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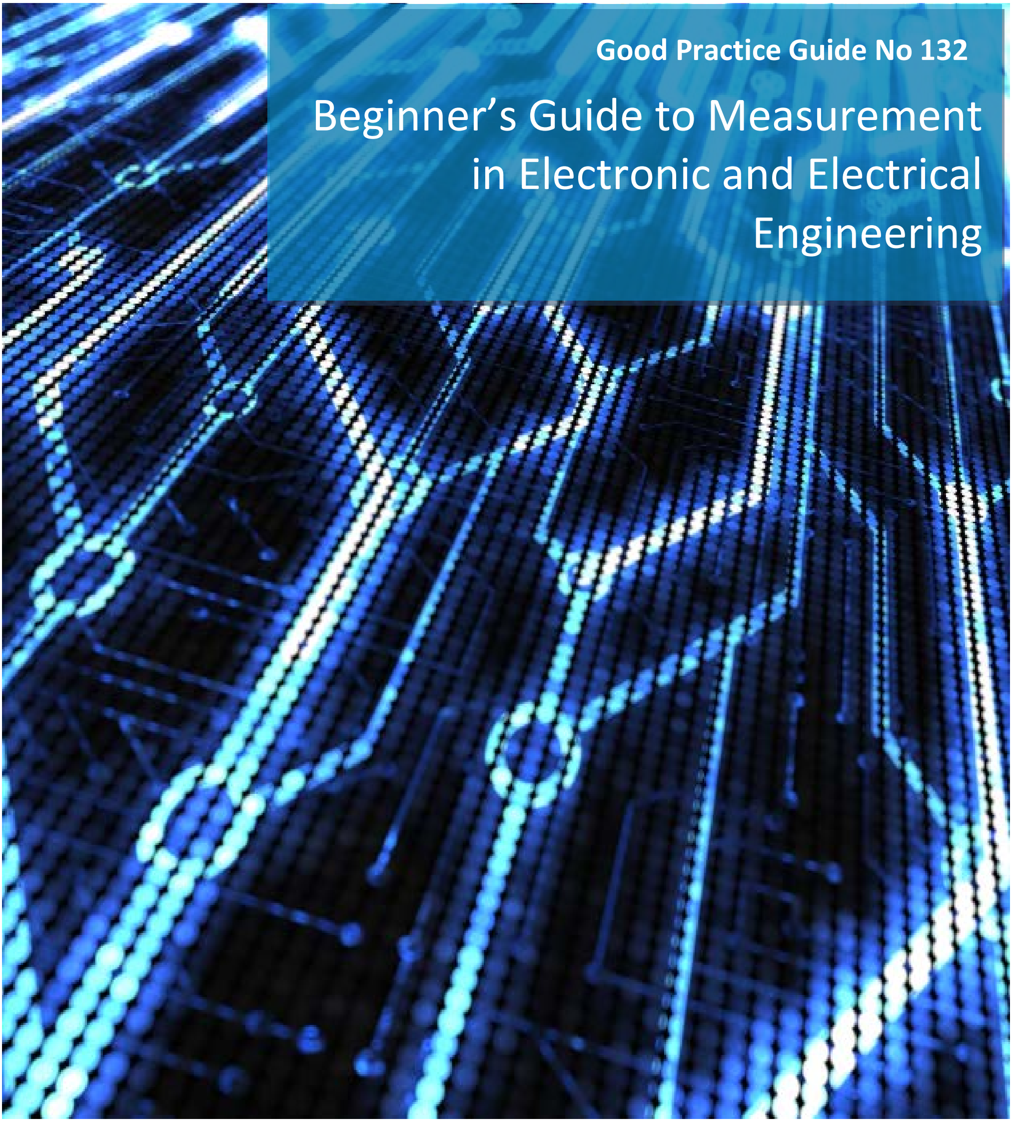

Good Practice Guide No 132

Beginner's Guide to Measurement in Electronic and Electrical Engineering

The National Physical Laboratory (NPL)

NPL is the UK's National Measurement Institute, and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available.

NPL's mission is to provide the measurement capability that underpins the UK's prosperity and quality of life.

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Institution of Engineering and Technology (IET)

The IET is working to engineer a better world through our mission to inspire, inform and influence the global engineering community, supporting technology innovation to meet the needs of society. It is the Professional Home for Life® for engineers and technicians, and a trusted source of Essential Engineering Intelligence®.

The IET has nearly 160 000 members in 127 countries, with offices in Europe, North America, South Asia and Asia-Pacific.

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Key to icons:

! Need to know

? Nice to know

✓ Checklist

Foreword

Mr Barry Brooks BSc (Eng) CEng FCGI FIMarEST FIET (President of the IET 2013-2014)

Measurement is a multidisciplinary, cross-sector topic critical to all engineering and control systems and to quality of life. Although life in the 21st century relies heavily on precision measurement, often we are not even aware of it.

Satellite navigation systems are dependent on ultra-stable clocks; different electrical components work together in personal electronic goods; and food producers use the optimal temperature necessary for perfection to prevent energy wastage.

Precision measurement is at the heart of each of these products and services, many of which we take for granted.

All engineers measure things, but do you know what use will be made of the measurements? Are you making the right measurement and using the right tools? Do you know the SI rules? Do you understand the need for planning your measurement? Do you know the effects of instrument performance limitations?

This beginner's guide will open your eyes to the significance of good measurement and will help you to understand how to use this to best effect in your area of engineering.

Through the practical application of theory, alongside lively, interesting and relevant case studies, you will learn how electrical and electronic engineers' measurements relate to national standards. And you will see how good measurement practice is necessary for you to make the most appropriate measurements.

For over 140 years, the IET has been inspiring, informing and influencing the global engineering community, supporting technology innovation to meet the needs of society and, as such, we are delighted to have worked with NPL on this joint publication – a publication that shares and advances knowledge to enable you to make a positive difference as an electrical or electronic engineer. This guide will equip you with the guiding principles and good practice to measurement in electronic and electrical engineering.

The IET: working to engineer a better world.

The action of measuring something where ‘measuring’ ascertains the size, amount or degree (of something) by using an instrument or device marked in standard units.

Measurement in Electronic and Electrical Engineering

The business or study of designing and building electrical systems, especially those that use power and control machines or are involved in communication and the use of equipment.

The world of the electronic and electrical engineer.

Introduction

Life in the 21st century relies heavily on precision measurement. Often we are not even aware of it:

- Satellite navigation systems depend on ultra-stable clocks, as any small error in timing can throw navigation a long way off course.
- Electrical components ordered from different suppliers will work together in your personal electrical goods.
- Food producers know the optimal temperature for preparing biscuits perfectly, so that they do not waste any unnecessary energy.

Precision measurement is at the heart of each of these experiences, and many more that we often take for granted.

NPL has a special role in measurement. Every measurement is a comparison between a quantity we want to know about and a standard amount of that quantity. In the UK, NPL is responsible for maintaining these ‘standard quantities’ and making them available to industry throughout the country, giving UK businesses a competitive advantage.

When it all goes wrong: even simple measurement mistakes can be very costly!

- **NASA's Mars Climate Orbiter.** Programming teams in Europe and the USA used two different measurement systems, imperial and metric, to calculate the trajectory of the spacecraft. The probe consequently entered the Martian atmosphere at the wrong angle, and promptly disintegrated.
- **The ‘Gimli Glider’.** An Air Canada Boeing 767-233 jet was refuelled in Montreal using 22 300 pounds of fuel instead of 22 300 kilograms. The pilot calculated how much fuel he needed thinking he was getting his fuel in pounds per litre. When the plane ran out of fuel mid-flight, the pilot had to make an emergency 'gliding' landing at Gimli Canadian Air Force Base.

Improvements in measurement can have far-reaching consequences.

For example, aero engines are built to a very high accuracy and require about 200 000 separate measurements during production. Some measurements are simple, and others more complicated. Some are made on a factory floor, others in specialist measurement laboratories.

But by having confidence in each individual measurement, manufacturers save time and money, and improve the quality of their products.

All engineers measure things, but try asking yourself the following questions:

- Are the measurement results accurate enough?
- Is the measurement device working correctly?
- How critical is this measurement? If it is wrong, will someone lose money? Or could someone lose their life?

This guide aims to explain how an electrical and electronic engineer's measurements relate to the national standards – and to encourage good measurement practice to help you make the best measurements possible

Metrology – the science of measurement

The definition of metrology is 'the science of measurement'.

Metrologists (those working in measurement science):

- Define the internationally accepted units of measurement
- Realise the units of measurement by scientific methods
- Establish traceability chains enabling the determination and documenting of the value and accuracy of a measurement

Metrologists work in three areas:

- Scientific metrology – defines and organises the measurement standards and undertakes research into new or improved measuring techniques required
- Industrial metrology – ensures adequate functioning of measurement instruments in industry such as those used in manufacturing, processes and quality assurance
- Legal metrology – verifies and ensures the applications of measurement standards that enable economic transactions such as buying fuel

Good measurement practice

NPL has defined six guiding principles of good measurement practice.

NPL’s six guiding principles for good measurement results	
1. The right measurements	Measurements should only be made to satisfy agreed and well specified requirements
2. The right tools	Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose
3. The right people	Measurement staff should be competent, properly qualified and well informed
4. Regular review	There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures
5. Demonstrable consistency	Measurements made in one location should be consistent with those made elsewhere and across time
6. The right procedures	Well-defined procedures consistent with national or international standards should be in place for all measurements

You can make a significant difference to your measurement capabilities by simply following these principles, which should all be part of your own quality system.

In this booklet we bring a few more areas to life that we feel will help you make better measurements:

- **Using the International System of Units (SI)**
- **Ensuring the measurements are valid**
- **Understanding the concepts:**
  - Precision, accuracy and uncertainty
  - Repeatability and reproducibility
  - Acceptance criteria (tolerance)
  - Traceability and calibration
- **Estimating the overall uncertainty of the measurements**
- **Introducing a defined measurement procedure**
- **Reading instrument specifications**

International System of Units (SI)

The International System of Units has the abbreviation SI from the French 'Le Système International d'Unités'. The SI is at the centre of all modern science and technology and is used worldwide to ensure measurements can be standardised everywhere. There are tremendous benefits to using SI units and countries routinely compare their SI measurement standards. This keeps measurements made in different countries compatible with one another.

Base SI units

There are seven base units of the SI, in terms of which all physical quantities can be expressed.

SI		
Quantity	**SI Unit**	**Symbol**
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin or degree Celsius	K or °C
Luminous intensity	candela	cd
Amount of substance	mole	mol

Notes

1. The first letters of the names of the units are in lower case, e.g. four kilograms or eight seconds. The one exception is the Celsius, which is capitalised because its full version is ‘degrees Celsius’ with a small ‘d’.
2. For clarity, it is normal practice to put a single space between a number and its unit symbol, e.g. 4 mm rather than 4mm.

Derived SI units

All measurements can be expressed using combinations of the seven base units (and angle if needed). These combinations are called derived units.

Derived units – examples

Quantity	Unit	Symbol
Energy	joule	J
Power	watt	W
Quantity of electricity	coulomb	C
Electromotive force	volt	V
Electric field strength	volt per metre	
Electric resistance	ohm	Ω
Electric conductance	siemens	S
Capacitance	farad	F
Magnetic flux	weber	Wb
Magnetic flux density	tesla	T
Inductance	henry	H
Magnetic field strength	ampere per metre	
Magnetomotive force	ampere	A

A full list of derived units can be found at www.kayelaby.npl.co.uk

Further Reading

BIPM (2006), The International System of Units (SI), Eighth Edition, (Paris: Organisation Intergouvernementale de la Convention du Mètre) available at: www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf

BIPM (2012), International vocabulary of metrology — Basic and general concepts and associated terms available at: www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

Fenna, D. (2009), *Oxford Dictionary of Weights, Measures and Units* (Oxford: Oxford University Press)

Jerrard, H. G. & McNeill, D. B. (1992), *A Dictionary of Scientific Units: including dimensionless numbers and scales* (New York: Chapman and Hall)

Prefixes used for multiples of units

A shorthand system of prefixes was agreed as part of the SI. All prefixes are related to each other by powers of 10, making them very easy to use.

SI prefixes

Prefix	Symbol	Decimal	Power of 10
yotta	Y	1 000 000 000 000 000 000 000 000	10^{24}
zetta	Z	1 000 000 000 000 000 000 000	10^{21}
exa	E	1 000 000 000 000 000 000	10^{18}
peta	P	1 000 000 000 000 000	10^{15}
tera	T	1 000 000 000 000	10^{12}
giga	G	1 000 000 000	10^{9}
mega	M	1 000 000	10^{6}
kilo	k	1 000	10^{3}
hecto	h	100	10^{2}
deca	da	10	10^{1}
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0.001	10^{-3}
micro	µ	0.000 001	10^{-6}
nano	n	0.000 000 001	10^{-9}
pico	p	0.000 000 000 001	10^{-12}
femto	f	0.000 000 000 000 001	10^{-15}
atto	a	0.000 000 000 000 000 001	10^{-18}
zepto	z	0.000 000 000 000 000 000 001	10^{-21}
yocto	y	0.000 000 000 000 000 000 000 001	10^{-24}

The highlighted section above indicates the range that electrical measurement routinely covers.

Using the right scale

It might seem that some of these prefixes are somewhat extreme, but they can be useful. For example:

- The Sun delivers 5.6 YJ (yottajoules) of energy to the Earth every year
- A proton is 1.6 fm (femtometres) in diameter

There is one exception to the system of prefixes. For historical reasons we do not apply the prefixes to the kilogram, but instead to the gram. This is to avoid the need to refer to a gram as a millikilogram!

There are a small number of agreed SI exceptions which you will be familiar with and are shown in the table below.

Internationally agreed SI exceptions

Name	Symbol	Quantity	Equivalent SI unit
minute	min	time	1 min = 60 s
hour	h	time	1 h = 3 600 s
day	d	time	1 d = 86 400 s
degree of arc	°	angle	1° = (π/180) rad
minute of arc	‘	angle	1’ = (π/10 800) rad
second of arc	“	angle	1” = (π/648 000) rad
hectare	ha	area	1 ha = 10 000 m^2
litre	l or L	volume	1 l = 0.001 m^3
tonne	t	mass	1 t = 1 000 kg

Realisation of the SI base units

The definitions of the SI units allow scientists to create unit amounts of the SI base quantities.

Six of the SI definitions are the procedures needed to 'realise' – literally, to make real – the standard or a close approximation of it. This applies to the second, metre, kelvin, ampere, candela and mole.

The seventh base unit – the kilogram – is not based on a procedure, but instead on a single physical artefact: a cylinder made up of platinum and iridium metals, which is kept in a safe in the International Bureau of Weights and Measures (BIPM) on the outskirts of Paris, France.

The beauty of the SI system is that if every measuring instrument were destroyed tomorrow, six of the seven base units could be reconstructed using their definitions. It also means that these base units are truly international.

The current scientific measurement challenge is to develop a way to ‘realise’ a kilogram so that it can follow the other six units and no longer rely upon a single physical object.

The realisation of SI units requires expensive equipment and highly trained measurement scientists, and is extremely time-consuming. Therefore, it is done at specialised National Measurement Institutes such as NPL. The realised units, their multiples and sub-multiples are then disseminated for trade, industry, science and health and safety. This dissemination process is known as 'traceability' and is outlined later in the guide.

The ampere (A)

The ampere is the unit for electrical current in the International System of Units (SI).

The formal definition of the ampere is that it is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in vacuum, would produce between those conductors a force equal to 2×10^{-7} newtons per metre of length. However, in practice the ampere is difficult to realise with sufficient accuracy, so it is realised via the watt (the SI unit for power). The electrical power generated in a controlled experiment is compared to mechanical power, and using an accurate measurement of resistance the ampere can be calculated via:

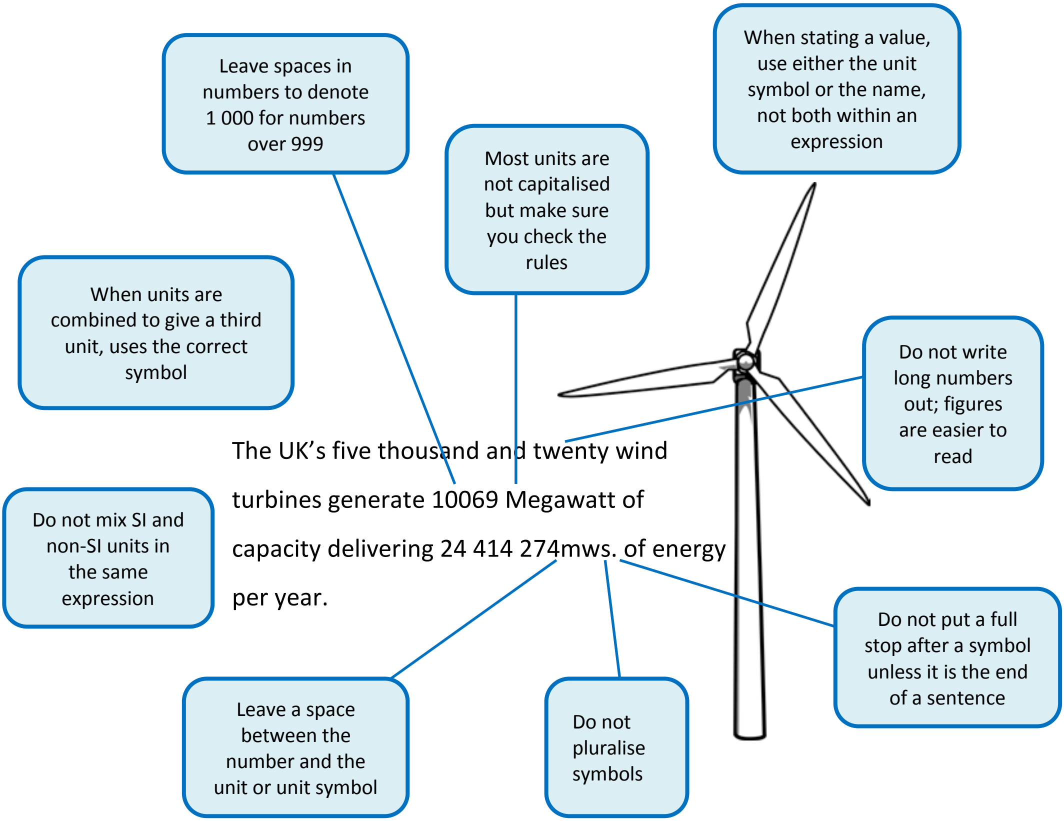
$$\text{Power} = (\text{Current})^2 \times \text{Resistance}$$

At the National Physical Laboratory the volt is maintained using the AC Josephson effect. Due to this effect, the potential difference between two superconductors separated by a narrow gap and exposed to electromagnetic radiation takes discrete values dependent on the Josephson constant (483 597.9 gigahertz per volt) and the frequency of radiation.

Expressing measurement results

Measurement results need to be written down clearly. The good news is that the SI system has guidelines to help you.

In the example below the most important rules are broken!



Leave spaces in numbers to denote 1 000 for numbers over 999

Most units are not capitalised but make sure you check the rules

When stating a value, use either the unit symbol or the name, not both within an expression

When units are combined to give a third unit, uses the correct symbol

Do not write long numbers out; figures are easier to read

The UK’s five thousand and twenty wind turbines generate 10069 Megawatt of capacity delivering 24 414 274mws. of energy per year.

Do not mix SI and non-SI units in the same expression

Do not put a full stop after a symbol unless it is the end of a sentence

Leave a space between the number and the unit or unit symbol

Do not pluralise symbols

A correct version would be:

The UK’s 5 020 wind turbines generate 10 069 MW of capacity delivering 24 414 274 MWh of energy per year.

Full details are given in Section 5 of the BIPM publication on the International System of Units (SI), which is freely accessible at: www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf

Measurement in practice

People make measurements for many reasons: to make sure an item will fit, to determine the correct price to pay for something, or to check that a manufactured item is within specification. In all cases, a measurement is only useful if it is suitable for the intended purpose.

Consider the following questions:

- Do you know how accurate your measurement result is?
- Is this accurate enough?
- How strongly do you trust the result?

These questions relate to the quality of a measurement. When talking about measurement quality, it is important to understand the following concepts.

Precision, accuracy and uncertainty

Precision is about how close measurements are to one another. Accuracy is about how close measurements are to the 'true value'.

In reality, it is not possible to know the 'true value' and so we introduce the concept of uncertainty to help quantify how wrong our value might be.

The difference between accuracy and precision is illustrated here. The idea is that firing an arrow at a target is like making a measurement. Accuracy is a qualitative measure of how close a measurement is to the centre of the target – the 'true value'. Precision is represented by a cluster of consistent measurements, but there is no guarantee that these are accurate.

**Low accuracy,
but high precision**

**Higher accuracy,
but low precision**

**High accuracy and
high precision**

Accuracy	a qualitative term that describes how close a set of measurements are to the actual (true) value
Precision	describes the spread of these measurements when repeated - a measurement that has high precision has good repeatability

In practice we are not able to view the target and assess how close to the 'true value' our measurements are. What interests us is the answer to the question "How far from the target could our arrows have fallen?" We also need to ask "How wrong could we have been?"

To answer these questions we need to look at all the factors that go into making a measurement and how each factor could have affected the final estimate of the answer.

The answer to "How wrong are we likely to have been?" is known as the 'measurement uncertainty', and this is the most useful assessment of how far our estimate is likely to lie from the 'true value'.

For example, we might say that the length of a particular stick is 200 cm with an uncertainty of ±1 cm.

See the section on Uncertainty Analysis (page 20) for further information on how to work this out.

Don't confuse mistakes with errors!

Measurement scientists use the term 'error' to specify the difference between an estimate of quantity and its 'true value'. The word 'error' does not imply that any mistakes have been made. Where the size and effect of an error are known (e.g. from a calibration certificate) a correction can be applied to the measurement result. If the value of an error is not known, this is a source of uncertainty.

Uncertainty	is the quantification of the doubt about the measurement result and tells us something about its quality
Error	is the difference between the measured value and the true value of the thing being measured
True value	is the value that would be obtained by a theoretically perfect measurement

What is not uncertainty?

- Mistakes made by operators are NOT uncertainties – operator mistakes can be avoided by working carefully through a procedure and checking work.
- Tolerances are NOT uncertainties – tolerances are acceptance limits chosen for a process or product.
- Accuracy is NOT uncertainty – the true value of a measurement is never known.

Repeatability and reproducibility

'Measure twice and cut once.' This popular proverb expresses the need to make sure we have a good measurement before committing to a potentially irreversible decision. It is a concept that you should adhere to. By repeating a measurement many times, a mean (average) value can be calculated. If the repeatability is high, the statistical uncertainty in the mean value will be low.

However, if different measuring equipment is used, a different result may be obtained because of errors and offsets in the instruments.

If you take a voltage measurement three times in one minute using the same multimeter, you would expect to get a similar answer each time. Repeatability describes the agreement within sets of measurements where the same person uses the same equipment in the same way, under the same conditions.

But if your colleagues each had a go at taking the same measurement on different days using different measuring equipment, a wider range of answers would be much less surprising. This is known as 'reproducibility' and describes the agreement within a set of measurements where different people, equipment, methods, locations or conditions are involved.

Repeatability	is the closeness of agreement between repeated measurements of the same thing, carried out in the same place, by the same person, on the same equipment, in the same way, at similar times
Reproducibility	is the closeness of agreement between measurements of the same thing carried out in different circumstances, e.g. by a different person, or a different method, or at a different time

Tolerance

How is it that nuts from one supplier and bolts from another supplier work together? The answer lies in tolerance, also known as 'acceptance criteria'. The tolerance is the agreed allowable variation in the shape of the nuts and bolts that allow them to still fit together.

Tolerance	is the maximum acceptable difference between the actual value of a quantity and the value specified for it

For example, if an electrical resistor has a specification of 10 ohms and there is a tolerance of ±10 % on that specification, the minimum acceptable resistance would be 9 ohms and the maximum would be 11 ohms.

What affects your measurements?

Many factors can reduce accuracy or precision and increase the uncertainty of your measurement result. Some of the most common are:

- Environmental conditions – changes in temperature or humidity can expand or contract materials as well as affect the performance of measurement equipment.
- Inferior measuring equipment – equipment which is poorly maintained, damaged or not calibrated will give less reliable results.
- Poor measuring techniques – having consistent procedures for your measurements is vital.
- Inadequate staff training – not knowing how to make the right measurement, not having the confidence to challenge the results and not being willing to seek advice can all have a negative impact.

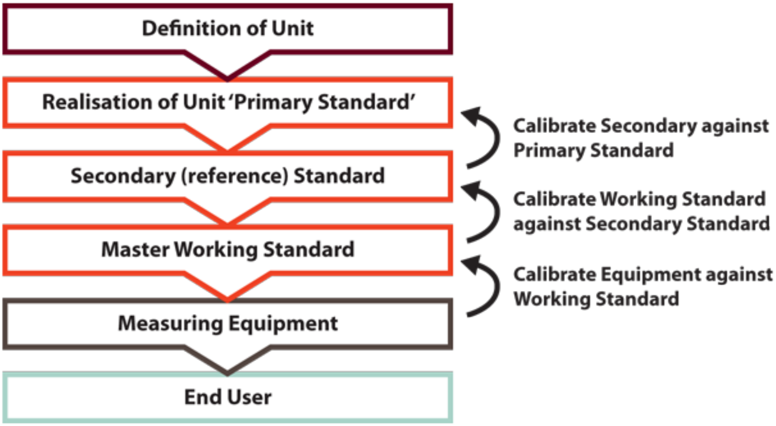
How important is measurement in your environment – do you encourage a ‘measurement right first time’ culture?

Traceability and calibration

When we talk about traceability of measurements, we mean that the measurements can be related to a national standard through a documented unbroken chain of calibrations.

The primary standards at NPL are used to calibrate reference (secondary) standards held by accredited calibration laboratories. These reference standards are subsequently used to calibrate working standards, which may be company master standards owned by industry or hospitals, for example.

Reference and working standards can be measuring instruments such as multimeters, or physical objects such as voltmeters.



Traceability Chain

During a calibration process, instrument readings are compared to the certified values produced for a reference standard. The results are recorded in a calibration certificate. If the results are consistent with the reference values (the differences between them are within acceptable limits) then no further action is required.

If the results are significantly different, calibration corrections must be applied to measurements made with the instrument. Sometimes the instrument can be adjusted until it reads correctly, and these adjustments are recorded on the certificate. Each calibration must be accompanied by a statement of uncertainty.

Calibration	is the comparison of a test instrument or artefact against a more accurate standard
Measurement traceability	refers to the unbroken chain of calibrations linking an instrument or standard to primary standards

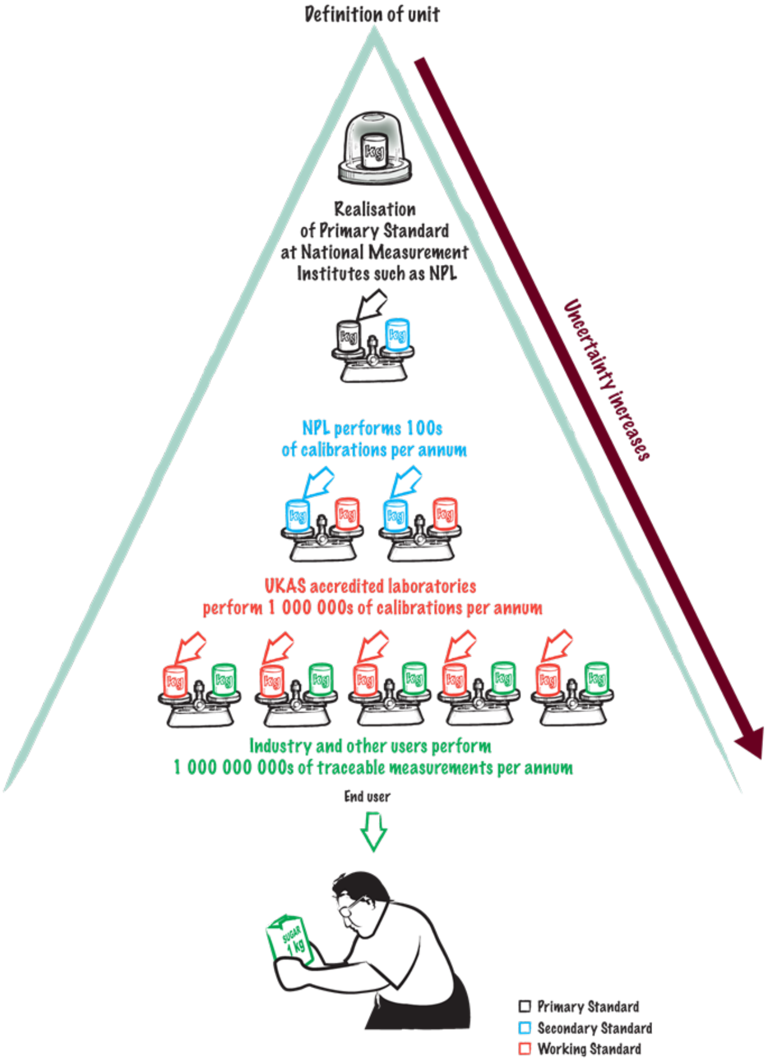
Accreditation	means that a calibration laboratory in a specific field has been independently assessed and audited to show that it is competent to carry out specific tests and calibrations in that field. The internationally agreed procedures that describe how a laboratory should carry out accurate measurements on specific items are called 'International Standards', and the International Organization for Standardization (ISO), based in Geneva, Switzerland, is responsible for publishing and revising them. National standardisation bodies such as the BSI (British Standards Institution) participate in the preparation of international standards and also prepare standards which address national measurement needs not covered by ISO standards. ISO 17025, ‘General requirements for the competence of testing and calibration laboratories’, is the standard that specifies how the United Kingdom Accreditation Service (UKAS) and its overseas equivalents accredit calibration laboratories.

Many large companies have their own internal calibration hierarchies where they calibrate, at appropriate intervals, the company’s own working standards against reference standards calibrated by NPL or an accredited calibration laboratory.

It is important to note that for every step away from the national standard, the uncertainty increases. Measurement uncertainty is calculated at each step of the traceability chain and then an overall uncertainty for the whole chain is calculated.

Generally then, it is best to try to shorten this chain as much as possible – this is usually done by using each standard to calibrate a large number of lower accuracy standards, in parallel, rather than chaining them together, one after the other.

The process then looks like a pyramid, with one or two highest accuracy standards at the top being used to calibrate many standards at the next level, then more and more standards at lower levels as the pyramid widens. By minimising the number of levels in the pyramid, the length of the chain is kept short, while supporting a large number of standards at the lowest level.



Electrical Standards	Agreed standards eliminate the need for multiple testing of the same product in different countries and this enables the acceptance of products in different countries, thus facilitating international trade. There are many organisations that publish electrical standards. The three most relevant ones are: **International Electrotechnical Commission (IEC)** www.iec.ch **European Committee for Electrotechnical Standardization (CENELEC)** www.cenelec.eu **British Standards Institution (BSI)** www.bsigroup.co.uk CE marking is used for products traded on the single market in the European Economic Area (EEA), indicating the product's compliance with applicable EU legislation.

Instruments should be recalibrated at appropriate intervals and at the appropriate level in the calibration chain, keeping them fit for purpose for the requirements of your organisation.

Do you know when your measurement instruments were last calibrated and who is responsible for this?

Rolls-Royce uses over 200 000 measuring instruments with traceability back to national standards in the production of each of their engines around the world. Rolls-Royce is critically dependent on capable measurement. The entire life cycle of the company's products and the services derived from them is underpinned by measurement.

Uncertainty analysis

As we mentioned earlier, an accurate measurement is one that is close to the ‘true answer’. However, in practice we do not know what the ‘true answer’ is. In the real world, what interests us is the answer to the question:

“How wrong are we likely to have been?”

The answer to this question is called the 'uncertainty of measurement', which generally can be quite hard to evaluate.

In short, we are looking to identify the possible sources of uncertainty, evaluate the uncertainty from each source and, finally, combine the individual uncertainties to get an overall figure.

Have a go at evaluating uncertainty by following our eight point plan:

1. Decide what you need to find out from your measurement

Identify the type of measurement and how it is to be measured, as well as any calculations required in the process such as effects that require a correction.

For this example, suppose you decide to use a resistance meter to measure the resistance of a component.

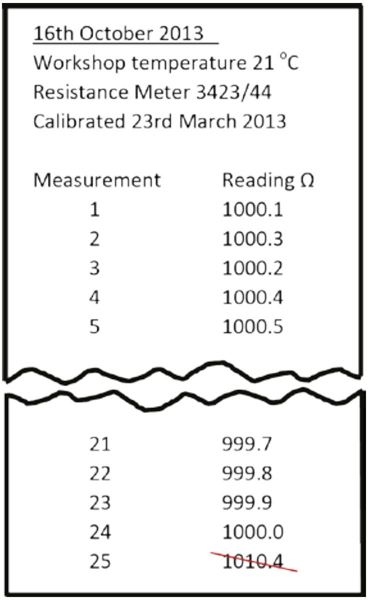
2. Carry out and record the measurements needed

At this point you should ideally be following a specified measurement procedure to ensure that your measurement is consistent with that of other colleagues in your organisation.

Here, we will assume that you checked that the resistance meter is well maintained and calibrated, and then you took repeated readings.

Set out your notebook clearly with a date, initials, the instruments you are using, a note of the calibration sticker on the resistance meter and a record of the temperature. This is good practice.

Since the numbers are laid out neatly, it should be easy for you to spot that Measurement 25 is out of line with the others. Having confirmed this is a mistake, cross it out without making it illegible. In statistical terms, this reading is considered an outlier and is clearly not part of the natural variability of measurement. It is therefore ignored in any further



16th October 2013
Workshop temperature 21 °C
Resistance Meter 3423/44
Calibrated 23rd March 2013

Measurement	Reading Ω
1	1000.1
2	1000.3
3	1000.2
4	1000.4
5	1000.5
21	999.7
22	999.8
23	999.9
24	1000.0
25	~~1010.4~~

calculations and you simply take the average of the other 24. This gives your best estimate of the resistance as:

$$(1\,000.1 + 1\,000.3 + 1\,000.2 + 1\,000.4 + \ldots) \div 24 = 1\,000.042\ \Omega$$

To avoid numerical errors from rounding, you should use at least one ‘guard digit’ beyond the resolution of the readings. Here, we have used two.

3. Evaluate the uncertainty of each input quantity that feeds in to the final result (Type A and Type B evaluations). Express all uncertainties in similar terms (standard uncertainties)

How wrong is this result likely to be? What factors could have affected your measurement?

Type A uncertainty evaluations are carried out by statistical methods, usually from repeated measurement readings. In this case, you have 24 readings and have used these to gain an average of 1 000.042 Ω.

Type B uncertainty evaluations are carried out using any other information such as past experiences, calibration certificates and manufacturers' specifications; and from calculation, published information or common sense. In this example we look at the manufacturer’s specification sheet and read any accuracy specifications that need to be taken into consideration.

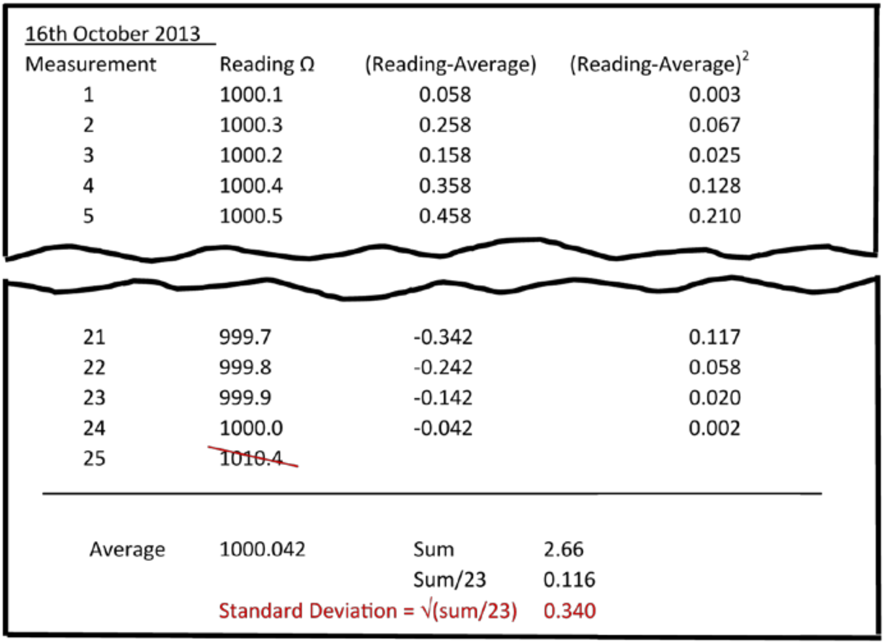
Both of these uncertainties need to be expressed in similar terms so that you can compare and combine them. So you need to associate a number – called a 'standard uncertainty' – with each term.

Type A uncertainty evaluation

For Type A uncertainty evaluation, you characterise the variability of *n* readings by their standard deviation, given by the formula below:

$$\text{standard deviation} = \sqrt{\frac{\sum_{i=1}^{n} (\text{reading}_\text{i}\ - \text{average})^2}{n - 1}}$$

$$\sqrt{\frac{(\text{reading}_1 - 1\,000.042)^2 + (\text{reading}_2 - 1\,000.042)^2 + (\text{reading}_3 - 1\,000.042)^2 + \ldots}{24 - 1}}$$



16th October 2013

Measurement	Reading Ω	(Reading-Average)	$(\text{Reading-Average})^2$
1	1000.1	0.058	0.003
2	1000.3	0.258	0.067
3	1000.2	0.158	0.025
4	1000.4	0.358	0.128
5	1000.5	0.458	0.210
21	999.7	-0.342	0.117
22	999.8	-0.242	0.058
23	999.9	-0.142	0.020
24	1000.0	-0.042	0.002
25	~~1010.4~~		

Average 1000.042

Sum 2.66

Sum/23 0.116

Standard Deviation = √(sum/23) 0.340

Two significant figures are normally sufficient for an uncertainty result. You should always round your number up as it is better to obtain a more pessimistic result.

The notebook excerpt above shows how you calculate the standard deviation by hand, although many calculators or spreadsheets can calculate this function more easily. The standard deviation of 0.34 Ω is an estimate for the likely spread of individual resistance readings.

If you made an additional 100 readings, the readings would be individually just as variable. However, taking more readings would improve your confidence in the estimate of the average.

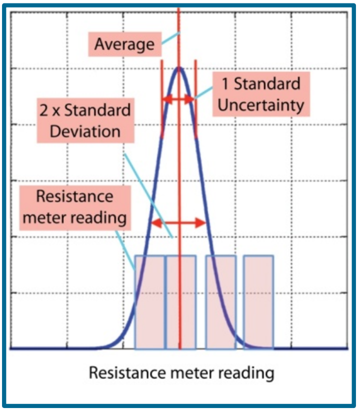
For *n* readings this fact is expressed in terms of the standard uncertainty associated with the average:

$$\text{standard uncertainty} = \frac{\text{standard deviation}}{\sqrt{n}}$$

The standard uncertainty associated with the average is thus:

$$0.34/\sqrt{24} = 0.069\ \Omega$$

This uncertainty is based upon the idea that the readings you took were drawn from a normal probability distribution. You used your 24 readings to estimate the characteristics of this distribution and then worked out the standard uncertainty – how well you can estimate the position of the centre of the distribution.

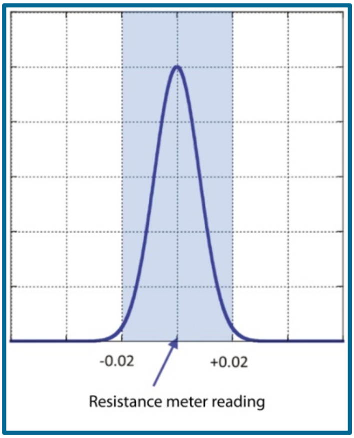


Type B uncertainty evaluation

Type B uncertainty evaluation is needed to assess uncertainties where statistics are not applicable, for example where there are biases - errors that always affect the reading in the same way. You might only be able to provide the upper and lower limits for some effect described by a 'rectangular distribution', in which the value is equally likely to fall anywhere within the interval.

In order to compare the uncertainty from Type A and Type B evaluation you need to convert the range of the rectangular distribution into a standard deviation to be used as the standard uncertainty.

To do this, you divide the half range by the square root of 3 (approximately 1.73).



$$\text{standard uncertainty} = \frac{\text{half range}}{\sqrt{3}}$$

In this example, the specification sheet for the resistance meter states that for a one year calibration interval, the instrument has an accuracy of ±0.006 0 % of the reading plus 0.000 2 % of the range, provided the temperature is within the range 23 °C ±5 °C. The specification sheet also gives a range of figures for different configurations. In this case:

$$(0.006\,0\ \%\ \text{x average measurement}) + (0.000\,2\ \%\ \text{x range})$$

$$(0.000\,060 \times 1\,000.042) + (0.000\,002 \times 1\,000) = 0.062\ \Omega$$

The standard uncertainty associated with the calibration of the device is thus:

$$0.062/\sqrt{3} = 0.036\ \Omega$$

Additionally, the resistance meter has a resolution of 0.1 Ω. You need to include this as a Type B uncertainty:

$$0.05/\sqrt{3} = 0.029\ \Omega$$

Type A	Evaluated by statistics (usually from repeated readings)
Type B	Evaluated from any other information: past experiences, calibration certificates, manufacturers' specifications, calculations, published information and common sense

Standard uncertainty	Uncertainty of the result expressed as a standard deviation

Most measurements contain several uncertainty contributions. To combine these uncertainties they must be given in the same units and expressed as standard uncertainties. As the saying goes, you ‘cannot compare apples with pears’.

4. Decide whether the errors of the input quantities are independent of each other

- Could a large error in one input cause a large error in another?
- Could an outside influence such as temperature have a similar effect on several aspects of uncertainty at once?

If the errors are independent, which is typical and assumed in this example, you can use the formula in step 6 to calculate combined standard uncertainty. If not, extra calculations are needed, beyond this guide.

Assuming that there is no correlation can lead to an unreliable uncertainty evaluation.

5. Calculate the result of your measurement (including any known corrections, such as calibrations)

You get your result from the mean reading and by making all necessary corrections to it, such as calibration corrections listed on a calibration certificate. When devices are calibrated, the laboratory usually provides corrections but does not make the adjustments to the equipment. So you end up with two factors: the uncertainty from the calibration certificate (included in your Type B uncertainty) and the calibration corrections, which are added to or subtracted from the original mean reading.

It is very important to double check whether you are adding or subtracting the correction!

Below is an extract from the calibration certificate for a resistance meter. It shows the applied value and the actual instrument reading. The measurement uncertainty is also included.

Range	Applied Value	Reading	Uncertainty of Measurement
100 Ω	99.990 61 Ω	99.981 4	1.6 mΩ
1 kΩ	0.999 925 7 kΩ	0.999 867	12 mΩ
10 kΩ	9.999 685 kΩ	9.999 82	110 mΩ

The reported expanded uncertainty is based on a standard uncertainty multiplied by a covering factor k=2, which provides a 95 % level of confidence.

6. Find the combined standard uncertainty from all the individual uncertainty contributions

Once you have your individual standard uncertainties they need to be combined. But how do you combine the Type A and Type B evaluations of uncertainty? You could simply add the two numbers, but that would give a pessimistic assessment of the uncertainty because it is unlikely that both factors would be at the limit of their range. So in order to evaluate the uncertainty you add the components 'in quadrature' (also known as 'the root sum of the squares'). The result of this is called the 'combined standard uncertainty'.

$$\text{combined standard uncertainty}=\sqrt{(\text{standard uncertainty}_1)^2+(\text{standard uncertainty}_2)^2+\ldots}$$

You now have three terms which will contribute to the evaluation of how wrong your resistance meter reading could have been:

Type A - from the variability of the data

Type B - from the calibration certificate and from the resolution of the instrument

So, in this case you combine the three components:

$$\text{combined standard uncertainty} = \sqrt{(0.069)^2 + (0.036)^2 + (0.029)^2}$$

$$= 0.083\ \Omega$$

The best estimate of the resistance is the average of the 24 readings. The associated standard uncertainty is evaluated by combining (in quadrature) the standard uncertainties relating to the main factors that could cause the resistance meter to read incorrectly. Finally, you have an estimate of the resistance and its associated standard uncertainty.

7. Calculate expanded uncertainty for a particular level of confidence

The combined standard uncertainty may be thought of as equivalent to one standard deviation, the mean ± one standard deviation covers about 68 % of the normal distribution - see table below.

You can increase the level of confidence that the true answer lies within a given range by multiplying the standard uncertainty by a coverage factor to give an expanded uncertainty.

Expanded uncertainty U = coverage factor k × combined standard uncertainty

You can increase the confidence level to 95 % or even 99 % by combining with the appropriate coverage factor (assuming a normal distribution).

Standard Uncertainty	Coverage Factor	Expanded Uncertainty	Probability that true value lies in range
0.083 Ω	1	0.083 Ω	68 %
	2	0.17 Ω	95 %
	3	0.25 Ω	99.8 %

Expanded uncertainty	is the standard uncertainty (or combined standard uncertainty) multiplied by a coverage factor k to give a particular level of confidence

Coverage factors (assuming normality)	Multiply the standard uncertainty by a coverage factor to give an expanded uncertainty with a stated level of confidence. Describing a coverage factor as $k = 1$ means that (because of the nature of the normal distribution) we ‘cover’ 68 % of the volume under the graph - we are 68 % certain the true value lies within the standard uncertainty of the best estimate. For $k = 2$, the area under the graph has not doubled, instead we are now at the 95 % confidence level.
Confidence level	Anyone can make a measurement. The important part of expressing a result is in showing how confident you are with it in a standard way that everyone understands. If a result is known to be absolutely correct, you will have 100 % confidence that the difference between your value and the true value is zero. As this is never the case, it is important to be able to describe your confidence. This is where coverage factors play a part.

8. Write down the measurement result and the uncertainty, and state how you got both of these

It is important to express the result so that a reader can use the information. The main things to mention are:

- The measurement result, together with the uncertainty
- The statement of the coverage factor and the level of confidence
- How the uncertainty was evaluated

Source of Uncertainty	**Value (Ω)**	**Probability Distribution**	**Factor**	**Standard Uncertainty (Ω)**
Variability	0.069	Normal	1	0.069
Calibration	0.062	Rectangular	1/√3	0.036
Resolution	0.5	Rectangular	1/√3	0.029
			Standard Uncertainty	0.083
			Expanded Uncertainty (coverage factor 2)	0.17

In this example, you write:

$$1\,000.04 \pm 0.17\ \Omega$$

The reported uncertainty is based on a standard uncertainty multiplied by coverage factor $k = 2$, providing a level of confidence of approximately 95 %, assuming normality.

The eight main steps to evaluating uncertainty	
1	Decide what you need to find from your measurements and what actual measurements and calculations are needed to produce the final result.
2	Carry out the measurements needed.
3	Evaluate the uncertainty of each input quantity that feeds in to the final result (Type A and Type B evaluations). Express all uncertainties in similar terms (standard uncertainties).
4	Decide whether the errors of the input quantities are independent of each other.
5	Calculate the result of your measurement (including any known corrections for things such as calibrations).
6	Find the combined standard uncertainty from all the individual aspects.
7	Express the uncertainty in terms of a coverage factor together with an expanded uncertainty at a stated level of confidence.
8	Record the measurement result and the uncertainty, stating how you got both of these.

This is a simple example; we do not deal with special cases where different rules apply, such as:

- Small number of repeated readings
- If one aspect of uncertainty dominates the calculation
- If the inputs to the calculation are correlated

Further Reading

www.npl.co.uk/publications/a-beginners-guide-to-uncertainty-in-measurement

UKAS publication M 3003, *The Expression of Uncertainty and Confidence in Measurement*

ISO/IEC Guide 98-1:2009, *Guide to the expression of uncertainty in measurement (GUM)*

Introducing a defined measurement procedure

Sometimes it just takes simple steps to make a significant difference to your measurement readings.

A measurement workshop organised by NPL at the Coordinate Measurement Systems Conference (CMSC) invited people to participate in a measurement study based on a variety of ‘hand tools’ commonly used to measure the dimensions of engineered parts.

Measurement experience ranged from newcomers to people with more than five years' experience across a range of industries including aerospace, nuclear and automotive. The study consisted of two separate sessions where each participant was asked to measure different products, using vernier calipers, height gauges, micrometers and gauge blocks.

During Session 1 the participants needed to make their own decisions about the measurement process and a mixture of good and bad practice was observed:

þ Checking calibration status
þ Cleaning the instrument before use
ý Measuring incorrectly
ý Making only one measurement
þ Checking the instrument before use
ý Misunderstanding the scale and units

During Session 2 the participants were asked to follow a defined procedure.

And the results?

Session 1: Measurement errors on a standard object were 0.2 mm

Session 2: Measurement errors on a standard object were less than 0.06 mm

This demonstrates that by implementing good measurement practice and following a defined measurement procedure, the same people can make better measurements - in this case, 70 % better!

Reference: www.cmsc.org

Reading instrument specifications

When you look at the data sheet for your measurement instrument, you will find many different figures and formulas to help you determine the uncertainty. It is important to recognise the relevant and important sections, and know how to understand them. The tables below show example accuracy specifications for an instrument that measures resistance.

The accuracy of a device decreases over time

The two figures must be added together to represent accuracy in relation to the range and reading

		± (% of reading + % of range)		
Range	**Test Current**	**90 Day** **23 °C ± 5 °C**	**1 Year** **23 °C ± 5 °C**	**Temperature Coefficient** **0 °C - 18 °C** **28 °C - 55 °C**
1.000 0 Ω	10 mA	0.005 0 + 0.000 2	0.007 0 + 0.000 2	0.000 5 + 0.000 02
100.00 Ω	10 mA	0.004 0 + 0.000 2	0.006 0 + 0.000 2	0.000 5 + 0.000 01
1.000 0 kΩ	1 mA	0.004 0 + 0.000 2	0.006 0 + 0.000 2	0.000 5 + 0.000 01

The current used by the instrument to measure the resistance

These two columns indicate the instrument's stability since its calibration if it has been kept within the specified temperature range

If you are working outside the normal operating range of 18 °C to 28 °C, you need to add on these factors for each °C

Three important details to know before reading instrument specifications	
1	The test current
2	How long it has been since the device was last calibrated
3	The temperature at which the device is being kept

Even if tests are carried out under identical conditions, the measured values will not necessarily be the same. This is caused by a variety of factors, such as thermal noise. The following table shows the noise introduced by an instrument measuring voltage. This would be included in your Type A uncertainty.

The standard deviation of noise voltage is the RMS value. These figures are for a measurement time of 2 minutes

	Observation Period
Range	**2-Minute RMS Noise**
1 mV	1.3 nVrms
10 mV	1.5 nVrms
100 mV	10 nVrms

An alternative to this specification is peak-peak noise, which is approximately 6 times larger

You can also decide to trade off the speed of the measurement against the accuracy by changing the number of digits.

The time the analog-to-digital (A/D) converter samples the input signal for a measurement

The number of digits an instrument can measure indicates its resolution

Digits	Integration Time (plc)	Integration Time
7 ½	200	4 s
7 ½	100	2 s
6 ½	20	400 ms
6 ½	10	200 ms
5 ½	1	20 ms
5 ½	0.2	4 ms
4 ½	0.02	0.4 ms

Integration time is given in seconds or power line cycles (plc). One plc equates to 20 ms in the UK

The device may have a filter to reduce the spread of the readings. This can be digital or analog.

Filters affect Type A uncertainty

Filter	
Analog	Low pass 2 pole @ 13 Hz
Digital	Moving average filter, 10 (fast), 50 (medium), or 100 (slow) reading averages

In summary

1	**Before making a set of measurements, do you know:** o what the measurements are for, and hence the uncertainty of measurements you are seeking? o how many times you should repeat the measurement? o the acceptance criteria (the tolerance, for example) for the result?
2	**Are you confident you will be:** o making the right measurement? o using the right tools? o involving the right people? o carrying out regular reviews? o able to demonstrate consistency? o following the right procedures?
3	**Has every measuring instrument you intend to use:** o been calibrated as and when needed? o been kept in appropriate conditions, not misused, or damaged?
4	**Will the instrument:** o be checked before the measurement begins? o need calibrating before the measurement begins?
5	**In planning your measurement, have you assessed and minimised the effects of:** o instrument performance limitations from the specification sheet? o the object to be measured? o sampling? o operator skill? o the environment?
6	**To express the results of your measurement, do you:** o know the SI rules? o understand how to calculate uncertainty?

Case studies

That’s all the theory done!

The following pages give examples from both IET and NPL of where measurement has been used to make a difference to an electrical or electronic engineer.

List of practical applications and case studies:

- Torque measurement
- Measurement saves networks £50 million
- New technique for MEMS power measurement
- Biomass use in power stations
- Comparative measurements of electric current

Torque measurement

Example application:
Torque measurement using an electrical transducer

Contributed by Jonathan Williams

Purpose of measurement

Torque transducers, based on a strain-sensitive resistance bridge, are routinely used for testing torque wrenches and power tools where control of the applied torque is required. The typical voltage levels from the resistance bridge are in the mV range and need to be measured on the ms timescale to obtain sufficient accuracy on the measurement of the peak applied torque.

What is to be measured

A wide range of torque tools, from basic hand wrenches to power tools.

Appropriate techniques and instruments

NPL recorded example voltage waveforms from a resistance bridge torque sensor when used with a variety of torque application tools. The digital records of the waveforms were analysed using signal processing techniques to establish the voltage and time resolutions required to meet the manufacturer’s desired overall uncertainty specification.

Measurement validity

NPL’s knowledge and expertise were used to help a company bring a new test and measurement product to market.

A specification was required that would guarantee a measurement uncertainty for the expected range of scenarios.

NPL prepared a detailed specification for the electrical measurement unit and the company used this as the basis for the electronic circuit and data analysis software designs. When the first production prototype was available, NPL subjected it to extensive electrical tests, using high accuracy standards and measurement instruments. NPL was able to demonstrate that the target uncertainty specification had been achieved and also verified the company's in-house calibration procedure for units in production.

A challenging specification for the electrical measurement unit required innovation in electronic design to achieve the required performance. National measurement standards were used at NPL to verify the prototype performance and to assure ongoing calibration of measurement units in production.

Measurement saves networks £50 million

Mobile network operators used measurement to optimise new network antennas, saving money and improving energy efficiency in the process.

The background

To support 3G, network operators had to install a new network of antennas, capable of handling higher data volumes and network transmission speeds. By moving from older fixed tilt antennas to new electronically variable tilt models, reliability and access to the network could be improved.

The challenge

There were many different antennas available and it was difficult to evaluate the best option because specifications were set by the manufacturers themselves, rather than by an independent organisation.

The measurement intervention

A variety of 3G clients, including network operators and antenna makers, carried out a series of tests at an independent measurement laboratory. The test results provided full information about how the antennas could be expected to behave, including their gain and directivity.

Mounting each antenna in a specialised test chamber gave accurate and repeatable readings, allowing comparison across the competing products. Manufacturers' measurement uncertainties were found to be typically 5 %, whilst the independent laboratory tests achieved 2 %.

The result

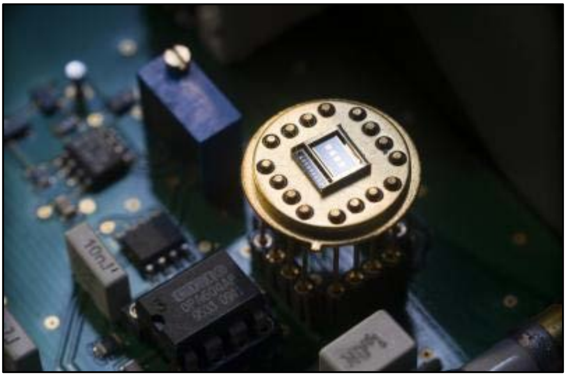
An antenna range, housed in an anechoic chamber, helped network operators such as O2 by providing independent testing services to verify claims made by antenna manufacturers. This helped to ensure that performance data was comparable between products. The calibration data improvements supplied by these specialised measurements could also equate to a 1 % one-off saving in network capital costs and a comparable saving in operational costs for the lifetime of the network. Since each UK 3G network cost £5 billion-£10 billion to establish, the minimal one-off saving was £50 million.

Improved measurement could provide better estimates of key performance parameters by as much as 1 dB. This would lead to substantial efficiency savings through fewer base-stations needed in rural areas, lower masts and less interference between adjacent base-stations in urban areas. Mobile phone networks account for more than 1 % of all UK electricity usage, so improvements in network efficiency would contribute to substantial energy savings (worth approximately £1 million a year).

> *"The upgrade of our network was hugely important. It was also a process that was fraught with challenges. It was important to get it right. Armed with these results, we were able to make well informed decisions about which supplier and product would best fit our needs, and the needs of our customers. We feel the project was a great success."*
>
> **Dave Westrup**
> **Antenna Systems Engineer, O2**

New technique for MEMS power measurement

Researchers developed a new technique to accurately measure the power requirements of micro-electro-mechanical systems (MEMS), delivering a competitive edge to EU companies and supporting large-scale manufacturing excellence.



The background

MEMS are very small devices that can be used both as remotely powered sensors to measure variations in the physical environment such as changes in force, light or motion, and as actuators that convert changes in energy back into motion. They are made up of components that interact with the outside environment such as micro sensors, and a central unit that processes data allows MEMS to make decisions based on the information they receive. Current applications for the devices include use in accelerometers in airbag deployment systems, inkjet printer heads and rotation measurement systems for smartphone displays.

The challenge

A lack of understanding of the potential power requirements and outputs of the devices held back developments, since mechanical components were often embedded in protective packaging, making them hard to access and consequently hindering developers and customers from understanding how best to use the devices.

The measurement intervention

A new experimental set-up was developed to find the mechanical values and properties of any MEMS device through electrical measurement. A current was applied across the device with a varying frequency allowing users to analyse the harmonic content of the output voltage of the component parts and to electrically determine all the mechanical characteristics of the MEMS device, including the damping factor (a negative impact on the amplitude of oscillations), and the frequency that determines the maximum electrical power generation from mechanical vibrations of MEMS transducers.

The result

Several MEMS devices were tested using the technique at Laboratoire national de métrologie et d'essais (LNE) in Paris, and their mechanical resonant frequencies were measured with only a tiny uncertainty. The researchers believe the technique can be used to provide feedback on production methods that will allow manufacturers to design MEMS to the needs of each particular system they operate in. More accurate knowledge of the product output and energy requirements will also affect the choice of device from potential consumers who will now be able to select only those with optimised performance for their particular sector. The technique should help improve performance, functionality and reliability of MEMS around the world.

"Our accurate and traceable technique could be implemented for on-line production tests and measurements. This could deliver a key competitive edge to EU companies and support large-scale manufacturing excellence by introducing metrological principles into industrial processes....It's very easy and quick to make the measurement because all you are doing is connecting your system with two wires, applying a current and sampling the output signal.

This method doesn't require any big investment but still delivers very precise knowledge of the parameters and limits in the performance of your device and could easily be scaled up to measure large-scale energy harvesting technologies across the microscopic and macroscopic scales."

Dr Alexandre Bounouh
Scientist, Laboratoire national de métrologie et d'essais (LNE)

Biomass use in power stations

Bespoke measurement models helped power station operators understand the corrosion effects of burning biomass in coal power stations, whilst saving CO_2 and over £1 million.

The background

Burning biomass alongside coal, which is attractive as a method of mitigating carbon emissions from coal power plants, has operational implications for the so-called 'fireside' of a power plant. This is where combustion and heat cause corrosion to key components.

A bespoke computer model based on specialist measurement knowledge of materials was developed to better understand the effect of burning biomass in boilers that had been intended for burning coal.

The challenge

Corrosion mechanisms when using biomass were not well understood, as the fuel contains a range of gases that can cause novel types of corrosion.

The measurement intervention

Leading-edge knowledge of materials and advanced software techniques were used to create models of materials behaviour in boilers burning biomass.

The models enable biomass to be burned without compromising the boiler's corrosion performance. They do this by enabling adequate material wastage allowances to be specified, helping to optimise component lives and plant availability, and minimising costly plant maintenance.

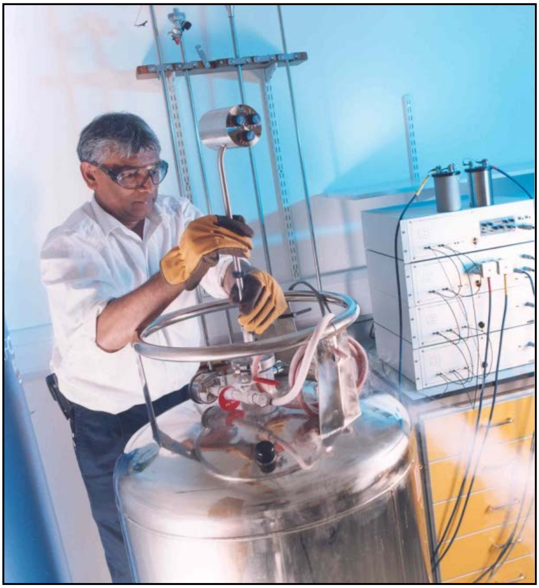
The result

The results gave operators confidence in using biomass in end-of-life coal power stations, bringing forward reductions in CO_2 emissions. In 2011, UK power station operators benefitted from the models' outputs when plans were drawn up to accelerate reductions in carbon emissions by converting two coal power stations to 100 % biomass. The power stations switched to burning imported wood, which enabled a 70 % reduction in the impact of CO_2 emissions compared to coal.

The fireside corrosion models could also be credited with enabling up to 726 000 tonnes of CO_2 emissions savings. They have facilitated the switch to burning biomass and will reduce the probability of plant failures (and highly expensive unplanned downtime), which would cut into the available period of biomass operation before the scheduled closure of the plants. It is estimated that reduced outages will save operators £1.4 million when applied across all plants using this knowledge.

> *"The use of the models in developing maintenance strategies will assist in preventing forced outages of power plants as a result of boiler tube failures. The prevention of even a single tube failure and associated repair outage could save the company in excess of £1 million in lost generation or revenue, this value exceeding the cost to E.ON in participating in the project."*
>
> **Colin Davis**
> **Director of Supply Chain, E.ON**

Comparative measurements of electric current



Researchers developed an electric current instrument to create a primary standard of resistance, enabling innovation.

The background

Accurately measuring electric current is vitally important for a range of applications, from billing people for electricity use and ensuring a stable electricity market, to calculating the right current input for controlling doses of ionising radiation in cancer treatment.

The challenge

Ionising radiation is measured in picoamps, while undersea cables, for example, carry hundreds of amps. Furthermore, some industries measure resistance or voltage rather than current itself and these all need to be related back to the ampere, the SI unit of current.

The measurement intervention

Researchers developed a new electric current instrument that provided the world's most accurate ratio of current. Together with the Quantum Hall effect - a phenomenon whereby electrical properties in 2D materials can be determined based on fundamental constants of nature - the Cryogenic Current Comparator (CCC) allows resistance to be measured to very high accuracy, creating a primary standard of resistance.

It measures in milliamps or ohms, and the CCC related this back to primary standards more simply and more accurately than ever before. It sits in a liquid helium dewar – a thermos flask that holds very cold liquids - keeping it at four kelvin and allowing superconductivity, delivering accuracy and sensitivity.

The CCC is accurate to better than 1 part in 10^{-9}. Using the optically isolated current sources, the resistance bridge can make comparisons between resistors with an accuracy and repeatability of better than 10^{-8}.

The result

The CCC was a significant accuracy upgrade on any previous system and has, for example, provided the most accurate measurements of the electrical impedance of the quantised Hall effect in graphene, which is a key to understanding this material's properties. It is the first digitally driven CCC, meaning set up and measurements are stored on the computer, reducing the chance of error.

This CCC also has another important advantage over previous systems – the dewar uses less liquid helium than other systems. Cryogens such as liquid helium are expensive and must be fed in continuously, so reductions offer a significant financial advantage to scientists.

The CCC can now be used by National Measurement Institutes (NMIs) and laboratories around the world to provide a more accurate standard for current ratio and ensure that current measurement is not a limiting factor in innovation.

> *"The ultimate goal is to go cryogen-free. Cryogenic has pioneered the use of liquid helium-free technology in various areas and we are now extending our know-how and years of experience to CCCs. We expect to play a key role in this important move towards cryogen-free measurement systems.”*
>
> **Jeremy Good**
> **Director, Cryogenic Ltd**

Next steps

To find out more about good measurement practice, visit the NPL website to access online modules and information about training days.

NPL Measurement Good Practice Guides

www.npl.co.uk/publications/guides

No. 4: Calibration and use of EMC Antennas

No. 10: Residual Stress in Polymeric Mouldings

No. 31: Calibration and use of Optical Time Domain Reflectometers (OTDR)

No. 65: The use of GTEM Cells for EMC Measurements

No. 66: Solderability Testing of Surface Mount Components and PCB Pads

No. 68: Good Practice Guide to Phase Noise Measurement

No. 73: Calibration and use of Antennas, focusing on EMC Applications

No. 76: Guidelines for Measuring Anionic Contamination of Printed Circuit Boards (PCB) and Circuit Assemblies (PCA) using Ion Chromatography

No. 120: Avoidance of Corrosion in Plumbing Systems

NPL training

www.npl.co.uk/training/dimensional1

www.npl.co.uk/training/dimensional2

www.npl.co.uk/training/metrologydata

www.npl.co.uk/foundation-metrology-degree

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NPL Good Practice online modules

www.npl.co.uk/publications/good-practice-online-modules/measurement

www.npl.co.uk/publications/good-practice-online-modules/measurement-uncertainty

Further reading

Dietrich, C.F. (1991), *Uncertainty, calibration and probability*, Second Edition (Bristol: Adam Hilger)

EURAMET (2008), Metrology – in short, available at: http://resource.npl.co.uk/international_office/metrologyinshort.pdf

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- 1972 - Coordinated Universal Time (UTC) was adopted as the official time for the world
- 1980s - Improved atomic clocks developed
- 2004 - Caesium fountain clock
- 2011 - NPL's caesium fountain atomic clock (NPL-CsF2)

Today, the second is realised using atomic clocks because they are based on the fundam

IV. Measurement in Practice

1. Principles for successful measurements

2. Defining the measurement uncertainty

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