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The cover design depicts the microwave planar near-field scanner being developed at NPL.

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An Overview of Basic Electrical Metrology

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Two decades of struggle with both fundamental electrical measurements and more mundane calibrations have reinforced the notion that some basic principles ought always to be applied, no matter how simple the measurement or modest the accuracy claimed.

Defining conditions.

All successful measurements start from the defining conditions that specify the measurand. It is often found that once these defining conditions have been properly set out, an apparatus to fulfil them (or conditions equivalent to them) will design itself. For example, in AC impedance comparison tight 'terminal-pair' electrical defining conditions lead directly to an appropriate coaxial bridge network (1).

Type B or 'systematic' errors can be viewed as being a direct result of insufficient or inappropriate definition of the measurand or the failure of the measuring method to conform to the defining conditions. This viewpoint emphasises even more strongly the crucial role played by defining conditions in the measurement act.

Designing a new measurement apparatus.

Experience indicates that whenever greater accuracy is sought the design of the new apparatus should be simpler and closer to first principles. By adopting this approach, not only is the measurement more elegant but there will be fewer places for type B (systematic) errors to hide. This desirable simplicity at the heart of the apparatus is often only made possible by peripheral complex modern instruments and control of real-time data acquisition using computers.

The design of a measuring apparatus is akin to an engineered structure in that it is often good practice to make sure that no element is called upon to serve more than one function, lest there be a conflict of interests. A trivial example might be the provision of separate current and potential terminals for an impedance standard.

Freedom of substitution measurements from type B errors.

If one measurand is substituted for another in a measuring apparatus capable of registering accurately any small difference between them, and if no aspect of the apparatus is significantly altered by the substitution ("it has no way of knowing that the substitution has been made"), the measurement will be free of type B errors. Therefore if they are practicable, substitution measurement methods are always to be preferred. There is still a small risk that the interpolation mechanism used to measure the difference between the measurands might introduce type B errors.

Macro- and micro- linearity of instruments.

All that is required for most kinds of measuring apparatus to be accurate is that they read correctly two very different inputs and that the output reading is linear with input. The verification of the macro-linearity of a measuring instrument is usually not difficult. Consider setting up a scale of mass. Starting with a defined 1kg, one could prepare two equal 0.5kg masses which together equal the 1kg. By iterating this process, accurate 0.25, 0.125 ... masses would be obtained. Since there is experimental evidence that weight is linearly additive, the binary weight-box thus obtained will form an accurate, linear set for weighing any object with a resolution equal to the fineness of the subdivision. A similar process is applicable to all macro-linearity investigations. Proving the accuracy of a digital voltmeter for example might well involve using it to measure combinations of potentials across resistors in series.

On the other hand to be confident that the linear relationship holds on a microscopic scale between the discrete values at the limit of the subdivision process, it is necessary to ascertain from a detailed knowledge of the workings of the measuring instrument that its response is a continuous and smooth function of measurand values over all possible values of the output. Ideally, this would be inferred from a physical property akin to that of magnetic or electric fields whereby they smooth themselves out in regions remote from sources or boundaries. Problems arise in many digital instruments in this regard because small step-function changes in reading occur as the instrument changes its working range automatically, and sometimes imperceptibly. Sometimes also an interpolation mechanism is used between major scale points which does not perfectly match the interval between them.

The three stages in commissioning a new apparatus.

- 1) A few days are spent making modifications and adjustments until the apparatus attains the desired resolution.
- 2) The next few weeks work involves climbing the learning curve until the results obtained are sufficiently reproducible.
- 3) And finally, anything up to several years are needed to make sure that the correct result - i.e. that which conforms to the defining conditions of the measurand - is being obtained.

It is sometimes supposed that stage 2) is sufficient for some measurements which happen not to interact significantly with other parts of the measurement system. But even here, a moment's thought shows that the only way to ensure compatibility between different metrologists using their own apparatus, in maybe different countries, is to demand that each obtain the unique correct result.

A major part of a metrologist's training is therefore to acquire the patience and persistence needed to continue until stage 3 has been completed. But what are the criteria for judging when to stop? Agreement of the result with one obtained by another metrologist, even if he is using a different measurement principle, is not sufficient. Instances abound where a prestigious metrologist has, despite his best efforts, obtained a slightly incorrect result, and those who follow have investigated type B errors only until their results agree with his - a process sometimes known as intellectual phase-locking. This state of affairs can persist until a new measurement method is evolved which has much better reproducibility. Then the greater ease with which small type B errors can be investigated often enables the error to be

uncovered.

The correct way to tackle this pernicious phase-locking problem is to cultivate the metrologist's suspicious mind, and believe that all results are wrong until proved right. A proof consists in making linearity tests and small changes and misadjustments of the apparatus of every conceivable relevant kind. Only then, if either the results of making these tests and changes can be shown to be immaterial, or they can be fully accounted and corrected for, should it be permissible to think that the result might possibly be correct after all.

Interference elimination.

This is important, not only because increased resolution demanding better signal-to-noise ratios is sought for all electrical measurements, but because the legions of semiconductor junctions in modern instrumentation can rectify interference to produce type B errors. Elimination is a matter of finding a topology of the measuring circuit which conforms to certain simple fundamental principles (2).

Treatment of errors.

These remarks are principally an appeal to commonsense. Often in electrical standards work, Type A errors which are amenable to statistical evaluation, are insignificant compared with Type B errors due to inadequate defining conditions, or errors in the presumed value of the standards which are the starting-point of the measurement, or even mistakes. Mistakes are likely to be discovered only if their magnitude is greater than the standard deviation of a single observation. Statistical analysis in these circumstances does not have any special status, it is a tool like many others to help arrive at an error estimate.

Communication of results.

All our measurements, calibrations and the apparatus used to make them become valueless with the passage of time. The only thing of permanence is the distilled knowledge gained. Therefore preserving this information and communicating it via published papers, internal reports and the grapevine is not a luxury - it is a duty.

References.

- 1) B.P.Kibble and G.H.Rayner. Coaxial AC Bridges. IOP Publishing, 1984.
- 2) B.P.Kibble and I.A.Robinson. Guidance on eliminating interference from sensitive electrical measuring circuits. NPL Report DES in preparation.