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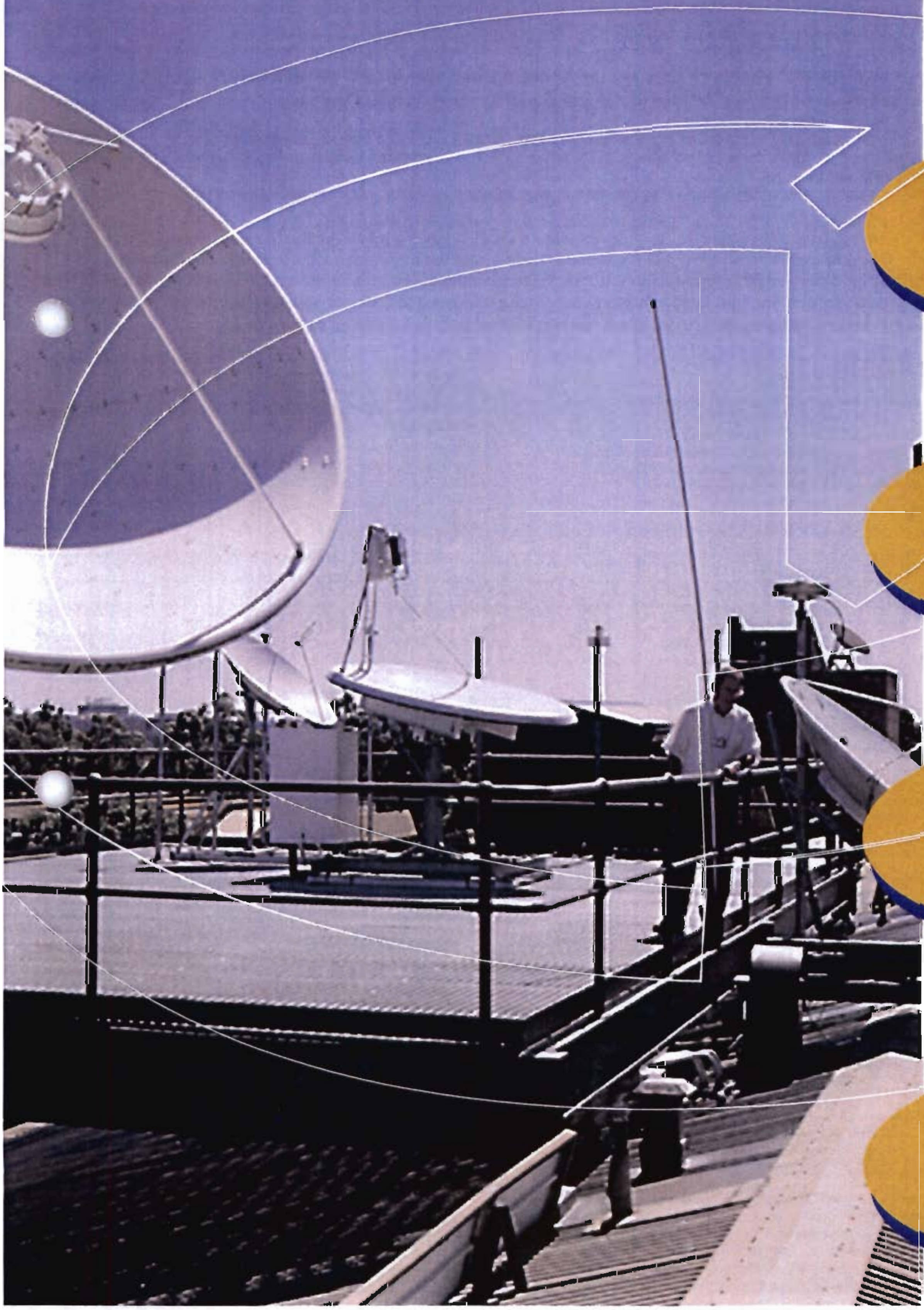

The Value of History

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The Kilogram in the News

Uncertainty Components from Expert Judgement

From the Editor

This is the first "home-grown" issue of TAM in the new format - the last one being produced professionally (and using different software). There have been a number of technical issues to overcome, which will be no doubt improved with each issue. The delay in the production of TAM 30 has been mainly due to coming to grips with the unexpected!

We had a carry over of articles from the last issue, but our store is now exhausted! Please consider making a contribution to the next issue, which I'd like to produce in September. Another possible area is the reprinting of suitable articles from other publications - your suggestions are welcome.

I received two articles dealing with the kilogram mass standard and decided to print them both - the subject has become the focus of the popular press which cannot be a bad thing.

Your attention is drawn to the Call for Papers for MSA 2004 to be held early next year.

- Maurie Hooper

Cover photo: The antenna deck on the roof of NML's Lindfield laboratory. These antennas, operated by the Standards for Time and Frequency Section, are for high accuracy comparisons between NML's atomic time and frequency reference, and atomic references operated in laboratories throughout Australia and the Asia Pacific Region. It is through these international comparison links that traceability to the international time scale, Co-ordinated Universal Time (UTC), is maintained.

The Australian Metrologist

The Australian Metrologist is published four times per year by the Metrology Society of Australia Inc., an Association representing the interests of metrologists of all disciplines throughout Australia. Membership is available to all appropriately qualified and experienced individuals. Associate membership is also available.

Contributions

Articles, news, papers and letters, either via e-mail, disk or hard copy, should be sent to:

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The deadline for the next issue is 16th August 2003.

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If you have a position vacant, write or e-mail the Editor with the details. A charge of $20 for up to 10 lines applies. (The circulation may be small but it is well targeted.)

The deadline for positions wanted/vacant is as above.

Letters to the Editor

Letters should normally be limited to about 200 words. Writers will be contacted if significant editorial changes are considered necessary.

Editorial Policy

The Editor welcomes all material relevant to the practice of Metrology. Non-original material submitted must identify the source and contact details of the author and publisher. The editor reserves the right to refuse material that may compromise the Metrology Society of Australia. Contributors may be contacted regarding verification of material.

Editor: Maurie Hooper

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Contact the TAM editor for further details.

Please note: **Camera ready artwork is to be supplied. Size and specifications are available from the editor. If extra typesetting etc is required an extra charge will apply. MSA members receive a 10% discount when they place advertisements in TAM.**

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Contact either your State Coordinators or the Secretary, Dr. Ilya Budovsky on (02) 9413 7201 or fax (02) 9413 7202, e-mail address Ilya.Budovsky@csiro.au or write to:

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President's Report - July 2003

This year seems to be flying by, here we are it is July, a new financial year the AGM looming and plans for the conference next year well under way. It seems only a few short while ago I visited NML to discuss Knowledge Transfer, The Australian Measurement System and MSA as part of an international review for the UK government.

The UK government has an ongoing programme to develop new measurement technologies and the transfer of these technologies and skills to the UK industrial base. As part of this they have commissioned a study of the measurement infrastructure of five countries (Australia, Canada, Germany, Sweden and USA) around the world to determine best practice in the transfer of knowledge from national measurement laboratories to industry. I was fortunate enough to have the opportunity earlier this year to go to NML and represent the MSA at a focus group on Australia's knowledge and technology transfer. The meeting had representatives from NML, NATA, NSC, Defence and the MSA.

While a significant proportion of the discussion centred on collaborations on specific programs between NML and industry, there was also a healthy discussion of the roles of the NSC and NATA in supporting the measurement system. The pleasure for me was to realise what an impact the MSA has had in its short life. It was clear throughout the discussion that the MSA has facilitated knowledge and technology transfer via both formal and informal channels. Among the runs on the board was the contribution the Keane Report, the Graduate Diploma that Swinburne runs, the bi-annual conferences that provides formal and informal communication paths, the state organisations and TAM. One of the unique aspects of Australia that became apparent was the need for a society like ours, given our geographic isolation in the world as an industry and as individuals our isolation within the country. It was apparent that while NML, NATA and NSC have been strong supporters of the society over the years both financially and in kind, it has not a one-way street.

The Metrology Society fulfils a unique and important role in the metrology infrastructure of Australia by providing for a healthy debate in a rapidly changing economic and cultural environment. We provide the "metrology heavyweights" (NML, NATA and NSC) with direct and effective access to the "shop floor" for the transfer of knowledge and by giving all metrologists an effective and respected forum to articulate their view of what the future of metrology in this country should and could be. If you like, the society is the neutral ground that connects the different component of the measurement system, from bench metrologist though the research and education sectors to government.

My reading of the response of the facilitator was that this was a unique model, at least among the countries studied. I also gained the impression that the contribution of the MSA was valued by the other components of the measurement system. We, as a society, can take a deep breath and pat ourselves the back. There may be things that we wish we did better, different or more often – and that are good, as this will drive us on. But we should also take stock of the achievements a relatively small group of volunteer people have achieved in an even shorter time frame. A lot of people have over the ten or so years contributed to the success so far, and I thank them for that, and I look forward to many more people furthering the success of the society in the coming years.

MSA 2004

This is another of many reminders about the conference next year that you will be getting over the comings weeks and months. The first call for papers is a part of this edition of the TAM. Abstracts need to be in by the end of August so get that thinking cap and typing fingers going. The conference can only be as good as the contributions you make! Forward them to the MSA Secretary c/o CSIRO NML Bradfield Road Lindfield, NSW 2070 or email to conference@metrology.asn.au marked MSA 2004 abstract. If you have any queries contact Steve Jenkins at sej@stevejenkins.com.au.

I hope you enjoy this edition of TAM. I will remind you that the AGM is coming soon and would encourage you to thinking about putting your hand forward to join the National Committee. It is a great way to move the Society forward and contribute in a broader manner to metrology. Think about and contact any member of the current committee if you are curious about what being on the committee involves. And if you feel that what is happening now is not good enough or we are not travelling in the right direction, join the committee and help us steer a better course!

- Dr Jane Warne

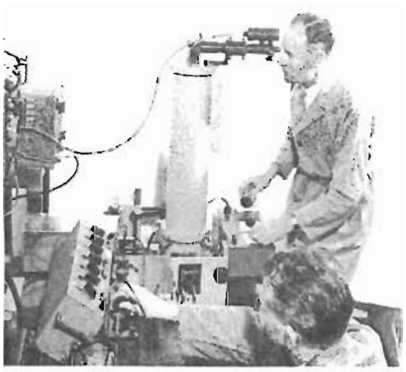
Contents

The Value of History

Philip E Ciddor
Honorary Fellow
CSIRO National Measurement Laboratory, Sydney

NML has an excellent international reputation in electrical metrology, founded on leading-edge research conducted from 1950 to 1970 into the establishment of fundamental standards for electrical quantities, and augmented by later contributions in ac electrical metrology and rf and microwave measurement.

The legacy of the work on fundamental standards provides value today, not only to NML but to metrologists from other national laboratories. In November 2002, Dr Yicheng Wang who is responsible for impedance standards at the National Institute of Standards and Technology, USA, visited NML for discussions with Greig Small, Peter Coogan and John Fiander. Dr Wang commented that he chose to visit the NML group because, internationally, it is one of the few repositories of a fundamental understanding of impedance standards. So how did this reputation arise?



Hugh Bairnsfather and Keith Clothier conducting measurements using NML's calculable capacitor.

If I have seen further it is by standing on the shoulders of giants.
Isaac Newton ***(1642 - 1727), Letter to Robert Hooke, February 5, 1675***

For about twenty years from 1968 the standard of resistance, the ohm, maintained at the BIPM in Paris, was monitored solely by NML in terms of the SI definition. The development of the required instrumentation was a striking example of the benefits of combining NML's expertise in several fields: electrical theory and measurements, mechanical engineering, and optical metrology. It also involved a very surprising theoretical discovery.

Until the 1950s, the accepted method of establishing a standard of impedance or realising the ohm started with the calculated inductance of a coil; this required the measurement of many dimensions of the coil. In the 1950s at NML, Keith Clothier was pursuing an alternative scheme that started with a parallel-plate capacitor whose value could be calculated from a single dimension. Mel Thompson was investigating other designs based on the cross-capacitances between sections of the internal surface of a cylinder of known length.

A new fundamental standard for capacitance – the calculable capacitor

The theory of electrostatics was one of the triumphs of 18th and 19th century physics, and was generally considered complete. It was therefore a considerable surprise when Thompson and Douglas Lampard announced a new theorem. They had considered a series of designs based on a cluster of parallel metal bars and found, to their surprise, that the particular shape of the structure had only a very small effect on the capacitance for a given length. They were able to establish a precise theory of this result, now known as the Thompson-Lampard Theorem. This approach w[as] adopted instead of Clothier's original design. Careful experimentation on test models by Clothier and Hugh Bairnsfather led to the establishment of design tolerances that would produce a capacitance of small, but useful, size (about 1/6 pF). The precise value would be controlled by moving a single electrode through a distance that was measured by an optical interferometer. The light source for the interferometer was originally a mercury-198 discharge lamp, and later a stabilized helium-neon laser.

Malcolm McGregor subsequently assisted the US National Bureau of Standards in building a similar calculable capacitor, and other laboratories adopted similar designs. However, the NML implementation, with its associated electrical measurement system, was judged to be the be[st] suited for use as an international working stand-ard.

Building the chain from capacitance to a 1 W dc resistance standard

A complex series of comparisons with successively larger transfer standard capacitors yielded the impedance of a 5000 pF capacitor, which was compared to the ac resistance of a 10 kW resistor. Dennis Gibbings transferred this to a dc value by theoretical calculations from the geometry of the resistor and extrapolation of its resistance-frequency curve to zero frequency. Bob Richardson then compared the dc resistance to a 1 W resistor, which constituted the laboratory's working standard.

The link between 10 kW dc and 1 W dc

This last comparison relied on the invention by Bruce Hamon of a 'build-up resistor', which allowed a single-step comparison between 4-terminal resistors differing in value by a factor of 100. Initially two stages were involved – from 10 kW to 100 W, and 100 W to 1 W. Later a single build-up resistor with 100 resistors of 100 W provided a direct transfer over the ratio of 10^4 to 1. Hamon's invention, which had the additional desirable feature that the dissipation in each resistor was the same in series and parallel connections, has been widely adopted in precise electrical measurements. Its success was dependent on extraordinarily skillful construction work and electronic developments by those mentioned above, and many others.

...at accuracies of a part in ten million

Because of the substantial number of steps involved in the transfer from the calculable capacitor to the 1 W dc standard, extremely high accuracy was required at every stage. It is evidence of the quality of this work that until 1983, one of the dominant sources of uncertainty was the speed of light, which is needed to calculate the capacitance of the basic capacitor in SI units. With the adoption in 1983 of a defined value for the speed of light, this component of uncertainty was removed, and the overall uncertainty of the 1 W standard was reduced to about 1 part in ten million.

... and adopting advances in technology

The NML calculable capacitor has been continually refined by Greig Small and Peter Coogan as new optical and electronic techniques became available, and NML is now collaborating with the BIPM in the design of an entirely new version.

... to provide the benchmark for new directions

Today, there are other ways of maintaining the ohm using the Quantised Hall effect in semiconductors* but the new techniques still rely on periodic comparison with the fundamental realisation obtained from the calculable capacitor to establish their absolute values.

* See NML"s website at http:/ www.nml.csiro.au/ResearchDevelopment/ R&Dimped.htm#acQHR ■

Miniature machine plugs metrology gap

Richard Leach

Centre for Basic, Thermal and Length Metrology, National Physical Laboratory, Teddington, UK

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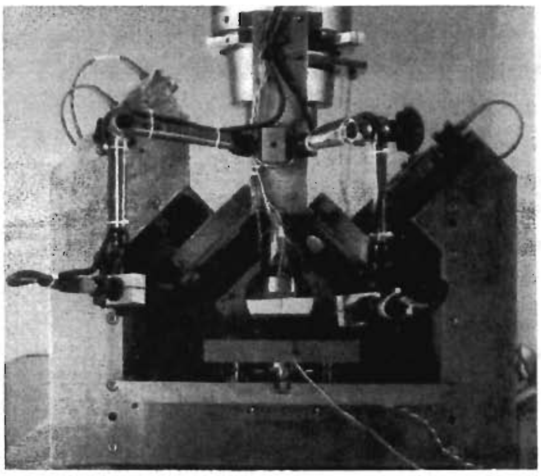
A new metrological device promises to speed the development of micromachines.

Micro-scale machines are becoming increasingly ortant across a wide range of industrial applications, including digital projectors containing millions of micromirrors and micro-scale motion sensors that sit in cars ready to deploy airbags. Many other examples of microsystems technology promise to have a major impact on our daily lives, such as palm-sized high-definition displays and grain-sized implantable medical devices. But these components will only work well if they are built with micrometre-level accuracy

As with macro-scale engineering and production, the key to successful manufacturing of micro-scale devices and products is proper process control. Without this control, the fraction of useable devices will be low and failure modes will be poorly understood, leading to costly modifications and slow acceptance of the devices. Metrology is fundamental to understanding and controlling production processes at the micrometre level. But while the metrology and standards infrastructure exists for traditional manufacturing industries, the need for traceable metrology of micro-scale components and devices has not been given the attention it deserves.

One example where improved metrology would be highly beneficial is in the commercial production of high-accuracy pressure-measuring instruments. Druck Holdings, for instance, uses micromachined



Mind the gap - the miniature coordinate-measuring machine that has been developed at the National Physical Laboratory.

continued on page 14

Correlations in Radiometry

Jim Gardner
CSIRO National Measurement Laboratory, Sydney

The key reference for handling uncertainties in modern metrology is the ISO Guide to the Expression of Uncertainty in Measurement (GUM). Most of you will be familiar with its prime equation,

$$u^2(y)=\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)+\sum_{i=1}^{N}\sum_{j\neq i=1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i,x_j)$$

This is an expression for determining the uncertainty in a quantity y formed by combining other quantities x_i whose uncertainties have been measured or estimated. The function f defines the combination relationship and the derivatives are the sensitivity coefficients (of the result on the measured quantities). The second sum term takes correlations between the measured quantities into account. In many fields, the correlation term can be safely discarded, leading to the familiar "sum-of-squares" rule for combining uncertainties.

Correlated quantities are those that vary together, because some underlying quantity is common to both. This might be the calibration factor for a DVM which flows through to resistance measurements that are combined with voltage measurements in determining some quantity, or it might be the mass of a common reference against which other masses added to build a larger mass are compared. If the underlying quantity changes, then all related quantities change. These changes may be positive or negative with respect to the underlying quantity, and the relative effects may be different. Similarly the sensitivity coefficients in the combination may be of different magnitudes and signs, so correlations can become complex.

The effects of correlations can often be removed by rewriting the form of the combination. For example, the ratio of two current measurements made with the same meter on the same range is independent of the calibration factor of the meter and the ratio reduces to that of the readings. Most metrologists are able to then safely ignore the effects of correlations, although this often leads to some false conclusions. A common one is that by making repeat measurements, we reduce the uncertainty through the sum-of-squares rule – this is only true if the repeats are random, but in fact the systematic errors often dominate in a measurement; uncertainty for these is not reduced by repeating the measurement.

Correlations are only important in estimating uncertainties when different quantities are combined. Combinations are common in the field of radiometry, largely because we determine quantities such as responsivity or irradiance at different wavelengths, then combine these for broad-band effects such as photometric response, colour quantities, integrated irradiance, filtered detector response, etc. Further, establishing the primary spectral references at all wavelengths is prohibitive in terms of time, and it is common to use interpolation or fitting processes to fill in the spectrum, which in turn introduces correlations in the primary spectral standards themselves.

Over the last decade, radiometric measurements for visible and near visible wavelengths have been improved by nearly two orders of magnitude through the introduction of the cryogenic radiometer, an electrical substitution device where cooling with liquid helium has greatly improved the equivalence between electrical and optical heating of a cavity absorber. Most laboratories, including NML, now trace their primary references to such devices. As a consequence of the increased accuracy, along with transfer through highly stable silicon photodiodes, systematic effects, previously masked by the dominant uncertainty of the primary power measurements, are now more important. It is then necessary to propagate uncertainties through the measurement process in a much more rigorous way than previously applied. This in turn means that correlations between spectral quantities at pairs of wavelengths have to be propagated through the measurement process.

In a typical traceability chain, measurements are made of the responsivity of a silicon photodiode (or usually a series of photodiodes assembled in a trap formation that absorbs most of the incident light) at a limited number of laser wavelengths. From these measurements and supplementary measurements of the trap transmission or reflection, we deduce the quantum defect, or departure from ideal behaviour, of the silicon of the photodiodes. This in turn is modelled, either with a simple form representing recombination loss in the silicon layers (4 parameters, used at NIST and elsewhere), or an empirical model reproducing the shape of the data. NML use a 2-parameter form of the latter, with our results shown in fig. 1. The independent parameter is the absorption coefficient of silicon, which determines the depth of penetration through the junction region.

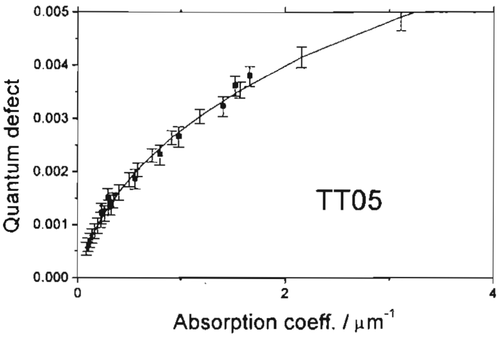


Fig. 1. Quantum defect for the NML primary reference detector. Solid points are measured values and uncertainties. The line is a functional fit to those, with uncertainties propagated through the fitting process.

The fit parameters are correlated, because they all depend on a common set of input data. The fitting process is a little different from that conventionally used to represent data (Bevington, *Data Reduction and Error Analysis for the Physical Sciences* is still an excellent reference for this process), because we know the uncertainties of the input points. We can then propagate the uncertainties through the fitting process – this is just application of the GUM equation through the mathematics of fitting, from which the sensitivity coefficients for the dependence of the parameters on the input measured values are determined. Most fitting methods make the assumption that the relative uncertainty in the input parameters is constant and in fact estimated from chi-squared, the "goodness of fit" parameter. Further, most methods assume the input points are uncorrelated. In fact this is not true, as there are common systematic components across all data points. For the data fitted here, the correlation coefficient between each pair of input values is about 0.35. Proper fitting takes this correlation into account. (See for example W. Woeger, *Uncertainties in models with more than one output quantity*, CIE Proceedings of the CIE Expert Symposium 2001, CIE Vienna 2001 pp12-1. A similar process is used of course in the analysis of the best estimates of the fundamental physical constants). Taking the correlations into account doesn't make a large difference to the values of the parameters, but it can greatly affect the correlation between them, and hence change both uncertainties and correlations for calculated values.

The fitting process has two outcomes. We can propagate uncertainties from the input points, yielding the "true error" – that which would be achieved for repeat sets of input points. However, the function we fit may not properly represent the data. The "goodness of fit" parameter, chi-squared, is then large. We allow for the lack-of-fit error by including the value of chi-squared, properly dimensioned, in the propagated uncertainty. The propagated uncertainty is that formed from the uncertainties and covariances of the parameters (both outcomes of the fitting process), through the GUM equation. We can then propagate uncertainties in responsivity of our trap detector at a given wavelength, and the covariance between responsivity values at any pair of wavelengths, using the variances and covariances of the fitted parameters. This calculation can be made at any wavelength in the range where we trust our fitting function, and it is typical to generate values at the order of 100 wavelengths in the visible range. At this stage it is easiest to recast the GUM equation in the matrix form

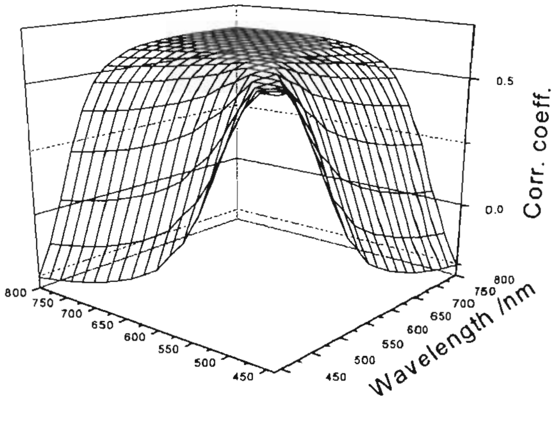
$$u^2(y) = \mathbf{f}_x{}^{\mathbf{T}}\mathbf{U}_x\mathbf{f}_x$$

where vectors **f** contain the sensitivity coefficients, and **U** is the uncertainty matrix, consisting of squares of uncertainty (i.e. variance) in the diagonal elements, and covariances in the off-diagonal elements. This form is particularly useful as the covariance between two calculated responsivity values at any pair of wavelengths is given by

$$u(y_1, y_2) = \mathbf{f}^1{}_x{}^{\mathbf{T}}\mathbf{U}_x\mathbf{f}^2{}_x$$

where $\mathbf{f}^1$ is evaluated at wavelength 1 and $\mathbf{f}^2$ is evaluated at wavelength 2. The surface of correlation coefficients for pairs of different wavelengths throughout the visible range are shown in fig. 2. Responsivity values at nearby wavelengths are strongly and positively correlated. As the wavelength separation is increased, the correlation decreases and in fact may become negative. This same behaviour is seen for both the NIST and NML methods. Now we have reference spectral responsivity values and complete uncertainties throughout the visible range, and we can determine the spectral responsivity of any other detector by a comparison process. This process adds uncertainty, possibly correlated depending on systematic errors in the transfer process, but we can propagate covariances through the transfer by adding relative covariances, just as we add relative variances for uncorrelated measurements.

Fig. 2. Surface of correlation coefficients for the NML reference detector through the visible range, for pairs of different wavelengths.



Filtered detectors are used to determine the temperature of a blackbody radiator, either through ratio measurements (as at NML) or a direct determination of irradiance (as at the US national laboratory, NIST). In the NIST process, the photocurrent produced by a filtered detector is given by an expression of the form

$$i = k\sum S_n \mathrm{L}_n(T)$$

where S_n is the spectral responsivity of the detector at the nth wavelength, $\mathbf{L}_n(T)$ is the Planck function for the radiance of a blackbody at temperature T, and k is a term containing some geometric terms (aperture areas and distances) and the emissivity of the blackbody. The photocurrent depends on individual measurements of spectral responsivity. Using implicit differentiation, we can obtain sensitivity coefficients for the dependence of the temperature of the black body on each of the spectral responsivity values represented in the sum and so propagate the temperature uncertainty. As these are not fully correlated, the uncertainty in the temperature is reduced from that which would be estimated from a single wavelength, although because they are correlated, the reduction is not as large as that predicted by a "sum-of-squares" calculation. In the case of NIST, the uncertainty in the temperature is of order 65 mK, compared to approx. 150 mK previously estimated.

Given the temperature of the black body, we now calculate reference values for spectral irradiance at any wavelength in the range, noting that these values are fully correlated because they depend on the single value of temperature. Transfer to working standards produces some decrease in correlation as the uncertainty increases through an uncorrelated process. A major component in quoted uncertainties for a client artifact is that due to drift with use. This is an ageing process that effectively changes the temperature of the lamp and final values of the spectral are highly correlated.

Interpolation processes are commonly used in spectral radiometry. These also produce correlations, as interpolated values depending on a common set of input values will be correlated. Interpolation is just a mathematical process for which sensitivity coefficients of output vs. input can be determined, and hence uncertainties propagated through the GUM equation. An interesting point arises here. If we treat the measured values as the entire set of knowledge and the correlation between them is small, the uncertainty of an interpolated point is less than that of the input points because the effective number of measurements is greater. However when we include the introduced correlations, uncertainties propagated through combinations of the input set are the same as those propagated through the interpolated set (for details, see J Gardner, *Uncertainties in interpolated spectral data*, NIST J. Research, **108**, 69-78 (2003)). On the other hand, if we expend the effort to make measurements at the interpolated points, we know that the uncertainty is likely to be that given by interpolation of the surrounding uncertainties. This is the Bayesian concept of including as much information as possible, rather than relying on the measurement set itself. The problem then arises that this implies that repeated interpolation can drive uncertainties in linear combinations such as colour coordinates zero (or at least to the base level set by systematic errors, i.e. correlations). It is not clear at this stage how Bayesian statistics treats correlations introduced by interpolation.

In a number of instances, particularly related to colour, propagated uncertainties appear small compared to those obtained by experience. This is an indication that not all effects have been included in the uncertainty estimation. Making accurate spectral irradiance measurements does not guarantee accurate colour measurements if the sample is not uniform, for example. Only by accurately propagating uncertainties, including correlations introduced by systematic components, can we reliably determine that factors may be omitted and so improve the radiometric measurement process. ■

The Kilogram in the News

For scientists, kilogram loses mass appeal

Standard used to define unit since late 1800s is becoming less precise.

Alexandra Witze

Dallas Morning News
18 November 2002

On the outskirts of Paris, in a locked vault to which only three people have the key, lies a treasure worth more than its weight in gold.

It's even worth more than its weight in platinum and iridium, which is what it's made of.

The squat metal cylinder weighs exactly 1 kilogram, as it should. It is the world's defini-n of mass, the standard kilogram against ..hich all others are judged.

But now *"le grand K,"* as the kilogram is known, is putting itself out of date. Since it was cast in the late 1800s, it has changed mass ever so slightly, drifting by a few millionths of a gram per year when compared with six copies made at the same time.

And that just won't do, physicists say.

"It's scientifically very unsatisfactory to have a mass standard that changes in mass," said Paul De Bièvre, a standards expert at the European Commission's Institute for Reference Materials and Measurements in Geel, Belgium.

It's time for a new kilogram standard, researchers say - one that won't depend on the vagaries of a gle chunk of metal. So physicists are striving to replace *le grand K* with a fundamental physical measurement to last forever.

Scientists have done so for other important units of measure. A second, for instance, is defined as 9,192,631,770 periods of a flickering between two levels of a cesium-133 atom. A meter is the distance light travels in a vacuum during 1/299,792,458ths of a second. (It used to be the distance between two scratches on a certain platinum-iridium bar, which is kept next to *le grand K* at the International Bureau of Weights and Measures, or BIPM, near Paris.)

To fix the kilogram, one group of physicists is trying to define mass based on voltage, resistance and other electromagnetic measurements. A second group wants to make a perfect sphere of silicon; by counting the number of atoms in it more accurately than ever, the scientists hope to arrive at a new mass standard.

One of these ideas - or both, or neither - may replace *le grand K* in the next decade or two.

"At least we can do no worse than it's been for the last 100 years," said Richard Steiner, a physicist at the National Institute of Standards and Technology in Gaithersburg, Md.

Why it's needed

Scientists are driven by more than just curiosity. They need a mass standard for use in their precision experiments. And adopting a standard kilogram is important for international trade, Dr. Steiner said; even tiny discrepancies in how much a shipment weighs can add up to headaches for people trying to sell goods. "The thing that unites us in the world is the definition of the units," Dr. De Bièvre said.

The metric system, used almost everywhere in the world except for the United States, was born during the French Revolution in an effort to unify the many weights and measures used at the time. In 1875, 17 nations signed the Metre Convention and adopted the metric standards.

Today, 51 countries have signed on to the International System of Units, or SI, after its French acronym. It defines seven basic units: meter for length, kilogram for mass, second for time, ampere for electric current, kelvin for temperature, mole for the amount of a substance and candela for luminous intensity.

Over the years, all units but the kilogram have received a physical definition that doesn't depend on a thing. The kilogram is last because it's not an easy thing to define.

It was first conceived of as the mass of a cubic decimeter of water at 4 degrees Celsius. (In English units, a kilogram equals roughly 2.2 pounds.)

Today, the kilogram is whatever the mass of *le grand K* is. It's a squat metal cylinder, about an inch and a half high and wide, made of 90 percent platinum and 10 percent iridium. That mixture is particularly stable and dense, making it a good candidate for a lasting mass standard.

In 1889, keepers of *le grand K* made six copies, which are kept in the same temperature- and humidity-controlled vault as the original. Most of the countries that signed the Metre Convention have their own copy of the kilogram, which they occasionally send to Paris for calibration.

Le grand K comes out of its vault only once every few decades - "only when there's a scientific reason to think that your uncertainty is too high," said Richard Davis, head of the mass section at the international standards bureau. It hasn't been out since 1992, when it was cleaned with a chamois cloth coated with solvents, then steamed with doubly distilled water.

Nobody knows why the mass of *le grand K* fluctuates compared with its copies, but some scientists think it might be absorbing atmospheric contaminants. Even weighing it is a delicate job, as bumping it against the scale flakes off tiny pieces, Dr. Davis said.

The new efforts aim to replace the kilogram standard with one that varies by less than 1 part in 100 million each year.

For one group of scientists, that means defining the kilogram as a certain number of atoms of a particular element.

Working backward

The scientists work backward, starting with a 1 kilogram mass and determining how many atoms are packed into its volume. The task is like trying to figure out, just by looking, how many gumballs are in a giant spherical gumball dispenser. "You essentially add up this huge number of atoms in the crystal just by knowing what the spacing between the atoms is," Dr. Davis said.

Once the scientists know how many atoms are in 1 kilogram, that number could redefine the kilogram standard.

The team works with the element silicon, fashioning spherical crystals a bit bigger than a billiard ball.

"All of this has to be done very carefully" because of the precision required, said Dr. De Bièvre, one of the project's leaders. "No national institute can do all of what is needed."

Labs in Australia, Belgium, Germany, Italy, Japan and the United States share the tasks of creating and polishing 1 kilogram spheres of silicon, then measuring their physical properties.

For years, the project was foiled by naturally occurring holes that dotted the silicon crystal like missing gumballs in a gum dispenser. Only recently have scientists realized that the presence of such holes could explain why silicon spheres made by different labs appear to have different densities.

The delay did have one spinoff, said physicist Frans Spaepen of Harvard University: Computer chip manufacturers now know exactly how many holes riddle silicon crystals.

The next step for the team is to make a sphere out of pure silicon-28. Until now, the scientists have used a mixture of the three naturally occurring silicon isotopes - silicon-28, -29 and -30 - which are forms of the element with different masses.

Scientists at the Institute for Crystal Growth in Berlin will soon make test crystals of silicon-28 to see how the material behaves. The project could have its kilogram replacement as soon as six years from now, Dr. De Bièvre said.

By then, the competing technique may also have an answer.

This second device, known as a "watt balance," was invented in the 1970s by Bryan Kibble of England's National Physical Laboratory.

The apparatus works by balancing the force of gravity pulling down on a 1 kilogram mass against an upward-pulling magnetic force. The device can indirectly define the kilogram because all the other units measured – such as time, length, voltage and resistance - are already precisely defined.

The idea "has a beautiful exactness about it," Dr. Kibble said.

But it's not so easy to pull off. Scientists have built two big watt balances - a two-story one at the U.S. standards lab in Gaithersburg and a room-sized one in England. Both devices work pretty well, but so far neither is accurate enough to do better than *le grand K.*

The British watt balance reported in 1988 that it had some encouraging results, which were confirmed a decade later by the American one. But now the British team has redone its experiment and reached a different conclusion.

"We're still not there," Dr. Kibble said.

The American team has also torn down and rebuilt its watt balance. Preliminary results are expected by the end of this year, said Dr. Steiner.

"Back in '98 when we agreed with them [the British lab], it looked real neat," he said. "That's why everybody is looking to see, once we've rebuilt our system, will we get the same number that we did four years ago?"

Other approaches

In the meantime, a laboratory in Switzerland is working on a smaller watt balance of its own. Finnish scientists are trying to devise a related experiment that uses magnetic levitation. And German researchers are modifying the atom-counting idea, by spitting atoms into a container one at a time and measuring them as they go. It's not clear which, if any, of these new approaches will finally go to the BIPM as the kilogram standard.

The teams see themselves as improving precision physics, not as competing for an international prize.

"If the purpose of all this work was to beat others, I would stop instantly," said Dr. De Bièvre of the silicon sphere project.

Eventually, he said, the watt balance and silicon sphere ideas might be used to cross-check each other.

Whatever the new kilogram standard turns out to be, it must hold true for the next 100, 1,000, or 10,000 years for measurers. It mustn't depend on a single thing sitting in a vault in Paris. And it must be reproducible anywhere in the world.

"It doesn't matter, you don't have to have it at the BIPM," said Dr. Davis. "Anyone could have one." ■

Weighty Matters

Jeff Tapping

News of fundamental measurement standards has reached the popular press. In February, *New Scientist* published a long article on the fundamental standard of mass (*Weigh to go* by Robert Matthews). It explained, (as most of us know, don't we?), that the kilogram is the only one of the seven fundamental standards that depends on an artefact. There are about 80 direct copies of the primary article, so if something happened to the primary we should be able to retrieve things, but it is disturbing to find that comparisons of this primary with the secondaries show disagreements of the order of 20 micrograms (20 parts per billion). Small stuff, but a bit disturbing all the same. The article describes some of the methods being investigated to find a definition for the kilogram that is based on something more stable, universal and reproducible, including the silicon sphere that our own NML has contributed to. Another proposal is to count and collect a current of ions of an element then define the standard in terms of the mass of the element, and a third is to use the force between two current-carrying wires.

The article ended with a quotation from the web site of the U.K. National Physical Laboratory, asking if anyone had any new ideas for a definition. It was interesting to read the letters that were sent in response. Two writers were concerned about the effects on derived units such as the newton and the watt, and clearly do not understand that any basic unit, however defined, has a limitation (its uncertainty), and this is transferred to any derived units. One suggested using the density of water, which would involve measuring a volume to a few parts in a billion, not to mention an incredible temperature uniformity and control. Another suggested using the gravitational attraction between two masses, without realising that the force between two 1 kg masses at a distance of one metre is about 7×10^{-11} newtons. Try measuring that to one part in a billion! Finally, one writer suggested defining the kilogram as a particular number of carbon atoms. He, like the others, failed to understand that creating a definition is easy, the hard part is realising it to an acceptable uncertainty.

I could understand why readers would have an imperfect grasp of the real difficulties in establishing basic standards, so letters like these did not surprise. But I was surprised that no follow-up explanations appeared to answer them. ■

NML Melbourne on the move . . .

Recently staff at National Measurement Laboratory, Melbourne Branch have been busily engaged in matters other than servicing clients' measurement and calibration needs, they are about to move to a new building across the road from their present location. Equipment from its Dimensional, Pressure and Electrical laboratories has been carefully packed for transport to the new premises. Still located within the CSIRO complex at Clayton Victoria, the new NML facilities feature more spacious laboratories and a newly constructed office area. There will be an intensive period of recommissioning equipment before NML Melbourne is able to accept calibration work from its clients again in early August.

Please take note of the contact details relevant from 7 July 2003:
Locked Bag 700 CLAYTON SOUTH VIC 3169
71 Normanby Road CLAYTON VIC 3168
Tel: (61 3) 9545 8225 *Fax:* (61 3) 9545 8260 *Web:* *www.nml.csiro.au*

News from NML

National Measurement Institute Announced

The Hon Ian Macfarlane, MP, Minister for Industry, Tourism and Resources, announced the formation of a new national measurement institute, as part of the Government's 2003-04 Budget initiatives. This announcement was the culmination of several years' work with many submissions and discussions being put forward by the parties concerned to various ministers and government bodies for agreement. The institute will be established by amalgamating the National Measurement Laboratory, the National Standards Commission and the Australian Government Analytical Laboratory and will be part of the Industry, Tourism and Resources portfolio.

This agency will enhance national and international exposure of Australia's capabilities in the areas of physical, chemical and biological metrology, giving Australia a better basis to provide a range of measurement services to industry. The new institute will have a focus on the needs of industry, emphasising innovation, but will also support research to underpin delivery of services.

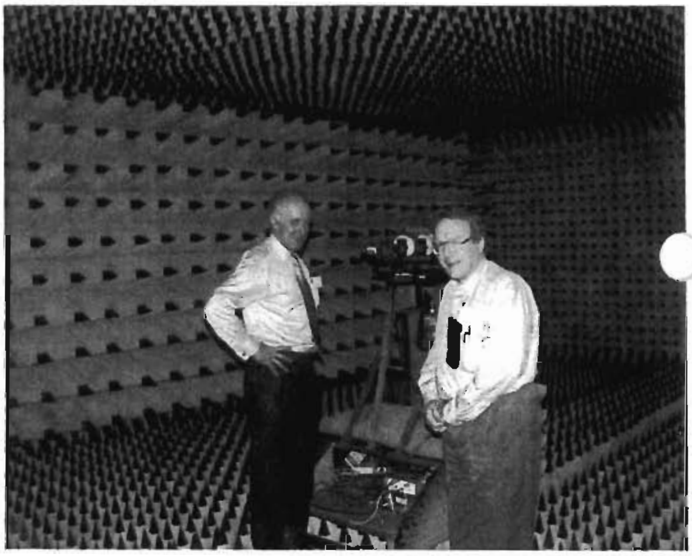
Changes to Commonwealth legislation will be required for the transfer of functions and responsibilities of the constituent organisations to the new institute. New corporate governance arrangements suitable for this body will also be created.

A website (www.measurement.gov.au) has been set up to provide general information to the stakeholders and the public during the transition phase, until the new institute becomes operational on 1 July 2004. Specific information about the services provided by the component organisations will continue to be available at their individual websites (www.nml.csiro.au, www.nsc.gov.au, www.agal.gov.au) until the transition is complete.

Visit by BIPM Director

The task of the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM), located in France, is to ensure world-wide uniformity of measurements and their traceability to the International System of Units (SI). It does this under the authority of the Convention of the Metre, a diplomatic treaty discussed previously in TAM (September 2002). BIPM operates through a series of Consultative Committees whose members are the national metrology laboratories of the Member States of the Convention (NML is one such member), and also contributes to these Committees through its own laboratory work. The BIPM operates under the supervision of the International Committee for Weights and Measures (Comité International des Poids et Mesures, CIPM). Dr Barry Inglis, Director of NML is Vice President of the CIPM and a member of its executive body, the CIPM bureau.

Recently, Dr Terry Quinn, FRS, Director of BIPM, visited NML to discuss NML's on-going contribution to international metrology, including the possible joint development of a new generation Calculable Capacitor (see last issue of TAM for discussion on calculable capacitor). Dr Quinn toured the laboratory facilities and is shown here (left of photo) with Mr John Peters, NML, inspecting the newly refurbished anechoic chamber.



Dr Terry Quinn, FRS, Director of BIPM, (left of picture) with Mr John Peters, NML, inspecting the newly refurbished anechoic chamber.

Dr Quinn retires as Director of BIPM in December 2003 and, while at NML, he presented a seminar titled "International Metrology and Developments at the BIPM" that reviewed achievements during his period of directorship.

Ultrasonics

Australia is one of over sixty members of the International Electrotechnical Commission (IEC), a body that prepares and publishes international standards for all electrical, electronic and related technologies, through the work of its technical committees (TC). The objectives of the Commission include contributing to the improvement of human health and safety and the protection of the environment. IEC also promotes the worldwide use of its standards by conformity assessment schemes in order to harmonise the requirements of the global market, minimise technical barriers to trade and encourage growth of new markets.

Recently, NML researcher Dr Stan Barnett was elected Chair of IEC TC87: Ultrasonics. The brief of this committee includes the preparation of standards covering those aspects of ultrasound pertaining to human safety (including those of biological effects and of corresponding limits) and to the methods of measurement and specifications for fields, equipment and systems.

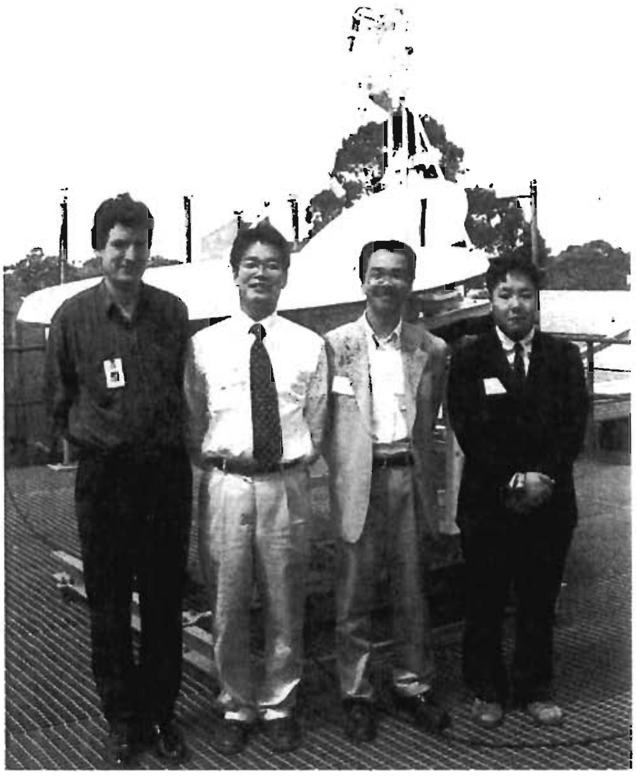
NML is currently undertaking the development of a robust, portable ultrasound power standard to enable in-situ proficiency testing of ultrasonic therapy machines for clinical use. A number of surveys have shown that up to 70% of such devices may deliver ultrasound that differs from the indicated dose by more than +/- 20%. To date, in Australia, there are no requirements for the use of documentary standards to specify testing procedures or for the accreditation of testing services.

New Modem for Japan-Australia Satellite Time Link

NML hosted three visitors from the Japan Standard Time Group at the Communications Research Laboratory, Tokyo, earlier in the year. Mr Noriyuki Kurihara - Head of the Japan Standard Time Group, and engineers, Dr Tomonari Suzuyama and Dr Fumimaru Nakagawa, installed a new multichannel modem for use in the Two-Way Satellite Time and Frequency Transfer (TWSTFT) link that has been in operation between CRL and NML for several years.

TWSTFT is one of the most accurate methods of time and frequency comparisons between atomic clocks located in geographically separated laboratories. In principle the technique, which involves each laboratory simultaneously transmitting a time signal to the other laboratory via a commercial communications satellite, should make possible time comparisons with uncertainties of less than 1 nanosecond.

Each laboratory participating in a TWSTFT requires a modem to generate a spread spectrum timing/data signal, derived from the local time reference, for transmission via satellite to the other participating laboratory. The modem also converts the spread spectrum timing/data signal received from the other laboratory into a time signal that can be measured against the local time reference.



Dr Peter Fisk, NML (left), pictured with visiting CRL scientists Dr Tomonari Suzuyam, Mr Noriyuki Kurihara and Dr Fumimaru Nakagawa, in front of the Ku-band satellite antenna, on the roof of NML, Lindfield. The Ku-band satellite antenna is used in Two-Way Satellite Time and Frequency comparisons between CRL and NML.

The new modem installed during the visit was developed in accordance with CRL specifications by a private Japanese company. Similar systems have been installed at SPRING Singapore, TL Taiwan, The Chinese Academy of Sciences Shaanxi Observatory, and KRISS Korea. In conjunction with installing these new multichannel modems, CRL has also secured medium-term leases on transponders on communications satellites covering the Asia-Pacific region, thereby allowing the continuous, fully automated, operation of TWSTFT links between the laboratories in CRL's TWSTFT network.

NML stands to benefit from participating in the CRL TWSTFT network through the improvement in the uncertainty of Australia's national official timescale with respect to the international atomic timescale, Co-ordinated Universal Time.

Training Courses at NML

Many readers will be aware of the ISO "Guide to the Expression of Uncertainty in Measurement" courses being run on a regular basis at NML, available both in Sydney and Melbourne. These courses are beneficial both to those who require a general knowledge (1-day course) through to those who require a detailed understanding of the estimation of uncertainty (3-day course). Courses can also be delivered at company sites for in-house training, and are available subject to demand in States other than NSW and Victoria.

NML also offers 2 and 3-day training courses in specific areas of measurement. Most recently the Lindfield site in Sydney hosted two courses on electrical measurement and pressure measurement. Coming up later in the year will be a two-day intensive on Time & Frequency Measurement. Next year will see the inclusion of a course on Introductory Radiometry. These courses, as well as others delivered previously, will be repeated yearly or biennially as warranted by demand.

Technical monographs are prepared to accompany each training course, and are available for purchase separately.

Further details of the courses and the technical monographs, as well as general information about NML and its services, are available at the NML web site http:// www.nml.csiro.au. ■

MSA Notices

MSA 2004 - Valuing Metrology

Call for Papers

The Metrology Society of Australia's
5th Bi-Annual Conference in
Edmund Barton Centre, Melbourne
15 to 17 March 2004.

What does measurement add to the value of a business? How does metrology improve the quality of the products? What does measurement add to our economy and our lives? Government, businesses and industry sectors are all asking these hard questions. It is no longer enough to say it's the right thing to do. We need to be able to demonstrate the Value of Metrology to our bosses and to the country at large.

This is the sub-text of the conference, Value. What are the new and clever ways in which the science of metrology is being advanced? How is metrology being applied at the shop floor level?

This is a call for papers for the 5th Bi-annual Conference in Melbourne. It will be held at the Edmund Barton Centre, Moorabbin from the 15th to the 17th March 2004. We are looking for technical papers on new methods of measurement and standards in all areas of metrology – dimensional, electrical, physical, chemical etc. But we are also looking to open up discussion on the broader issues facing the metrologist. Do metrologists tend to go for over kill when it comes to measurement and uncertainty? How do you demonstrate the contribution your metrologists add to the business in a tangible way?

The submission date for abstracts or papers need is the 31st August 2003.

The submission date for papers is the 1st December 2003.

Start drafting your paper for the conference as the call for papers will close the beginning of September 2003. Tell your colleagues about the conference and pencil it in your diary. Abstracts and Papers should be forward to the MSA Secretary c/o CSIRO NML Bradfield Road Lindfield, NSW 2070 or email to *conference@metrology.asn.au* marked MSA 2004 abstract. If you have any queries contact Steve Jenkins at *sej@stevejenkins.com.au*.

See you in Melbourne in March 2004, great weather, great events and great fun.

The MSA Crossword

Well, dear members of the MSA, believe it or not, no-one was able to complete the Metrology crossword in the last issue of TAM completely correctly, and go on to win the excellent book prize "The Measure of All Things" by Ken Alder. It seems that our President's crossword–writing ability has stumped our finest minds? Surely not! We are extending the competition by just one more edition of TAM. If you can get your correct entries in before the end of August, you could have a shot at that book. Send your entries to the editor, marked "Crossword Competition".

Around the Branches

- from our State Representatives

SA

In 2002/3 South Australia has continued to run meetings in a informal manner. The main objective was to select interesting guest speakers that used measurement in one form or another.

Our first meeting was actually a visit to Ellex Laser Systems, manufacturers of eye surgery laser units.

The Christmas meeting had Graham Smith talking on force measurement.

In February we heard from Richard Duncan on surface finish measurement - as you know Richard is a member of the committee that set the standard for this type of engineering measurement.

Our May meeting had us listening to Andrew Skinner, whose talk on instrumentation for remote environmental monitoring. This last meeting enticed 24 members and guests compared to our usual 16 persons

- Les Felix

Vic

On May 21 the Metrology Association meeting was held at the Melbourne Monash Science Centre. Mark Thomas from Tenix Defense Pty Ltd presented a talk on Laboratory Information Management Systems and Automated Calibration. He demonstrated step by step how their laboratory moved from mixed card & computer management systems to a fully computerized management system.

The information on each device included technical ID, description, location, contact names, calibration intervals which automatically allow the sending of messages to the device owner when it is due for calibration, as well as references against which equipment were calibrated, calibration data and conformity statement to specification. Reports can be printed and presented to gauge owner on request.

Following Mark's talk, Mr. Jack Stompii from the Fluke Company demonstrated their new software package METCAL, which they say can be used not only for electrical measurements but also can be used for dimensional metrology.

During the presentation many questions were asked about how the data was set up and organized. It was an interesting and informative session as our laboratory is going through a similar experience and it was good to hear so many ideas expressed.

- Galina Sirant
(Robert Bosch (Aust.)/QAT)

WA

The last activity undertaken was a survey of the W.A. membership, to which there was a low and disappointing response. One of the survey proposals was for members to get together for informal meetings, luncheons etc., but further investigation into this has demonstrated that the membership is actually located around the perimeter of the Perth metropolitan area. This means travelling time to a central location would be considerable for most members. Another factor has been the closure of a number of laboratories with facilities concentrating in the Eastern States.

W.A. has one basic feature, that of the remoteness, both physically in terms of distance and psychologically, from the Eastern States where the Metrology Society activities are centred as with most other relevant activities.

- David Pack

continued from page 3

Micro-scale metrology

silicon diaphragms as the transducer elements in its range of pressure sensors, which are used in a number applications ranging from laboratory-environment monitoring and marine sensing to automotive production and aerospace altimetry.

The diaphragms are machined using methods borrowed from the semiconductor industry and are then inspected by human operators who decide if the component is fit for production. Each diaphragm is then interfaced with signal-processing electronics to optimize the response function of the sensor. With proper metrology, these costly manual-inspection and optimization processes could be completely avoided. According to Roger Jones, group engineering director at Druck, measurements of the 3-D structure of the individual diaphragms could lead to significant cost savings. But to date, no system that can traceably measure the diaphragms is commercially available.

Engineering at conventional scales benefits from a wide range of metrology tools, ranging from specialist devices designed to measure just one particular feature to more versatile tools such as coordinate-measuring machines. These instruments measure the 3-D position of points on the surface of an object, using either a contacting probe or a microscope. Typical coordinate-measuring machines can survey objects up to a few metres across with an accuracy of the order of 10 micrometres.

On the nanometre scale, the closest analogues of coordinate-measuring machines are scanning probe microscopes. Although these instruments can achieve accuracies of a few nanometres, their range is limited. Moreover, they tend to be restricted to height measurements across a 2-D plane. Between these two regimes, there is a significant lack of 3-D metrology tools.

In order to fill this gap, our group at the National Physical Laboratory in the UK has developed a miniature coordinate-measuring machine that operates over a restricted range (up to 50 millimetres along the x, y and z axes) and has an accuracy of 50 nanometres. It therefore extends the metrology capabilities of coordinate-measuring machines to measure smaller, more delicate objects, while achieving measurement uncertainties that are an order of magnitude better.

The new instrument comprises a novel contact probe that applies a tiny force to the component so that measurements can be made without significantly damaging its surface. The tip of the probe is monitored by six laser interferometers, which measure both its displacement and rotation with high precision.

Any imperfections in the structure of the machine are compensated for by a self-calibration technique, which makes use of the redundancy of information from the six laser interferometers and other angle-sensitive devices mounted on the machine. In this way, we can derive a 3-D vector model of the positions and alignment axes of the laser interferometers, and map any errors in the flatness of the optical components.

In spite of the technical advances made so far, there is still a major gap that our group plans to fill in the near future. We are aiming to develop an even smaller instrument - a truly micro coordinate-measuring machine that will be able to measure complex 3-D microstructures with nanometre accuracy. This will involve the development of tiny probes made from carbon nanotubes which are akin to those found in conventional devices, and novel optical probes.

Once the appropriate measurement standards and instruments have been established, calibrated commercial devices can be used more effectively on the wealth of microstructures that are being developed. These devices will pave the way for formal standards in microsystems technology that will eventually improve future micro-scale products and the quality of life for everyone. ■

Letter to the Editor

I would like to make a suggestion to address the lack of time which seems to be the main contribution factor to the slow progress in some of o. MSA inititatives. The problem as I see it is that we urge volunteers to step forward to run the Metrology society but find communication faltering when those volunteers have to prioritise their work requirements before the Society's need. This causes inconveniences and a drop in the value of the society. Therefore we must either step back or leap forward.

I propose that there be an increase of $20 or so to the membership fees and that the Society hire a part time person to maintain communications, mail address updates, meeting minute distribution etc (all the things that seem to go astray). I estimate one day a week would be sufficient (55 days a year, one fifth of a $30k salary). I am sure that there are suitable people in the industry who could do this job and do it well.

- *L. Felix, SA*

Uncertainty Components from Expert Judgement

Jeffrey Tapping

Adelaide

tapping@ozemail.com.au

MSA member Richard Duncan is a member of ISO Technical Committee 213 which deals with standards on Dimensional and Geometrical Product Specifications and Verification (known in the trade as GPS long before those navigation devices came along). This committee has been responsible for the development of ISO14253, which is a family of standards dealing with topics relating to dimensional measurement of products, including conformance to specification and uncertainties. Of particular interest is Part 2, "Guide to the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification". Recently the committee has been working on a guide to estimating uncertainty components using "expert judgement", and the following article was written as the request of Richard, for presentation to the committee.

An important part of the uncertainties system prescribed by the Guide to the Expression of Uncertainty in Measurement ("The Guide"), is the use of Type B components. A significant proportion of these are in practice estimated by judgement based on past experience or from an assessment of information other than direct measurement. It might at first sight seem strange that the system of numerical uncertainties has worked so well with such an informal estimation process, but it should not really be seen as surprising at all. Expressing expert judgement numerically is an integral part of everyday life, and the common approaches taken to making such judgements are the key to formalisation of it in the measurement process.

In discussing this topic it is important to note that estimating a value for an uncertainty component is a measurement, which itself has an uncertainty. That is, an uncertainty component has a probability distribution and therefore a standard deviation (or standard uncertainty). This is discussed in The Guide in Annex 4, where guidance is given for transforming between degrees of freedom and the standard deviation of a standard deviation. It follows that an informally estimated component also has these properties

Another point to note is that "expertness" is not a single, precise state, but is a continuum. As soon as a person acquires one piece of information about measurement, they have taken the first step on a journey of experience. The term "expert" should be treated as The Guide treats "accuracy", as a qualitative term. Each expert will produce an estimate of an uncertainty component with a different uncertainty, and a method must be worked out which takes account of this fact.

I return to the point that expert judgement is part of everyday life. People seem to have a strong drive for absolutes (guilty or not guilty, drunk or sober, big enough or not, and so on). But in spite of this there seems to be an implicit general understanding that uncertainties exist. If any person gives you an estimated value of something (for example the age of a person they have just met, how long before they will be ready to depart), they will be able to give you some form of uncertainty if you question them. Sometimes this uncertainty is expressed as a percentage (such as the odds for success), but for measurement quantities it is most often as a range within which they think the actual value will be. If you ask how far to the next bus stop, you might be told "About 100 to 200 metres." This statement gives you quite a lot of information: the most probable value is 150 metres with a high, but not <u>very</u> high, probability that the true value is within the stated range.

We also readily appreciate degrees of expertness. Suppose we assemble three people: the first is a butcher, the second is a new apprentice in his shop, the third a customer who is a house-husband. Suppose we now ask each of them to estimate the weight of a parcel of 1100 grams of sausages. Each person has a different amount of experience in estimating weights, and each would probably be able to give an estimated range of weight which would reasonably accurately reflect their experience. In fact any of us could probably make quite a good guess of the range they would give: say within 100 grams for the butcher, 200 grams for the apprentice, and 250 grams for the customer. I believe that using this talent most people seem to have is the key to addressing varying reliability of estimates.

The formal way of dealing with reliability is using effective degrees of freedom. Laboratory accreditation bodies such as NATA favour this method, but GPS standards such as ISO 14253 do not even mention the existence of degrees of freedom, so two different approaches will be considered.

Using Degrees of Freedom

An uncertainty component is a standard uncertainty (standard deviation). The only means suggested in The Guide for obtaining a degrees of freedom for a Type B component is using the relationship given in Annexe E (Table E.1 and the associated formula), between degrees of freedom and the standard deviation of a standard deviation. Unfortunately this relationship applies only to normal distributions. If the probable values of the uncertainty component are believed to have another type of distribution such as rectangular or triangular, then strictly the relationship does not apply.

Consider now a component given as a range. In the kind of situation described above the bounds of the range will almost certainly not be absolutely defined, so the distribution cannot be purely rectangular (or triangular for the same reason). In fact if an expert was pressed about the bounds, they would probably either say that the bounds had a particular high probability of containing the true result, or expand the bounds to cover what was considered to be near enough to absolute certainty. The expanded bounds leave us with a problem finding degrees of freedom, so it makes more sense to ask the expert to give the bounds for a given probability. If the bounds and probability are then taken to represent a normal distribution (even if is not exactly so), it is easy to then to calculate the standard deviation, which can then be used with the formula or table in Annexe E to get degrees of freedom. It is most unlikely that the distribution of an expert judgement could be rectangular, and a normal distribution is a reasonable assumption.

Without Degrees of Freedom

The approach taken in ISO 14253-2 to the estimation of uncertainty, called the PUMA method, directs that components are initially overestimated, and then refined if the combined uncertainty is not small enough. If degrees of freedom are to be ignored, then a similar approach may be taken for expert judgement. A simple method would be to take the upper limit of the range for a component as the value of the component, clearly a substantial overestimate. A slightly more rigorous method would be to require that the value used is at least large enough to cover a specified fraction of the distribution of probable values. For example suppose it is required that the value chosen for the component has a 95% probability of being at least as great as the actual value. Then the value chosen must be such that only 5% of probably values are higher, which means that it must be very close to the upper limit of the specified range. In this case there would be little difference between this value and the upper limit. For the component without degrees of freedom to give a similar number to the one where degrees of freedom are used, the probability that the actual value is larger must be accepted as 50%. This incidentally illustrates one reason why we use degrees of freedom – they allow us to account for the uncertainty in a component without inflating that component.

Shape of Distribution

If the uncertainty of an uncertainty component is large fraction of the component, as will often be the case in expert judgements, expressing the estimate as a probable value plus an upper and lower limit, may give the appearance of an asymmetrical distribution. For example the estimated value could be 100 with an upper limit of 140 and a lower limit of 80. But, as discussed above, this mode of expression is an artefact of our desire for a single value when in fact the answer is a range. So the asymmetry is actually an illusion. The estimate should be taken as the midpoint of the range, an approach in line with the recommendation in The Guide, 4.3.8 for handling asymmetrical distributions.

Summary

An expert judgement should not just be a numb plucked out of the air, but should be a formal quantification based on knowledge and experience of previous measurements. The process should take account of the following points.

- Each expert judgement of an uncertainty component will itself have an uncertainty.
- Each expert judgement is based on a combination of the experience of the expert, and the quality of information available to the expert on the particular influence producing the uncertainty. These two factors must be used in establishing the uncertainty of the uncertainty component.
- The estimate of an uncertainty is best expressed as a range of values within which the true value of the component is believed to be with some specified level of confidence.

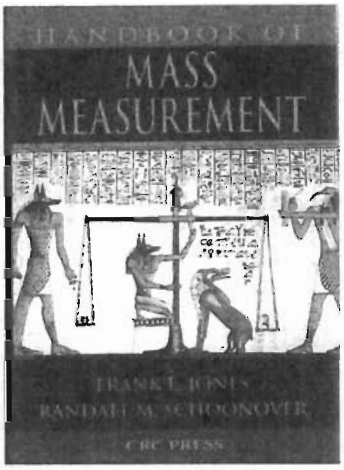
Book Review

Handbook of Mass Measurement

Frank E. Jones and Randall M. Schoonover
CRC Press, FL, USA 2002
Xxv + 307 pp, US$99.95 (hardcover)
ISBN 0-8493-2531-5

This is a welcome addition to the available literature on mass measurement. Perhaps this is one time it is reasonable to quote from the publisher's literature about the book:

"The ultimate resource for mass metrology. 'How much does it weigh?' seems a simple question. To scientists and engineers, however, the answer is far from simple, and determining the answer demands considera-tion of an almost overwhelming number of factors.



"With an intriguing blend of history, fundamentals, and technical details, the Handbook of Mass Measurement sets forth the details of achieving the highest precision in mass measurements. It covers the whole field, from the development, calibration and maintenance of mass standards to detailed accounts of weighing designs, balances, and uncertainty. It addresses the entire measurement process and provides in-depth examinations of the various factors that introduce error.

"Much of the material is the authors' own work and some of it is published here for the first time. Jones and Schoonover are both highly regarded veterans of the US NIST. With this handbook, they have provided a service and resource vital to anyone involved not only in the determination of mass, but also to the entire field of precision measurement."

It must be stressed at the outset that many of the procedures for surveillance etc are US and NIST based. Australian approaches to these differ but this is a minor criticism. It is the sheer breadth of useful and interesting material presented which will interest the reader.

The contents include Mass and Mass Standards; recalibration, contamination and cleaning of masses; statistical terms; meas-urement uncertainty; direct reading analytical balances; electronic balances; buoyancy corrections; air density equation; density of solid objects; hydrostatic weigh-ing; density of water; error propagation; magnetic errors; gravitational effects; and more. Further disciplines are included where necessary - for example in the measurement of air density, temperature is discussed, with explanations of fixed points such as ice point, triple point and steam point and the relevant apparatus used, Relative Humidity and pressure measurement.

The authors combine a clear and readable text with rigorous mathematical treatment where necessary. This will make the book useful for workers with widely varying skills in mass measurement.

Realistically, the number of laboratories in Australia that would consider the handbook useful for them is probably not great – that is just a fact of life. However, those who do place it on their reference shelf may be surprised at its usefulness.

If only such a book was available when I started working in the fields of precision mass and density measurement nearly forty years ago!

- Reviewed by Maurie Hooper

from previous page

- If degrees of freedom are used in calcula-tions of the combined uncertainty, the relation-ships given in The Guide can be used to convert the range to degrees of freedom. The uncer-tainty of the component will then be taken into account.
- If degrees of freedom are not used then the component must be inflated by an amount based on the size of the range and the desired degree of certainty that the component is greater than the true value. ■

WHAT'S ON

ISMCR 2003

13th International Symposium on
Measurement and Control in Robotics
Madrid, Spain
September, 2003

Environmental Measurements

1st International Conference on
Environmental Measurements
Budapest, Hungary
October 13-17, 2003

MSA 2004 - Valuing Metrology

The Metrology Society of Australia's
5th Bi-Ennial Conference
Melbourne
March 2004

Next Issue

- AGM Information

Call for Papers

We are looking for technical papers on new methods or measurements and standards. What are the new and clever ways in which the science of metrology is being advanced? How is metrology being applied at the shop floor level? But we are also looking to open up discussion on the broader issues facing metrologist. How do you demonstrate the contribution your metrologists add to the business in a tangible way?

Start drafting your papers now, (September closing date).