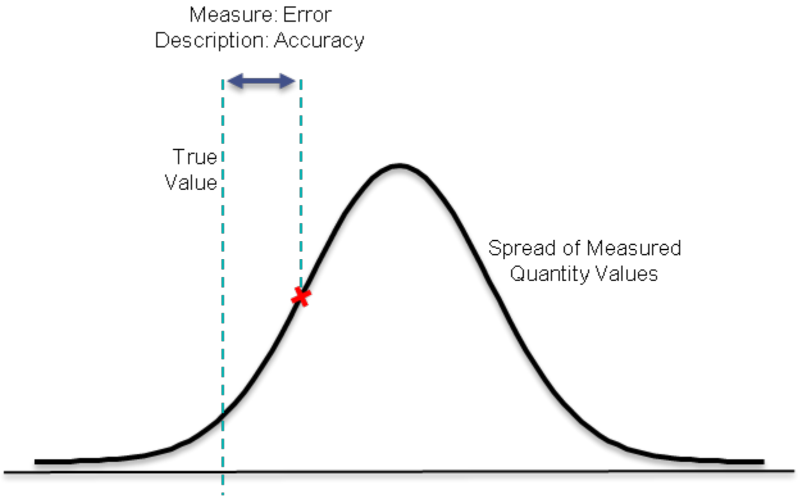
The aim is to standardise definitions and align them where possible to recognised definitions from international standards.

Throughout this section explanations maybe found following the referenced definitions in italics. Often there are related quantitative and qualitative terms; these are described in the diagrams as the 'measure' and 'description'.

## Accuracy

closeness of agreement between a **measured quantity value** and a **true quantity value** of a **measurand**. *The concept 'measurement accuracy' is not a quantity and is not given a numerical quantity value. Accuracy is used to describe a single measurement with a small* ***measurement error****.*

JCGM 200:2012, Para 2.13




## Attribute measurement system

attribute measurement systems are the class of measurement systems where the measurement value is one of a finite number of categories. *This is contrasted to the variables measurement system which can result in a continuum of values.*

AIAG MSA 3rd Edition, p.125

## Attribute agreement analysis (previously called Attribute Gauge R&R)

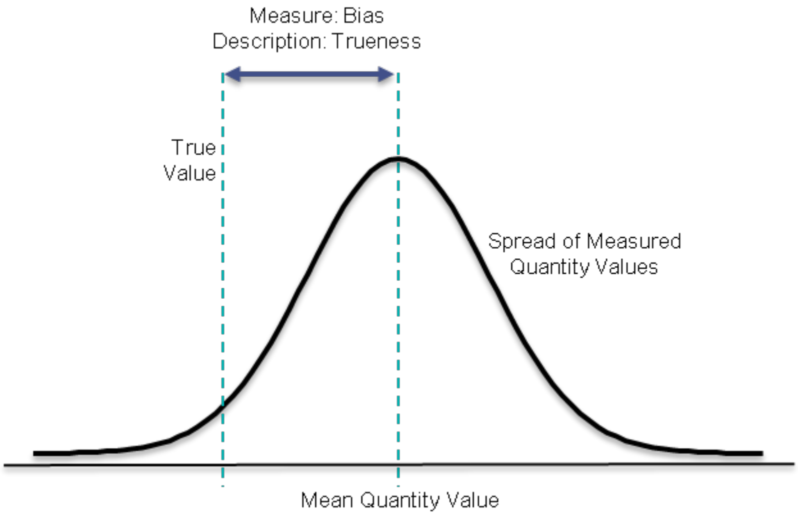
technique to assess the agreement of nominal or ordinal ratings given by multiple appraisers.
***Attribute Agreement Analysis*** *was previously called Attribute Gauge R&R Study in Minitab Release 13.* ***Attribute Agreement Analysis****, a technique to assess appraisers' agreement, is different from Attribute Gauge Study (Analytic Method), a method to examine the bias and repeatability of an attribute measurement system.*

Minitab® 15.1.1.0. Help function

## Bias (of a measuring instrument)

estimate of a systematic measurement error. Mean of replicate indications minus a **reference quantity value**

JCGM 200:2012, Para 2.18




## Calibration

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.

JCGM 200:2012, Para 2.39

*In simple terms this means applying known input standards (with their uncertainties) which are traceable to national/international standards and measuring the resultant output, the differences being errors to the standard which are bias/systematic error.*

## Capability

short-term estimate of measurement system variation.

AIAG MSA 3rd Edition, p.7

## Coefficient of thermal expansion (CTE)

the fractional increase in length of a material for a unit increase in temperature.

## Correction

compensation for an estimated systematic effect.

*See GUM:1995, 3.2.3, for an explanation of 'systematic effect'. The compensation can take different forms, such as an addend or a factor, or can be deduced from a table.*

JCGM 200:2012, Para 2.53

## Correlation

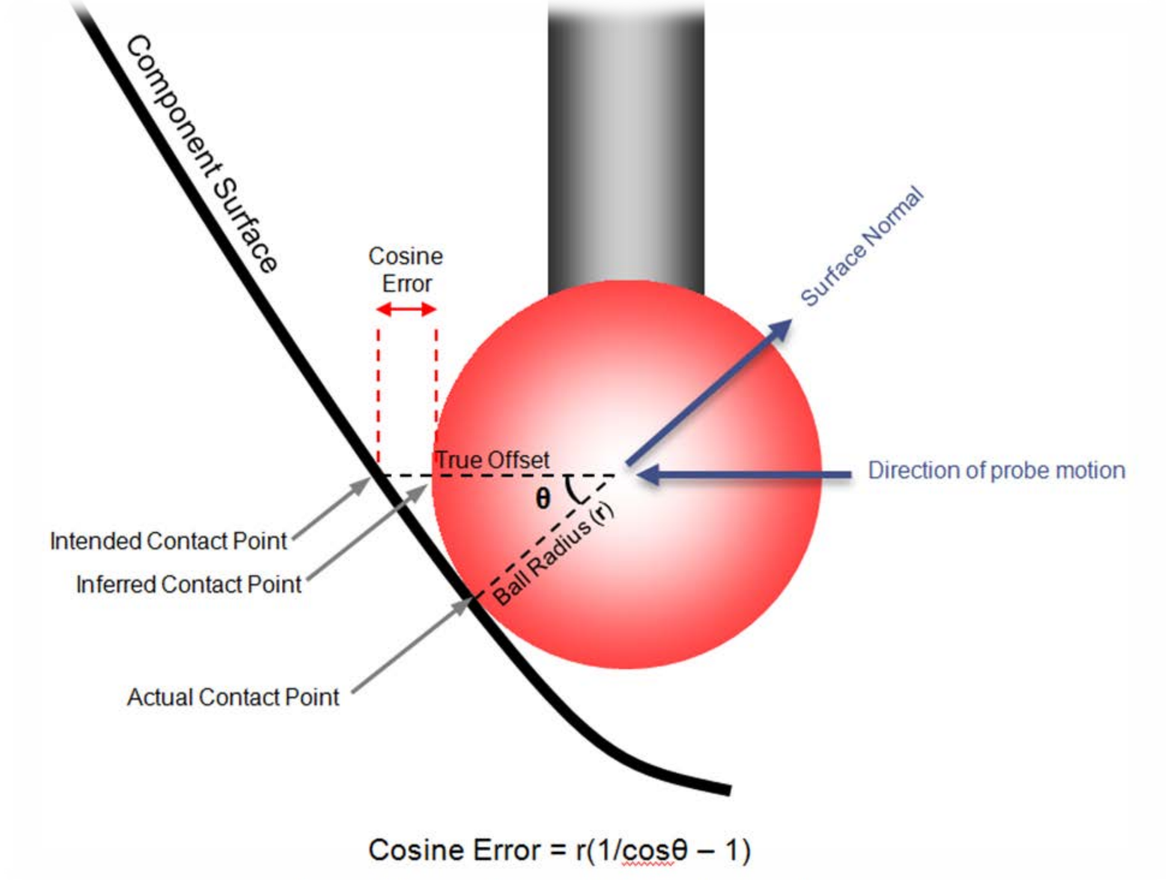
the relationship between two or several random variables within a distribution of two or more random variables *Most statistical measures of correlation measure only the degree of linear relationship.*

[ISO 3534-1:1993, definition 1.13]

## Cosine Error

An error caused by the angular difference between the surface normal and direction of probe motion.

*A CMM will infer the contact point by offsetting the ball radius in the direction of probe motion from the ball centre coordinates. The cosine error is the distance between the inferred contact point and the intended* *contact point whose coordinates the CMM is trying to obtain. It is calculated by subtracting the ball radius from the true offset (the distance between the ball centre and component surface along the axis of probe motion, given by* **r/cosθ***).*




## Coverage factor

number larger than one by which a **combined standard measurement uncertainty** is multiplied to obtain an **expanded measurement uncertainty**. *A coverage factor is usually symbolized k.*

JCGM 200:2012, Para 2.38

## Coverage interval

interval containing the set of true quantity values of a measurand with a stated probability, based on the information available. *A coverage interval does not need to be centred on the chosen measured quantity value. A coverage interval should not be termed "confidence interval" to avoid confusion with the statistical concept.*

JCGM 200:2012, Para 2.37

## Coverage probability

probability that the set of true quantity values of a measurand is contained within a specified **coverage interval**. *This definition pertains to the Uncertainty Approach as presented in the GUM. The* ***coverage probability*** *is also termed "****level of confidence****" in the GUM.*

JCGM 200:2012, Para 2.37

## Drift

continuous or incremental change over time in indication, due to changes in metrological properties of a measuring instrument.

JCGM 200:2012, Para 4.21

## Error

**measured quantity value** minus a **reference quantity value**.

JCGM 200:2012, Para 2.16

## Estimated standard deviation

The positive square root of the variance. The variance is a measure of dispersion, which is the sum of the squared deviations of observations from their average divided by one less than the number of observations.

PD 6461-3:1995, Para.C.2.20

## Expanded measurement uncertainty

product of a combined standard measurement uncertainty and a factor larger than the number one.

JCGM 200:2012, Para 2.35

## Gauge R&R (Gauge repeatability and reproducibility)

an estimate of the combined variation of repeatability and reproducibility for a measurement system. The GRR variance is equal to the sum of within-system and between system variances.

AIAG MSA 3rd Edition, p.206

## Hysteresis Error

Hysteresis is the dependence of a system on not only is current environment but its past environment. In measurement hysteresis error is the difference in two measurements of the same quantity when the measurement is approached from opposite directions.

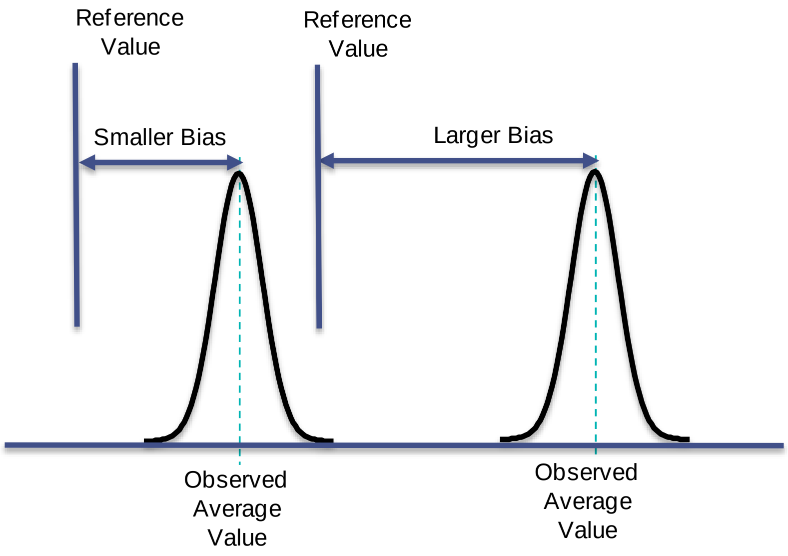
## Inspection

Inspection is the official process used to verify that a component or product complies with the design or legal requirements. This can range from assessing measurement results against a specification, detection of defects or simply ensuring all manufacturing processes/operations have been completed.  The result of inspection is either pass or fail.

## Linearity

The difference in bias errors over the expected operating range of the measurement system.  Linearity expresses the correlation of multiple and independent bias errors over the operating range.

AIAG MSA 3rd Edition, p.207



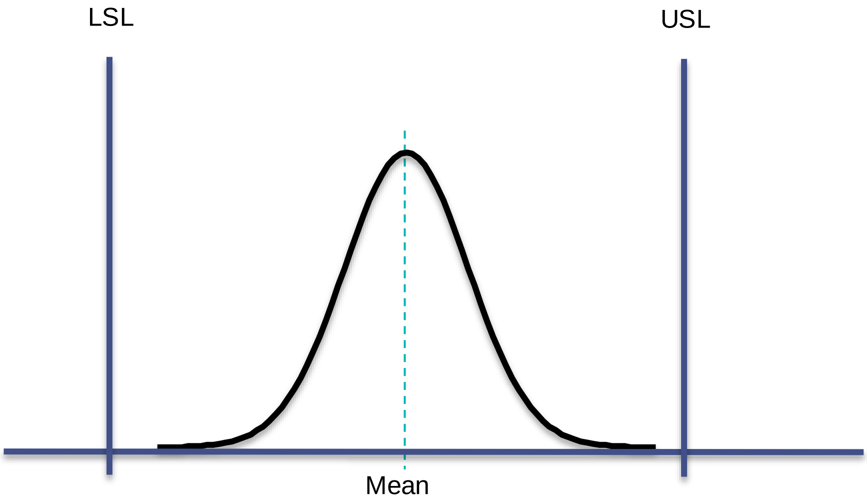

## Lower Specification Limit (LSL)

specified value giving either:

— the lower boundaries of the permissible value of the tolerance limits of a workpiece characteristic; or

— the lower boundaries of the permissible value of the permissible errors of a measuring equipment characteristic.

ISO 14253-1:1998, Para.3.9




## Measurand

quantity intended to be measured. *The specification of a measurand requires knowledge of the kind of quantity, description of the state of the phenomenon, body, or substance carrying the quantity, including any relevant component, and the chemical entities involved.*

JCGM 200:2012, Para.2.3

## Measurement

process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity. *Measurement presupposes a description of the quantity commensurate with the intended use of a measurement result, a measurement procedure, and a calibrated measuring system operating according to the specified measurement procedure, including the measurement conditions.*

JCGM 200:2012, Para.2.1

## Measurement Error

See Error.

## Measurement System

Any equipment, fixtures, people, environment, methods etc that are used to determine a quantitative or qualitative determination of a characteristic.

## Measurement Uncertainty

non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. *An estimated range of values about the measured value in which the true value is believed to be contained.*

JCGM 200:2012, Para.2.26

## Metrology

science of measurement and its application. *Metrology includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application.*

JCGM 200:2012, Para.2.2

## Normal distribution

continuous distribution having the probability density function

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where $-\infty < x < \infty$ and with parameters $-\infty < \mu < \infty$ and $\sigma > 0$. *The normal distribution is one of the most widely used probability distributions in applied statistics. Owing to the shape of the density function, it is informally referred to as the "bell-shaped" curve. Aside from serving as a model for random phenomena, it arises as the limiting distribution of averages. As a reference distribution in statistics, it is widely used to* *assess the unusualness of experimental outcomes. The location parameter μ is the mean and the scale parameter σ is the standard deviation of the normal distribution.*

ISO 3534-1:2006, Para.2.50

## Parallax Error

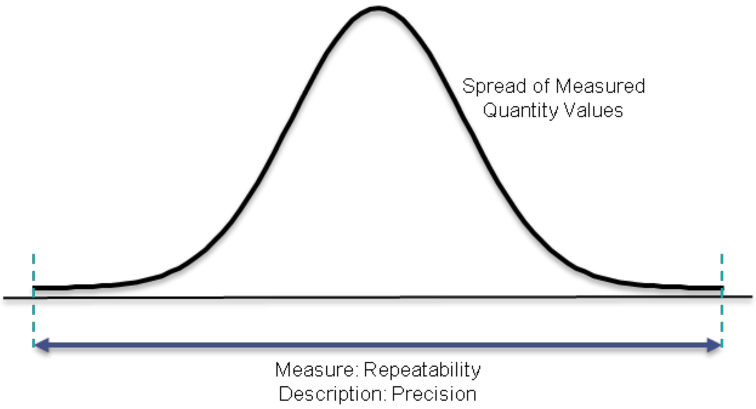
The apparent displacement of an object as seen from two different points that are not on a line with the object.
*If a measurement scale is not in direct contact with the indicator (e.g. a pointer slightly raise above the scale on a dial indicator, the increments on a vernier scale are slightly above the main scale) viewing the gauge from different angles will yield different results. This is a parallax error.*

NPL Good Practice Guide No.80, p.169

## Precision

closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions. *Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement.*

JCGM 200:2012, Para.2.15




## Random error

component of measurement error that in replicate measurements varies in an unpredictable manner. Random measurement errors of a set of replicate measurements form a distribution that can be summarized by its expectation, which is generally assumed to be zero, and its variance.

JCGM 200:2012, Para.2.19

## Range (of a nominal indication interval)

absolute value of the difference between the extreme quantity values (of a nominal indication interval) The *difference between the highest and the lowest of a set of values.*

JCGM 200:2012, Para.4.5

## Reading

quantity value representing a measurement result.

JCGM 200:2012, Para.2.10

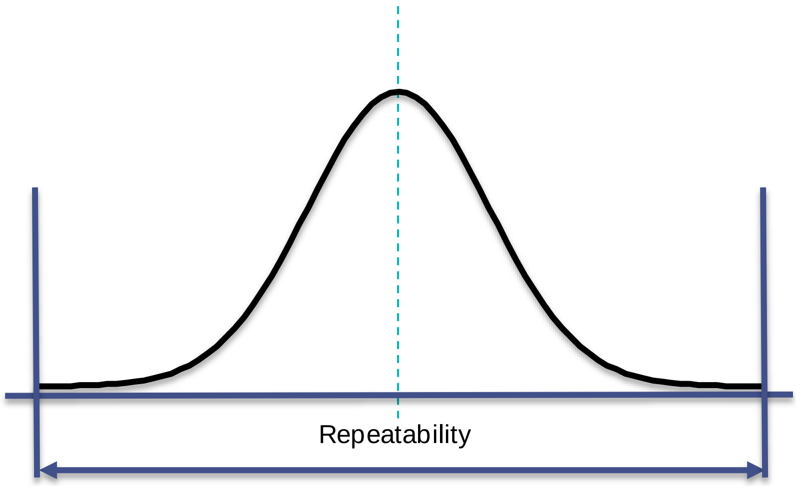
## Repeatability (of an instrument or of measurement results)

measurement precision under a set of repeatability conditions of measurement.

JCGM 200:2012, Para.2.21

In the field of Measurement Systems Analysis, Repeatability is defined as:
The common cause, random variation resulting from successive trials under defined conditions of measurement. *Often referred to as equipment variation (EV), although this is misleading. The best term for repeatability is within-system variation when the conditions of measurement are fixed and defined - fixed part, instrument, standard method, operator, environment and assumptions. In addition to equipment variation, repeatability will include all within variation from the conditions in the measurement error model.*

AIAG MSA 3rd Edition, p.208



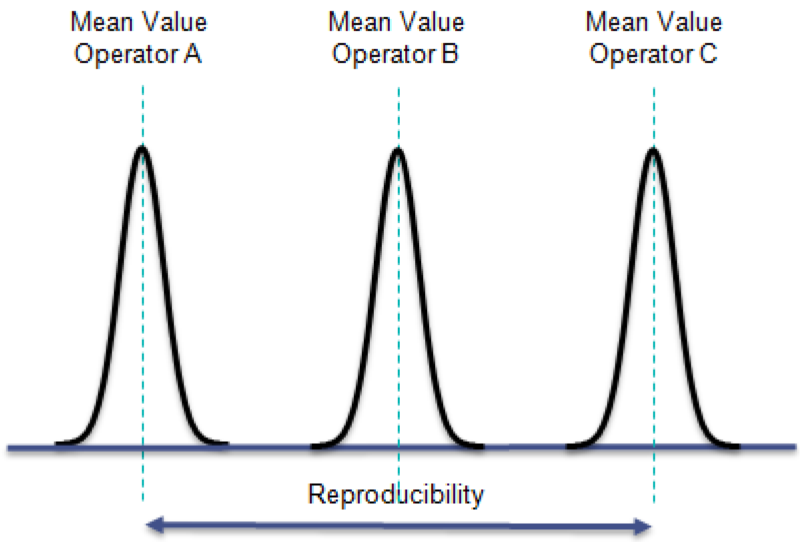

## Reproducibility (of an instrument or of measurement results)

measurement precision under reproducibility conditions of measurement. *A set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects. A specification should give the conditions changed and unchanged, to the extent practical.*

JCGM 200:2012, Para.2.25

In the field of Measurement Systems Analysis, Repeatability has a distinctly different meaning:
the variation in the average of measurements caused by a normal condition of change in the measurement process. *Typically, it has been defined as the variation in average measurements of the same part between different appraisers using the same measurement instrument and method in a stable environment.*

AIAG MSA 3rd Edition, p.209




## Resolution

smallest difference between displayed indications that can be meaningfully distinguished

JCGM 200:2012, Para.4.14

## Result (of a measurement)

set of quantity values being attributed to a measurand together with any other available relevant information.
*A measurement result is generally expressed as a single measured quantity value and a measurement uncertainty. If the measurement uncertainty is considered to be negligible for some purpose, the measurement result may be expressed as a single measured quantity value. In many fields, this is the common way of expressing a measurement result.*

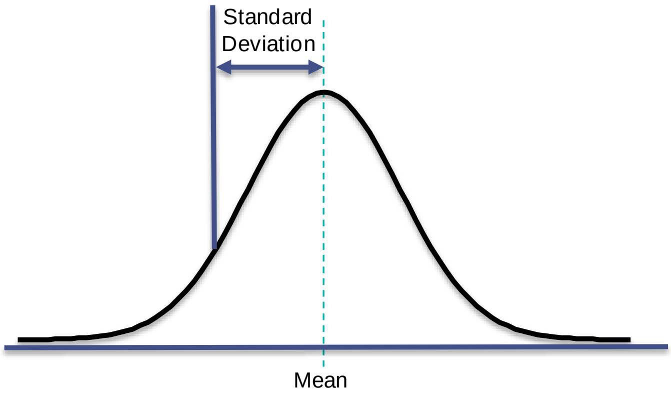
JCGM 200:2012, Para.2.9

## Sample mean (arithmetic mean)

sum of random variables in a random sample divided by the number of terms in the sum.

*The sample mean, considered as a statistic, is often used as an estimator for the population mean.*

ISO 3534-1:2006, Para.1.15




## Sensitivity

quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured

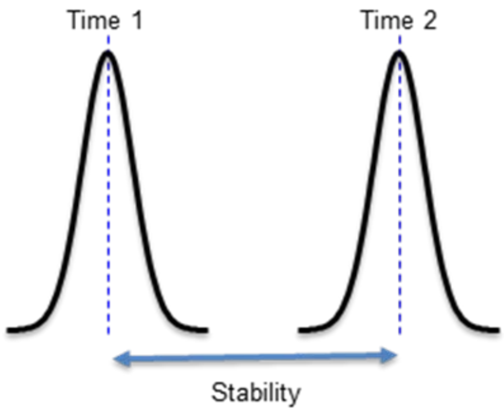
JCGM 200:2012, Para.4.12

## Stability

property of a measuring instrument, whereby its metrological properties remain constant in time. Stability may be quantified in several ways:

- In terms of the duration of a time interval over which a metrological property changes by a stated amount.
- In terms of the change of a property over a stated time interval.

JCGM 200:2012, Para.4.19




## Standard deviation

non-negative square root of the sample variance.

ISO 3534-1:2006, Para.1.17

## Standard uncertainty

measurement uncertainty expressed as a standard deviation.

JCGM 200:2012, Para.4.19

## Systematic error

component of measurement error that in replicate measurements remains constant or varies in a predictable manner.

*Systematic measurement error, and its causes, can be known or unknown. A correction can be applied to compensate for a known systematic measurement error.*

JCGM 200:2012, Para.4.19

## Tolerance

difference between the upper and lower tolerance limits

ISO 14253-1:1998, Para.3.1

## Tolerance zone tolerance interval

variate values of the characteristic between and including the tolerance limits

ISO 14253-1:1998, Para.3.1

## Traceability

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. *Metrological traceability requires an established calibration hierarchy.*

JCGM 200:2012, Para.2.41

## True value

quantity value consistent with the definition of a quantity.
*The value that would be obtained by a perfect measurement. (In practice this can't be achieved, a measurement result will always be an approximation of the true value)*

JCGM 200:2012, Para.2.11

## Type A evaluation of measurement uncertainty

evaluation of a component of measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions.

JCGM 200:2012, Para.2.28

## Type B evaluation of measurement uncertainty

evaluation of a component of measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty. *Evaluation based on information:*

- *associated with authoritative published quantity values,*
- *associated with the quantity value of a certified reference material,*
- *obtained from a calibration certificate,*
- *about drift,*
- *obtained from the accuracy class of a verified measuring instrument,*
- *obtained from limits deduced through personal experience.*

JCGM 200:2012, Para.2.29

## Type 1 gauge study

a study evaluating the combined effects of bias and repeatability based on multiple measurements from a single part.
*A Type 1 Gauge Study should be done prior to conducting other gauge repeatability and reproducibility studies, which determine how much of your observed process variation is due to measurement system variation.*

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## Uniform distribution

Distribution of values with equal likelihood of falling anywhere within a range. Also sometimes referred to as rectangular distribution.

## Upper Specification Limit (USL)

specified value giving either:

- *the upper boundaries of the permissible value of the tolerance limits of a workpiece characteristic; or*
- *the upper boundaries of the permissible value of the permissible errors of a measuring equipment characteristic*

ISO 14253-1:1998, Para.3.8

## Variance (Sample variance)

sum of squared deviations of random variables in a random sample from their sample mean divided by the number of terms in the sum minus one. *For a random sample of sample size n, i.e.* $\{X_1, X_2, \ldots, X_n\}$ *with sample mean* $\bar{X}$*, the sample variance,* $S^2$*, is:*

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2$$

## Change History

| Revision | Date | Description of Change | Author | Owner | Approval |
|---|---|---|---|---|---|
| V1.0 | 04/02/2011 | First Issue | V Venkatesh | P Bamforth | P Bamforth |
| V2.0 DRAFT | 22/09/2011 | Added various sections and framework for next major release | P Bamforth | P Bamforth | P Bamforth |
| V3.0 | 31/08/2012 | Major Update | W Ross-Skinner | P Bamforth | P Bamforth |
| V3.1 | 31/05/2013 | Guide reformatted for SABRe | C Johnstone | J Mansell | J Mansell |
| V3.2 | 11 / 09/ 2015 | Update to section 1 and 2 on use of tables, general wording and minor corrections in other sections (show with sidelines) | J Mansell | J Brownell | J Brownell |
| V3.3 | 03/11/2015 | Up-date to 4.19.7 to dis-allow the use of capability charts for CMMs | J Brownell | J Brownell | J Brownell |
| V3.4 | 25/10/2018 | Removal of R-R branding and references | J Brownell | A Wall | A Wall |

### Document update policy

This document may be updated periodically. Major amendments will be shown as an update from one revision number to a higher revision number (e.g. revision 1 to revision 2) and therefore the content of the higher revision will be regarded as the latest requirements. A minor amendment will be shown as a number change after a decimal point (e.g. revision 1.1 to revision 1.2) and therefore any of these revisions may be regarded as the latest requirements until a major amendment is introduced