EMINDA

Electromagnetic Characterisation of Materials for Industrial Applications up to Microwave Frequencies

The Role of Metrological Good Practice

with Particular Reference to RF and Microwave Dielectric Measurements

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Good Practice? Why?

When we are developing measurement systems and carrying out measurements there are many good reasons for adopting practices that can:

- Give us confidence in our measurements
- Allow others to have confidence in our measurements
- Allow us to perform better measurements
- Save long-term time and effort

These are generally our aims when we carry out measurements.

So we should take practical steps to implement measurement practices that can achieve these goals.

Measurements in General

- Beyond the level of simple counting, all measurements are imperfect.

- Whenever we make a measurement, we can usually only determine the quantity that we are measuring to within a range of values.
- The range within which we think the correct value lies is our **Measurement Uncertainty.**

- **Sources of uncertainty (examples):**
    - The limited resolution of our measuring instrument
    - Uncertainty in the calibration of our measuring instrument
    - The departure of the shape of material samples from the shape assumed in our measurement theory.
    - Contamination of specimens.
    - Further difficulties arise when we try to combine the effects from these sources of uncertainty into a **total** uncertainty in our measurement.

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Key Concepts
for Good Measurement Practice

- Repeatability & Consistency
- Reproducibility

- Planning ahead in design.

- Quantification: ‘not just grey scales’.
- Uncertainty and Error - ‘Significance’ - Traceability,
- Instrument Sensitivity
- Are measurements meaningful?

- Software Validation
- Efficacy of Electromagnetic Field Modelling

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Key Concepts (1)

Repeatability: Closeness of the agreement between repeated measurements of the same property under the same conditions.

Good repeatability requires:

- stable, robust instrumentation
- good signal-to-noise
- low drift
- stable working conditions
- design for ease of measurement
- experienced operators …

Questions: What could affect repeatability?

temperature, humidity, vibration, light,
impedance matching of systems, length of leads, etc.

Key Concepts (2)

Reproducibility: Closeness of the agreement between repeated measurements of the same property carried out under changed conditions of measurement

- e.g. *on the same equipment by a different operator* **or** *at a different time* **or** *with a different calibration* **or** by a *different method* … .

- We ***want*** to be able to compare different methods to gain confidence in our measurements.
- Comparisons help us to understand measurement uncertainties.

So:

- Ideally, we should adopt or design measurement systems *that can take dielectric samples that other methods can use.*
- Failing that, we may have to compare samples of different shapes that are expected to have identical measured properties (e.g. complex permittivity).
- In general, think about how reproducibility (the level of agreement) can be quantified.

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Key Concepts (3)

Planning Ahead in Design:

How can we ensure that our instrument is working properly?

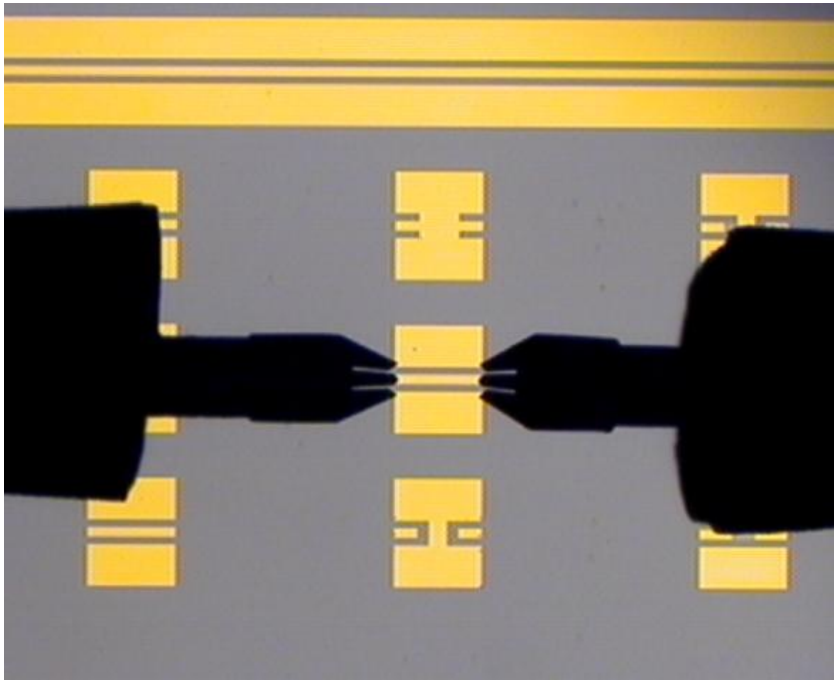
- **Don't** adopt methods that remove opportunities for checking correct operation.
- **Don't** adopt software control (or result delivery) systems that limit opportunities for improved measurement schemes.

  - e.g. Network Analysers that won't output raw measurement data can't be used with improved calibration schemes.
  - Be aware that stable instruments can often work better than their commercial specs, if access to raw measurement data is available.

- Plan ahead to facilitate instrument calibration and reproducibility checking

Planning Ahead: Example

An on-wafer measurement of Co-planar Waveguide (CPW) transmission lines using a probe station



CPW lines like this can be used to measure the dielectric properties of thin films that are deposited between the substrate and the metal CPW line

Can we include calibration structures on the same wafer on which we manufacture the test structures? That is what is shown here

We should be able to get better measurements if we do

Key Concepts (4)

Quantification: 'not just grey scales'.

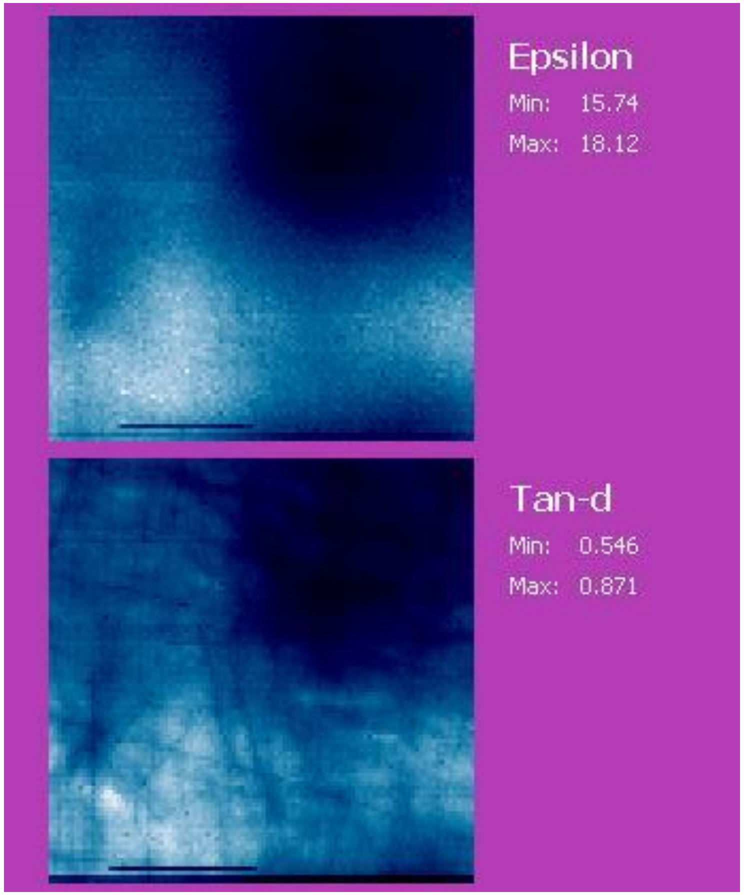
Are measurements meaningful?

If so, just how meaningful are they?

We need to understand:

'Uncertainty'
'Error'
'Significance'
'Traceability'

Scanning Microwave Microscope (SMM) scans of the surface permittivity of an inhomogeneous sample



Estimated values of permittivity (epsilon) and loss tangent (tan-d) shown in a grey-scale plot

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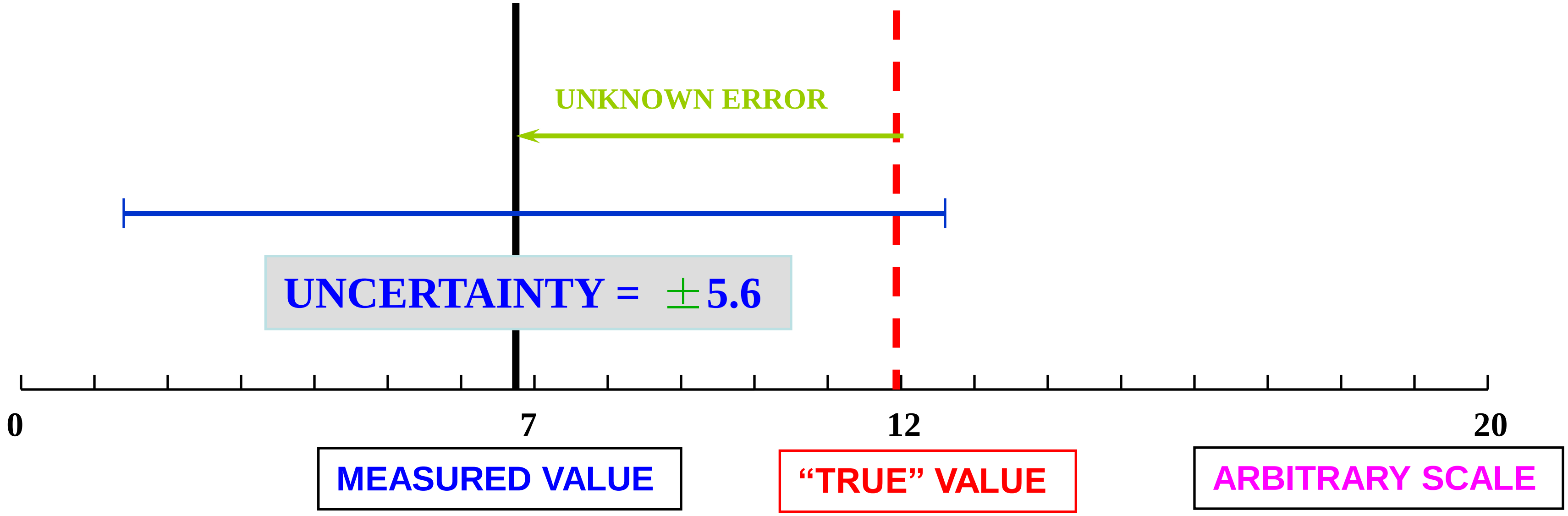
Distinguish Error and Uncertainty

An Error in measurement is an offset or deviation from the correct value (shown as the **green** arrow below)

The Uncertainty of a measurement is our quantified doubt about the result of a measurement (shown as the **blue** bar below)



Assessment of Uncertainty

There is Internationally agreed approach described in the 'GUM':
The Guide to the Expression of Uncertainty in Measurement

ISO/IEC Guide 98:1993: *Guide to the expression of uncertainty in measurement (GUM)*, available from ISO: http://www.iso.org/iso

The total uncertainty in a measurement system is obtained from an analysis and combination of estimates of all of the significant error contributions to the measurement process

What follows is what the textbooks and guides tell you!

(before proceeding to the real world of microwave dielectric measurement!)

Approach to the Assessment of Uncertainty

Two types of error have traditionally been distinguished:

RANDOM ERRORS	SYSTEMATIC ERRORS
Use 'Type A' treatment:	Use 'Type B' treatment:
Our uncertainty about them is estimated (quantified) by statistical methods	Our uncertainty about them has to be estimated (quantified) by "other" means

Systematic errors are caused by biases in measuring instruments.

- The "other" methods used to quantify them include measurement comparisons, or measurement of standard materials and artefacts.

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GUM ‘Type A’ Contributions i.e. random uncertainties
- Mean Value -

When a measurement is repeated under the same conditions the most probable value of the measurand is the arithmetic mean of the individual measured values:

If *n* measurements are made of a quantity *q* the mean value is the sum of the individual values, q_j divided by *n:*

$$\overline{q} = \frac{1}{n}\sum_{j=1}^{j=n} q_j = \frac{q_1 + q_2 + q_3 + \ldots\ldots q_n}{n}$$

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‘Type A’ Contributions – Standard Deviation (1)

The Standard Deviation of a series of measurements, made under the same conditions, is used as a measure of variability of a quantity being measured

For *n* measurements the Experimental Standard Deviation, *s*, is given by:

$$s = \sqrt{\frac{1}{(n-1)}\sum_{j=1}^{j=n}(q_j - \bar{q})^2}$$

The Experimental Variance is defined as s^2

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‘Type A’ Contributions – Standard Deviation (2)

The best estimate of the variation of the mean value is given by the Experimental Standard Deviation of the Mean obtained from:

$$s(\bar{q}) = \frac{s}{\sqrt{n}}$$

The Experimental Standard Deviation of the Mean is the value used as the Standard Uncertainty in a Type A evaluation of data obtained by repeating the measurement under the same conditions:

$$u(x_i) = s(\bar{q})$$

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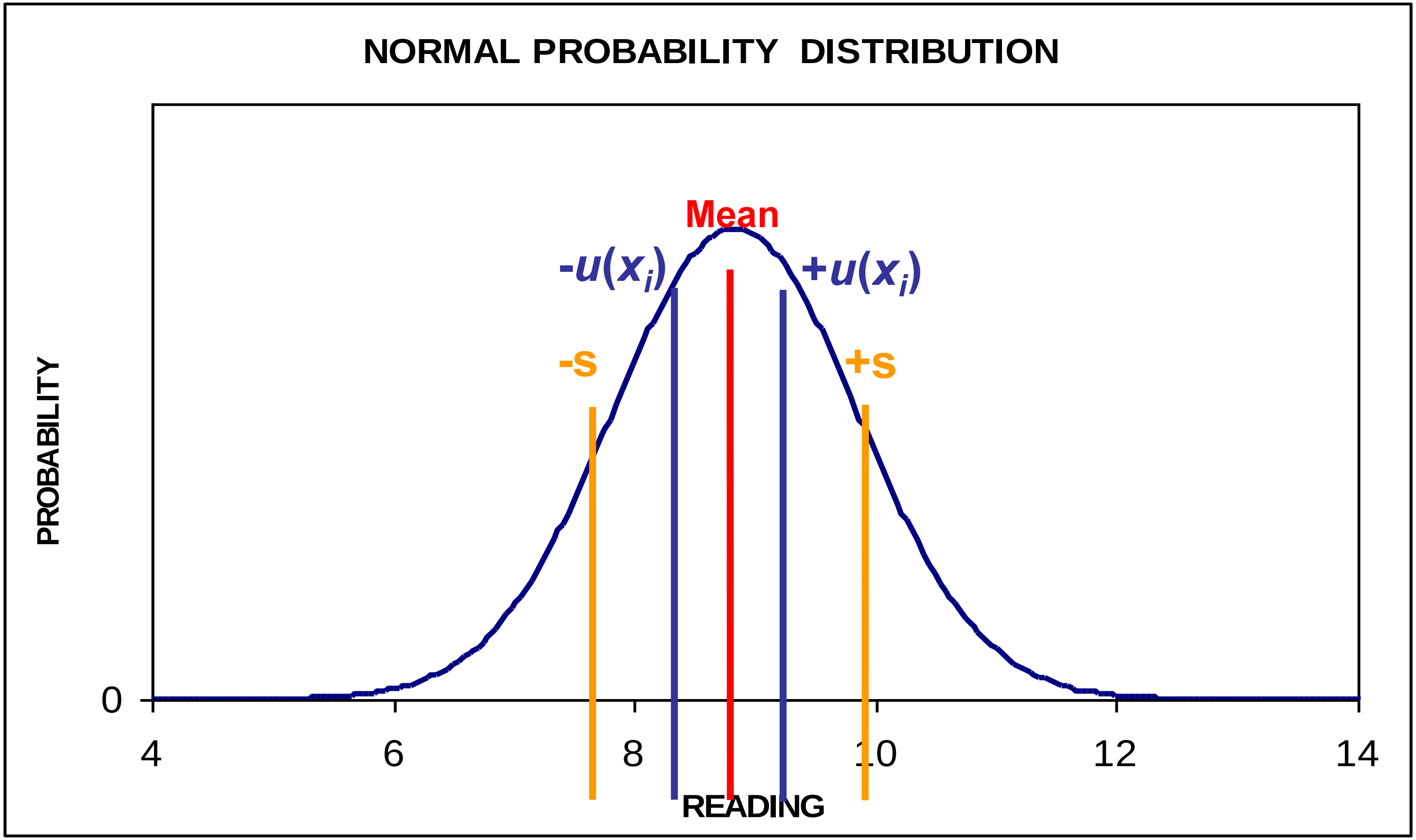
‘Type A’ Contributions – Normal Distribution



Uncertainty ranges shown as follows:

Experimental Std. Deviation shown in orange

Computed Standard Deviation of the Mean shown in blue

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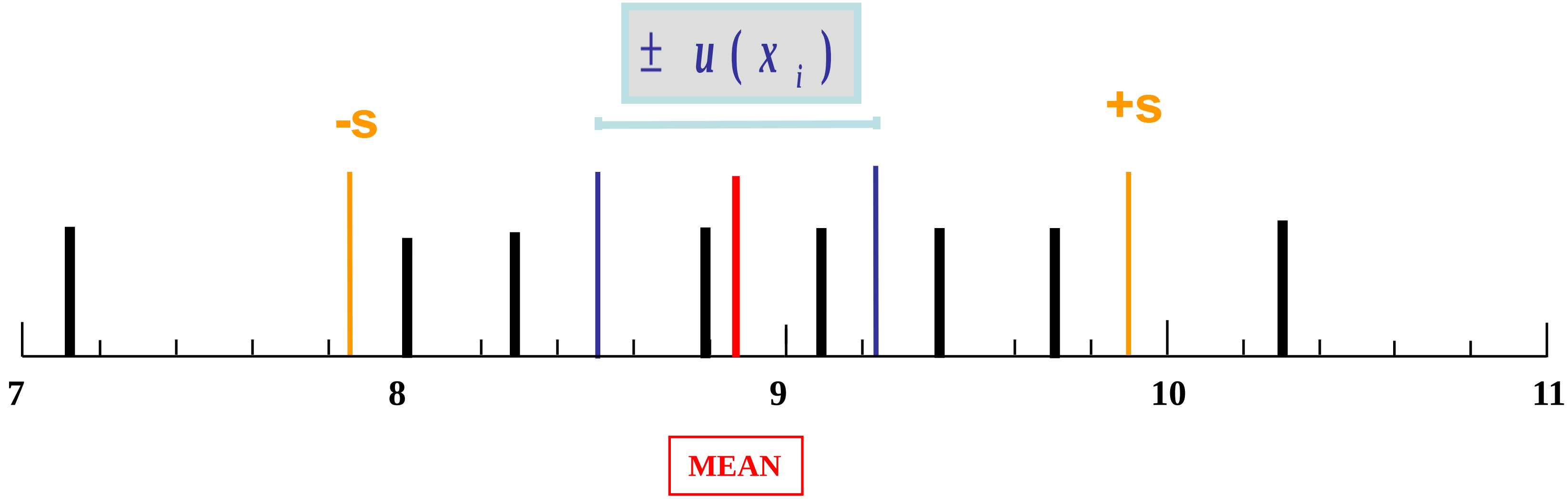
‘Type A’ Contributions – Typical Distribution



Uncertainty ranges shown as follows:

Experimental Std. Deviation shown in orange

Computed Standard Deviation of the Mean shown in blue

GUM ‘Type B’ Contributions

These are not just systematic uncertainties

When methods other than a statistical evaluation of data are required to determine the uncertainty one uses a ‘Type B’ evaluation, which could include the following:

- **Data provided in a calibration certificate**
- **Manufacturer’s specifications**
- **Previously measured results**
- **Uncertainties assigned to reference data taken from handbooks**

- **Properties of an instrument or system**
  - biases >> Systematic Errors

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Key Concepts (5) - Traceability of Measurements

Definitions:

Traceability: The property of a measurement whereby the result can be related to a reference through an unbroken chain of calibrations, each contributing to the measurement uncertainty.

Traceability chain: The sequence of measurement standards and calibrations that is used to relate the measurement result to a reference.

In general, any **"calibrated"** measurement should be connected by a *chain* of calibrations to the standards of the international measurements community.

Strictly speaking a measurement which is not traceable is not much use to anyone else!!

Note that traceable measurements **must** be accompanied by estimated uncertainties

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Table 3: Uncertainty Budget for the Permittivity of the YAG Specimen

Source of Uncertainty	Value ± % (1σ)	Probability Distribution	Divisor	c_i	$u_i(\varepsilon_r)$ ± %	v_i or v_{eff}
Actual Thickness Variation	0.92	Normal	1.0	0.89	0.82	8
Micrometer Reading	9.5E-02	Rectangular	√3	1.5	8.4E-02	∞
Tops of Bumps	⊥				0	∞
Warping of Specimen	⊥				0	∞
Repeatability of Empty SPDR (Frequency)	3.1E-05	Normal	1.0	§	0	0
Reproducibility of Empty SPDR (Frequency)	3.9E-04	Normal	1.0	19	7.4E-03	8
Repeatability with Specimen present (Frequency)	4.5E-05	Normal	1.0	§	0	0
Reproducibility with Specimen present (Frequency)	2.1E-03	Normal	1.0	0.39	8.1E-04	8
Software	*				0	∞
Homogeneity	§				0	∞
Isotropy	§				0	∞
Coupling	∅				0	∞
Temperature	ζ				0	∞
Combined Standard Uncertainty, *u* *(Permittivity)*		Normal			0.82	8
Expanded Uncertainty, U		Normal ($k = 2.37$)			1.9%	8

⊥ This source of uncertainty is not applicable in this particular measurement because its magnitude is insignificant (see Section 4.2)
* Refer to section 4.1
§ Refer to section 4.4
∅ Refer to section 4.5
ζ Measurements were performed in a temperature controlled laboratory over a time period of approximately 20 minutes so temperature uncertainty in this case is negligible (see Case Study 1, Section 3.4 for further details)

All estimated contributions to uncertainty are eventually combined into an **Uncertainty Budget**

as described in the guides

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Uncertainty Statements – Confidence Levels

A statement of uncertainty such as ε´ = 2.31 ± 0.03 ***<u>means nothing</u>*** unless it is associated by a statement of our confidence that the correct value of the measurand lies within the stated uncertainty limits.

Thus, ε´ = 2.31 ± 0.03 (S.D.) implies that the stated limits are the 'standard uncertainty', i.e. they correspond to one standard deviation: there is a 68% probability that the correct values lies within the limits.

or ε´ = 2.31 ± 0.03 (at 95% C.L.) .) implies that the stated limits describe a 95% Confidence Level that the a correct value lies within the limits (i.e. a one-in-20 chance that it might be *outside* those limits).

The Guides and textbooks tell us how to calculate C.L. from the S.D.

At RF & MW it is usually most helpful to work with ~95% C.L.

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Example of a Typical Uncertainty Statement:

Capacitance measurement:

The evaluated value of the capacitance (C) of the measured capacitor structure is **C = 335 fF ± 8 fF**

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with UKAS requirements.

This is all very well but …
Consider what the Textbooks won't tell you!

At RF and Microwave (RF & MW) frequencies and in dielectric measurements **systematic uncertainties are usually dominant**. The estimation and understanding of uncertainties is difficult in general but RF & MW dielectric measurements on materials are particularly fraught with difficulties:

- At microwave frequencies the finite size of components produces phase changes, which lead to errors that are difficult to quantify without EM field modelling of the measurement system (e.g. SMM probe).

- At RF frequencies, lumped impedance 'residuals' arise through unwanted inductances and conduction losses in measurement leads – these are often difficult to quantify.

- The instruments we use often measure complex quantities (e.g. reflection or transmission coefficients) and our ultimate measurand (if it is complex permittivity) is also a complex quantity. *Textbooks on uncertainty say nothing about complex measurands!*

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Return to:

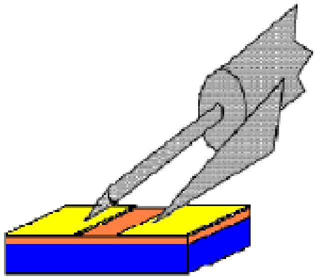
The Significance **of Measurements: i.e.** ***Are they Meaningful?***

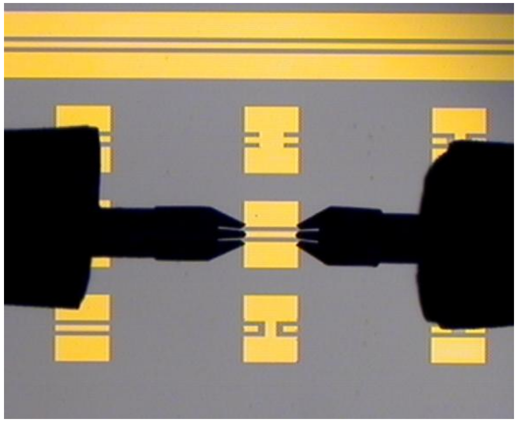
For a published example of the Application of Uncertainty Analysis to R & D

See P K Petrov, N McN Alford and S Gevorgian, 2005, *Techniques for microwave measurements of ferroelectric thin films and their associated error and limitations, Meas. Sci. Technol.* **16,** pp 583-589.

Measurement of Functional thin-films using Coplanar Waveguide & other probe techniques.

Capacitative or travelling-wave transmission measurements





Other approaches to Improving Measurement Confidence
(and getting better measurements)

Null and Substitution Methods:

- Bridge methods
- Compared measured samples with reference materials or artefacts that have known properties close to the sample/artefact being measured: Uncertainties in measured differences in properties are usually lower than the absolute uncertainties.

In **Microwave Measurements**, measure at a range of frequencies and check for consistency.

- Systematic errors in microwave systems usually vary with frequency, so this can be a way of detecting them and estimating their magnitude.

What about Software and Modelling?

- Most metrology these days relies upon computer-based analysis and modelling.

- The rise of *computer-centred* metrology, as opposed to *computer-assisted* metrology, has given birth to **a new major source of error** and uncertainty in our measurements – ***software errors***.

- How do we know that our software is giving us the correct results that we need?

- How do we *check and validate* metrological software?

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Software Validation

We can check the valid operation of modelling software for measurement systems in a number of ways:

- Use it to model geometries that are analytically calculable, i.e. simple geometries, before applying it to the geometry of our system.
- Compare it with other independent models of the same system
- Use it to model the measurement system when it measures known materials or devices
- Feed a wide range of artificial input data into it to see if it trips up e.g. by giving obviously erroneous results.

In some ways these checks are similar to our checks on our measurement hardware.

- Uncertainties should be assigned to the ability of our modelling software to model our measurement geometry.

In General:

Our best tools for gaining confidence in difficult measurements in the fields of:

- RF & Microwave measurements
- Dielectric Material measurements
- Nanoscale measurements

are:

- Reference materials
- Reference devices & artefacts
- Measurement comparisons with other techniques
- Null and substitution methods (but these are rarely possible in fast automated measurements)

Metrology Good Practice Guides:

On Uncertainties, Traceability, etc:

ISO/IEC Guide 98:1993: *Guide to the expression of uncertainty in measurement (GUM)*, available from ISO: http://www.iso.org/iso

A Beginner's Guide to Uncertainty of Measurement, Stephanie Bell, available from the NPL web-site: http://www.npl.co.uk

On Microwave Dielectrics:

NPL Good Practice Guide, *A Guide to the Characterisation of Dielectric Materials at RF and Microwave Frequencies*, R N Clarke, editor, published by the Institute of Measurement and Control and NPL, 2003, available from the NPL web-site: http://www.npl.co.uk

Other guides are available from the web-sites of BIPM (*Bureau International des Poids et Mesures*) http://www.bipm.org/ and National Measurement Institutes.

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