**Report to the National Measurement System Policy Unit, Department of Trade & Industry**

# INTERIM STATUS REPORT ON THE ELECTRICAL METROLOGY AREA

## FROM THE SOFTWARE SUPPORT FOR METROLOGY PROGRAMME

BY P M HARRIS, NPL

November 1999

# *Software Support for Metrology*

# Interim Status Report on the Electrical Area

**by P M Harris**

**November 1999**

## Abstract

This report describes the status of the mathematics and software used to support the Electrical area of metrology, particularly as used within the NMS Electrical programme. This is one of a set of status reports produced for the NMS Software Support for Metrology (1998-2001) programme mid-way through the current programme to inform the formulation of the next SSfM programme (2001-2004). The different aspects of mathematics and software are reviewed under the headings of the themes and project topics of the current SSfM programme. The SSfM programme is identifying best practice where it exists and disseminating guidance on that best practice to other metrology areas. The outputs of the SSfM programme will be generic, applicable to more than one metrology area. This report, therefore, not only identifies problems to be tackled and best practice to be disseminated by the SSfM programme, but also if appropriate possible future Electrical programme projects applying SSfM outputs to specific problems in the Electrical area.

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# Contents

# 1. Introduction

The purpose of this status report is to inform the NMS Software Support for Metrology (SSfM) programme (1998-2001) about the status of the mathematics and software used to support the **Electrical** area, concentrating on what is used within the NMS **Electrical Metrology programme**. This and the companion status reports for the other metrology areas will inform the formulation of the next SSfM programme (2001-2004). It may also lead to appropriate linkage between the Electrical Metrology programme and the SSfM programme.

The SSfM programme is an underpinning programme that provides generic support in the use of software and mathematics to the NMS programmes for each metrology area. For details of the programme, its expected deliverables and the results already produced, see the SSfM web site: http://www.npl.co.uk/ssfm/.

The NMS programmes for specific metrology areas provide metrological support to industry. The SSfM programme in contrast has relatively little direct impact upon industry, although there is some as evidenced by the SSfM Club membership. This relationship is depicted in Figure 1. It is because of this relationship that the Status Reports concentrate primarily on the use of software and mathematics in the other NMS programmes.

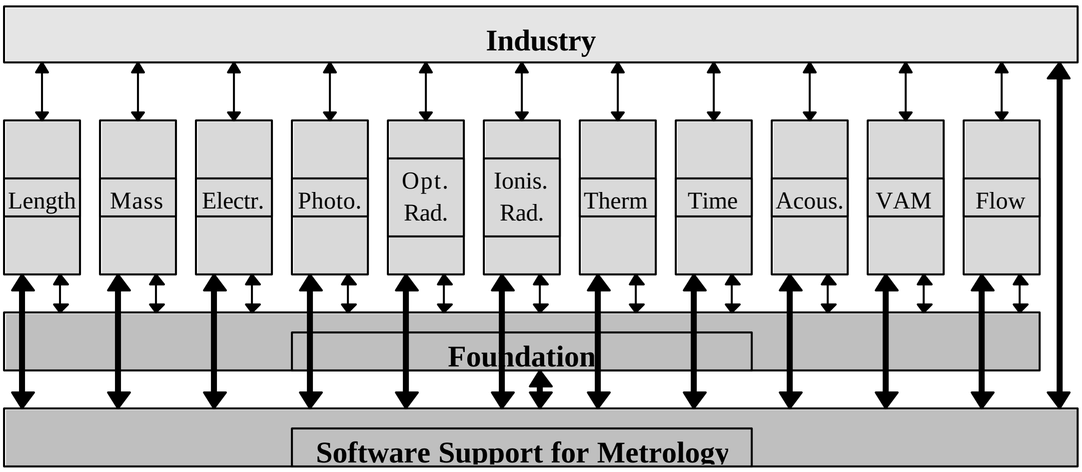


**Figure 1. Relationship of SSfM to other NMS programmes and industry**

In particular, this report addresses each of the themes within the SSfM programme and describes the status concerning the topics covered by each of the relevant projects. It also considers whether there are any important software or mathematics issues in the Electrical area which are not addressed by the current SSfM programme or which need to be taken further in the next SSfM programme.

This report is an update of an initial restricted status report produced in November 1998. That initial report was one of a set of restricted status reports which were synthesised into an overall status report for all metrology areas [3]. A summary of the differences from the initial Electrical status report is provided at the end of this report.

## 2. Scope of the Area Covered

The NMS Electrical programme covers the development, maintenance and dissemination of a wide range of measurement parameters across the electromagnetic spectrum. The programme is divided into four themes:

*Theme 1: DC and Low Frequency*

This theme provides facilities for the measurement of electrical and magnetic quantities from DC up to around 1 MHz. The theme covers voltage and resistance standards, impedance standards, AC standards, and magnetic standards and current transformer measurements.

*Theme 2: RF and Microwave Free Field Metrology*

This theme underpins the NMS for the measurement of electromagnetic fields in the RF and Microwave regions. Most activities are in the few megahertz to about 50 GHz range but some fall in the range from around 10 Hz to beyond 100 GHz. The main drivers are telecommunications, aerospace, defence, electromagnetic compatibility (EMC) testing and health and safety. The theme covers antenna metrology development, EMC measurement facilities development, field measurement and mapping, and electromagnetic materials characterisation.

*Theme 3: RF and Microwave Guided Wave Metrology*

This theme covers RF and Microwave measurement standards in transmission media such as hollow waveguides, coaxial lines, dielectric waveguides and planar lines in high frequency integrated circuits. The four main measurement parameters, power, attenuation, impedance and noise, are highly interdependent, and progress in the development of measurement standards in this field requires a predominantly integrated approach. The main application areas for guided-wave standards are broadly those served by the free field RF and Microwave standards, i.e. telecommunications, aerospace, defence, radar, EMC issues and health and safety, and free-field standards depend strongly on guided-wave standards for traceability.

*Theme 4: Ultrafast Measurements*

This theme is aimed at providing measurement standards to support traceable measurement in fast, high bandwidth systems, not just in the field of communications and broadcasting but in many areas of electronics and computing where there are demanding requirements. For example, measurement standards are required for the characterisation of electrical pulses, the calibration of high bandwidth oscilloscopes as well as new types of test instrumentation, and the electro-optical characterisation of monolithic microwave integrated circuits (MMICs). The theme also encompasses laser power and energy standards and traceable calibration to support optical communications.

The Electrical programme aims to provide:

- measurement standards, and related techniques and expertise to ensure an effective and timely technical capability at UK national level;
- access to standards through effective technical services made available by the NPL and other NMS contractors to the direct beneficiary community in the UK;
- awareness and availability of the expertise and knowledge generated by NMS-supported work to the beneficiary communities, and measures to ensure responsiveness of the NMS work to evolving need;
- activities to promote best practice and exploitation of the UK's expertise in the relevant measurement fields.

The major route for the transfer of measurement standards from the NMS programmes to industry and other beneficiaries is through the provision of calibration and measurement services. The maintenance of such services is part of the Electrical programme. A major part of maintenance is concerned with the realisation of primary standards and the calibration of secondary and working standards. However, activities also include the comparison of UK standards with those of our trading partners world-wide to assure international agreement of standards.

# 3. Modelling Techniques

## *3.1 Methods for Modelling Measurement Data*

### 3.1.1 Types of data

There are three categories of measurement data sets:

1. discrete measurement data, which means:
   a) data obtained by sampling a discrete variable: e.g., a variable that may take only integer values such as in counting processes, and
   b) data obtained by sampling a continuous variable.
2. continuous measurement signal, which means an analogue signal prior to any analogue to digital conversion, which would result in data of type 1b).
3. hybrid measurement data composed of both discrete and continuous data sets.

Most quantitative data in the Electrical area relates to essentially continuous variables. Examples include voltage, current and power, which vary continuously with time. However, such data is often collected and recorded as discrete data by digital sampling. Furthermore, the recorded output of instruments used in the Electrical area, such as digital voltmeters (DVMs), may result from the processing of raw measurement data. For example, digital filtering may be applied, so that the value output by the instrument is the arithmetic mean of data collected over a short time period.

Measurement data arising in the Electrical area may be

- *real-valued*, as in the measurement of time and voltage, or *complex-valued*, as in the measurement of the magnitude and phase of a reflection coefficient, and
- *univariate*, as in the collection of repeat values of a quantity, or *multivariate*, as in the collection of values of control (independent) and response (dependent) variables in calibration.

### 3.1.2 Modelling

**Types of model**

There are three categories of model:

1. discrete models in which the outputs of the measurement system are related to measurements of its inputs by a system of algebraic equations;
2. continuous models in which the outputs of the measurement system are related to measurements of its inputs by a system of differential equations;
3. hybrid models in which the outputs of the measurement system are related to measurements of its inputs by a system composed of both algebraic and differential equations.

It is appropriate to distinguish here between the nature of the model and the approach to solving the model (which for a continuous model typically also involves solving algebraic equations).

Given infinite precision arithmetic, the set of equations derived from a discrete model can be solved exactly. This is not the case for a continuous model which typically requires approximations to be made, for example, in terms of domain discretisation.

**Models used in the Electrical Programme**

Both *empirical* and *physical* models are used to describe the measurement systems and data arising in this area. For example:

- In the modelling of antenna gain, a third or fourth order polynomial is used. This is a physical model which has been validated by a great deal of theoretical work undertaken at NIST and NPL (Section 4.2).
- In the calibration of an automatic network analyser (ANA), the true reflection coefficient is related to the recorded modified reflection coefficient using a rational polynomial function. This is again a physical model.
- In the modelling of fast opto-electronic devices, polynomial and polynomial spline functions are used. These are examples of empirical models.

*Discrete* modelling is undertaken and includes:

- the calculation of summary sample statistics (sample mean and standard deviation) in the analysis of measurement repeatability,
- regression in which a (continuous) function is fitted to discrete data in a least-squares sense through the solution of a system of algebraic equations,
- deconvolution applied to discrete data.

Linear regression, as in the fitting of linear, polynomial and polynomial spline models to data with error in the response variable only, is widely used and well understood, although in the DC and low frequency theme, linear regression where there are several independent variables is regarded as outside the scope of many commercial packages.

Challenging regression problems arise, however, where there are

- errors in more than one variable,
- nonlinear models, and
- complex-valued quantities.

For example, in the Ultrafast measurement theme, the presence of jitter can lead to errors in the recorded values of time, and it is necessary to account for this both in the data modelling as well as in the associated uncertainty estimation. This is in contrast to other metrology disciplines where error in the independent variable (such as time) is often regarded as insignificant compared with other error sources. Furthermore, the calibration of ANAs in the RF and microwave guided wave theme, leads to regression problems involving nonlinear models, complex-valued quantities and errors in more than one variable. Similarly, such problems arise when analysing electro-optical measurements of MMICs in the Ultrafast theme.

Deconvolution is also seen to be a challenging problem, particularly with regard to providing estimates of associated uncertainties (Section 3.2).

*Continuous* modelling is also undertaken in which finite difference and finite element techniques are applied to the solution of systems of differential equations. For example, in the RF and microwave free field theme, software for finite element analysis is used in the solution of Maxwell's equations in a number of complicated situations.

Some further detail relating to the modelling techniques undertaken in the Electrical area are provided in Appendix 3.

### *3.2 Uncertainties and Statistical Modelling*

The estimation of measurement uncertainties in the Electrical area follows the principles of the ISO Guide to the Expression of Uncertainty in Measurement [1] and UKAS document M3003 [2]. However, in some areas of their application, these documents are believed to be technically insufficient, and to lack mathematical detail and good worked examples.

For example:

- There is material describing statistical tests for the comparison of estimates of the mean statistic, but not for the standard deviation statistic. There is a requirement for this in the DC and low frequency theme.
- Where measurements are complex-valued, the estimation of measurement uncertainties lies outside the scope of these documents.
- The estimation of uncertainties associated with deconvolution operations is not covered. There is a requirement for this in the Ultrafast theme.
- Measurements taken in the Electrical area may be highly correlated, and this is insufficiently covered within these documents.
- Measurements taken in the Electrical area may include outliers, and the use of robust statistical analysis techniques, such as those based on trimmed means and median estimators, lies outside the scope of these documents.
- There is a lack of guidance concerning the statistical analysis of data arising from interlaboratory comparisons.

It is generally the case that Type A contributions to uncertainty budgets are well understood as they can be quantified from the analysis of repeat measurements. But, as for many other metrology disciplines, difficulties arise in quantifying Type B contributions, and the tendency is to be pessimistic when estimating these. For example, in the DC and low frequency theme, it is environmental effects, such as temperature and humidity, that are often the dominant contributions to the overall uncertainty budget, and these effects are regarded as Type B and assigned a rectangular distribution.

### *3.3 Visual Modelling and Data Visualisation*

To date, visual modelling and data visualisation has not been greatly used within the Electrical area. However, this situation is now changing with the number of applications of visual modelling and data visualisation increasing significantly, and visualisation playing an important role in the following areas:

- The presentation of large quantities of data. For example, in the RF and microwave guided wave theme, calibration certificates can contain between 5000 and 10000 individual results, and there may be some benefit in a graphical presentation of these results.
- The visualisation of a number of correlated complex-valued quantities requiring dynamic visualisation within many dimensions.
- The electro-optic mapping of fields for MMIC measurements requires 2-dimensional presentation.

- Measurement of non-stationary waveforms, or in non-stationary conditions, as in the measurement of fluctuating harmonics in the DC and low frequency theme.

### 3.4 Data Fusion

Data fusion is generally seen to have limited application within the Electrical area, although the following particular problems are identified:

- In the Ultrafast theme, the matching of measurement data sets with different origins by appropriate shifting and scaling of those sets is undertaken. Generally, *ad hoc* methods are used at present for doing this.
- Where temperature is estimated from measurements made with a number of temperature sensors, no account is taken of the correlation between the sensor readings that arises from the calibration of the sensors using common calibration standards.

## 4. Validation and Testing

### 4.1 Spreadsheets and Other Mathematical Software Packages

In the RF and microwave guided wave theme, the use of commercial spreadsheet packages for data manipulation and presentation is widespread. As a consequence, there is a real requirement in this area for assurance to be provided concerning spreadsheet quality including information about the parameter ranges over which specific in-built functions are accurate and fit for purpose. The use of spreadsheets is seen to be unavoidable, and work in this area needs to reflect this and to concentrate on providing guidelines and information to underpin the use of such packages.

In addition, the requirement for validation and testing is not restricted to spreadsheets, such as Excel and Lotus 1-2-3, but applies similarly to other packages used in the Electrical area, including Visual-Basic, LabVIEW, Mathematica, MathCad and Matlab.

In the RF and microwave free field theme, the use of spreadsheets is restricted to simple calculations and their use is excluded from accredited measurement services. Limited testing of spreadsheet models is undertaken and includes

- comparison with hand calculation,
- spot checks of in-built functions such as the natural logarithm function, and
- the use of locked cells.

In the Ultrafast theme, spreadsheets are increasingly being used as part of research and development projects to investigate “what if” scenarios. Examples of such projects include the processing of experimental data in electrical waveform metrology and the analysis of calorimeter outputs from laser energy measurements. HT-Basic and LabVIEW software has been written to output data to files in a format that is suitable for direct input into Excel where further analysis is carried out. The Excel “Solver” function is used to fit various functions to the data, including sine waves (to determine the period of a cycle to calibrate timebases) or multiple exponentials (calorimeter responses). Uncertainties, for example, in a cycle period or the decay time of an exponential, are difficult to determine and, at present, tend to be determined by varying system parameters and seeing the influence on the root-mean-square residual error as well as the visual fit.

In other parts of the Electrical area, the use of spreadsheets is restricted to financial calculations and the presentation of results.

It is not common for a user of a commercial package to seek assurances from software suppliers that mathematical functions included in the package employ algorithms that are valid, accurate and stable over the likely range of values of the user's input data. It tends to be assumed that the developer of the commercial package will ensure that this is so.

### 4.2 Model Validation

Where possible, the models used in the Electrical area are validated. This is done, for example, by comparing quantities predicted by a computed model with results that can be measured independently or calculated from theoretical considerations. Where physical models are used, these are underpinned by theoretical analysis, and are generally accepted on this basis. Where empirical models are used, comparison of the results derived from models taken from within a *family* of functions may be undertaken.

### 4.3 Measurement System Validation

The approach taken to measurement system validation is generally to apply black-box testing to the system as a whole.

Instruments, such as oscilloscopes, used in the Ultrafast theme, contain software for performing numerical data processing. This software is validated by comparing the results returned by the instrument with results calculated using software written at NPL. This approach is akin to using reference software to generate reference data sets and results. In some cases, it is possible to inject the data into the instrument, but generally this is not done and the measurement system is tested in its entirety.

Even "simple" instruments, such as DVMs, used in the Electrical area, contain software for operating on the raw measurement data. For example, software is often included to undertake digital filtering. Typically, details of the algorithms used are not documented, and the software implementing the algorithm is not accessible to the user.

In addition, there are many instruments, such as network analysers, that contain software for performing significant numerical computation. For such instruments, the only feasible approach to validating them is to use calibrated components and artefacts. Furthermore, users of such instruments will tend to rely on the fact that the instruments have undergone a sensible design (in terms of both hardware and software). Ideally, these instruments would record their raw inputs and outputs so that the processing undertaken by the instrument could be independently validated.

## 5. Metrology Software Development Techniques

### 5.1 Software development methods

Software development within the Electrical area is undertaken according to NPL's software quality procedures. NPL is certified to ISO 9000 plus TickIT. However, a number of different approaches to software development are used within the Electrical area. These are described below.

#### 5.1.1 DC and low frequency theme

In the DC and low frequency theme, software is developed both for

- instrument control, and
- data processing.

Instrument control software is developed for hardware that is designed and built in-house. The data processing software is generally not complicated, covering simple statistical calculations and linear regression, and is also developed in-house. The requirement is for the software to be

- easily adapted, and
- easily controlled.

This is achieved by establishing pre-compiled modules (in Turbo-Pascal) that are combined into high-level macros geared to identified measurement tasks. This enables a high-level of software re-use and consequently reduces software maintenance costs (Section 5.2). Furthermore, the generated macro provides a statement of the processing undertaken, as well as enabling the measurement chain linking raw data to measurement result to be recreated. The approach is necessary because the particular use of instruments, and the way they are linked within the measurement chain, can change from day to day, but traceability from measurement data to measurement results must be maintained.

This approach to software development was initiated over ten years ago at a time when no commercial package could offer the desired flexibility. Even today, it is not clear whether modern commercial packages could satisfy the requirements of this theme.

### 5.1.2 RF and microwave free field theme

In the RF and microwave free field theme, as in the other themes, software plays a crucial part in supporting the measurement services provided. These are significant activities within this theme.

In the measurement of antenna gain, a measurement run can take of the order of 30 hours, and the software program involved may be controlling between 15 and 20 instruments. Software is used both for instrument control and data acquisition, and data processing. Software for the former was developed in (standard) Pascal. There is currently activity aimed at upgrading the software to operate within a PC environment. The use of a standard language will facilitate this upgrade and, furthermore, as the software is used by only a small number of trained users, a simple interface to the software can be maintained. The data processing software was developed in FORTRAN and uses the NAG library, which is known to contain high quality software modules, for performing numerical calculations such as polynomial curve fitting.

In the measurement of power-flux density and field strength, about 10 programs are used to cover the various types of equipment configurations and measurement set-ups. Again, the original software development was undertaken in Pascal. The software allows a unique reference identifier to be stored for each calibrated device, and includes an interface to certificate production software implemented in WordPerfect. Only simple data processing is undertaken. This software illustrates some of the problems that can arise with legacy software, i.e., software classified within the Quality System as extant (Section 5.2). The costs associated with upgrading or modifying the software are seen to outweigh the benefits that may be obtained from those modifications. The alternative is to consider re-writing the software, but development to the level required by the Quality System is also seen to involve considerable overheads and costs.

### 5.1.3 RF and microwave guided wave theme

In the RF and microwave guided wave theme, instrument control has been based around Hewlett-Packard architectures and languages, including HP-Basic. Effort is currently being put into bringing this software into a contemporary PC environment (Section 5.2).

### 5.1.4 Ultrafast theme

In the Ultrafast measurement theme, software development revolves around a small number of programs, each of the order of 20000 lines, written in HT-Basic and HP-Basic. The approach here is to *upgrade* the software as necessary to include new functionality rather than to *customise* the software to each measurement task. The approach works well provided appropriate software control mechanisms are put in place. Software is developed in this way for both data acquisition and data processing. The latter includes data smoothing using cubic polynomial splines and performing operations on these functions, calculating Fast Fourier Transforms (FFTs), regression (linear and nonlinear), and deconvolution operations. The output of this processing is directed to files and graphs when it is to be used in research and development projects, and certificates and technical reports. Further processing of the results using Excel may be undertaken (Section 4.1).

Following the proposal that LabVIEW should be the preferred software package for instrument control at NPL, LabVIEW was adopted in a new project to develop a technique for measuring MMICs and also for upgrading laser power and energy calibration software from an obsolete Tektronix platform to a PC system. While the results of this development have been satisfactory, and the developers and users like the LabVIEW software, the training cost is very substantial and it is felt that the cost of transferring all the software within the theme would not be justified, particularly given the investment and expertise in HT-Basic. In addition, the in-line code of HT-Basic is felt to be simpler for much of the processing of the data.

## *5.2 Software reuse*

As described in Section 5.1, software re-use is seen as an important means of reducing software maintenance costs. In some instances, software *re-use* takes the form of software *re-engineering* where existing software is modified for use in a similar context or to solve a similar problem.

There is generally a trend to migrate applications to modern systems, both hardware and software. As noted in Section 5.1, some legacy software suffers from hardware incompatibilities and will not operate on modern systems. In these cases, it can be difficult to re-use or re-engineer software, and consequently there can be significant overheads and costs involved in upgrading these systems, particularly within the context of Quality Systems.

Mixed language programming is beginning to be used in software development undertaken in the RF and microwave guided wave theme. Data acquisition and instrument control software is developed in Visual-Basic, and the numerical processing of the acquired data is performed using software written in FORTRAN. This approach has enabled substantial re-use of high-quality mathematical software routines that have traditionally been developed in FORTRAN. The FORTRAN NAG library (available on NPL's mainframe computer) is widely used within the Electrical area.

The Year 2000 (Y2K) problem has been recognised for some time. NPL has a task group working on this issue and is responsible for testing every piece of appropriate equipment for Y2K compliance.

### 5.3 Virtual Instruments

The use of LabVIEW is generally restricted to the development of prototype applications: see Section 5.1. Some new development within the DC and low frequency theme is being undertaken. Furthermore, in the Ultrafast theme, LabVIEW is used for the development of production software (software integrity level 3 in the NPL Quality System) within a number of projects (Section 5.1).

## 6. Support for Measurement and Calibration Processes

### 6.1 Automation of Measurement and Calibration Processes

It is generally recognised that it is a costly exercise to generate a calibration certificate. A Laboratory Information Management System (LIMS) is seen to provide a possible solution, but *reliability* of the system is an essential requirement. This is particularly so in the RF and microwave free field theme where a very large number of calibrations for customers is undertaken each year.

Within the DC and low frequency theme, a LIMS specific to that activity is currently being used. Elsewhere, a pilot LIMS is being implemented in the RF and microwave free field theme, with the intention of using the experience gained in this area to inform the other themes as well as other metrology programmes at NPL.

### 6.2 Format Standards for Measurement Data

There is generally little requirement within the Electrical area for format standards for measurement data. Where there is a requirement for transmitting or sharing measurement data and results with other organisations, the data is usually stored in the form of ASCII files or as spreadsheet files.

## 7. Suggestions for Future Activities

### 7.1 Expected Benefits of the SSfM Programme

Benefits for the Electrical area arising from the SSfM programme are looked for in the following areas:

- Modelling: for example, with regard to handling errors in all variables.
- Uncertainty estimation: particularly covering complex-valued variables, correlation, robust estimation, and the analysis of data from interlaboratory comparisons.

  The microwave reflectometer, as an example of a measurement system described by a model that is not directly dealt with by the documents [1, 2], has been used within the SSfM Uncertainties and Statistical Modelling project.

  A new milestone in the SSfM Uncertainties and Statistical Modelling project concerned with uncertainty aspects of interlaboratory comparisons will satisfy part of the requirement identified here.
- Validation of mathematical software packages: particularly, their in-built functions.

- Model validation: for example, the use of refinement in validating finite element model solutions.
- Support to software development by way of guidance and tools to help the development process.

### *7.2 Case Studies and Feasibility Studies*

Possible case studies and feasibility studies in the following areas have been identified:

- The application of robust methods for the statistical analysis of measurement data including that obtained from interlaboratory comparisons.
- The application of visual modelling techniques to the presentation of large quantities of data representing correlated complex-valued quantities, including the presentation of such models on interactive Web pages.
- The transfer of LIMS experience from the DC and low frequency and RF and microwave free field themes to the other themes in the Electrical area and possibly other metrology fields.

### *7.3 Future SSfM Topics*

There are a number of examples where novel tools for data processing are finding application within the Electrical area. These include the use of *wavelets* for harmonic analysis, *non-parametric* and *robust* methods for statistical analysis, and *genetic algorithms* for the design of instruments and measurement strategies. A generic study to identify the advantages of these tools over more traditional analysis methods, as well as their limitations, would help to promote the application of these tools across metrology and to support their particular application within the Electrical area.

Measurement system validation and the need to establish traceability of software embedded within instruments can be expected to continue to be of concern within the Electrical area. The example of a *multi-function calibrator* will provide a stern test of the work on metrology software development techniques carried out within the current SSfM programme, and will provide a suitable case study for disseminating and extending this work within the next SSfM programme.

There are a number of standards, e.g., in the EMC area, that are expected to benefit from a review of their mathematical and statistical aspects. Activity aimed at developing and influencing generic standards, or standards to be referenced by other standards, will help to promote good practice and uniformity across metrology areas.

In recent years, the use of the internet has greatly improved the ability to communicate efficiently between two or more remote locations. There is growing interest in exploring ways in which the internet might be used within metrology applications. This has led to some work within the RF and guided wave theme to consider how the internet might be used to transfer national standard measurement accuracy direct to the end-user by facilitating remote calibrations of customer's instruments. There is scope here for activity to undertake work on generic aspects to support this study, and to promote the idea within other metrology areas.

Finally, the use of visual modelling and data visualisation techniques in the Electrical area is expected to grow in the future as particular applications of these techniques (some of which are listed in Section 3.3) are identified. These applications can be expected to benefit from continued generic work and support in this area.

### *7.4 Future Electrical Programme Topics*

There are a number of SSfM topics that are expected to benefit the Electrical programme: these are detailed in Sections 7.1, 7.2 and 7.3. These could be progressed either in the Electrical programme, in the current or future SSfM programmes, or perhaps more usefully as combined activity between the Electrical and SSfM Programmes.

# 8. Summary of Changes

The principal changes from the initial restricted status report on the Electrical area are as follows:

- application of visual modelling and data visualisation (Section 3.3) to the Electrical area reviewed,
- subsections describing software development methods (Section 5.1) re-ordered to correspond to Electrical programme themes,
- the addition of future SSfM and Electrical programme topics.

# 9. Acknowledgements

We gratefully acknowledge the help provided by Stuart Pollitt, David Gentle, Nick Ridler, Alan Roddie, Jonathan Williams and Paul Wright in providing input to this report and in reviewing drafts.

# Appendix 1: Glossary of Abbreviations

| **Abbreviation** | **Expansion** |
|---|---|
| AC | Alternating Current |
| ANA | Automatic Network Analyser |
| ASCII | American Standard Character for Information Interchange |
| DC | Direct Current |
| DVM | Digital Voltmeter |
| EMC | Electromagnetic Compatibility |
| Hz | Unit of frequency (hertz) |
| ISO | International Organization for Standardization |
| LIMS | Laboratory Information Management System |
| MMICs | Monolithic Microwave Integrated Circuit |
| NAG | Numerical Algorithms Group (Ltd.) |
| NIST | National Institute of Standards and Technology (US) |
| NMS | National Measurement System |
| NPL | National Physical Laboratory |
| PC | Personal Computer |
| RF | Radio Frequency |
| SSfM | Software Support For Metrology |
| UKAS | United Kingdom Accreditation Service |
| Y2K | Year 2000 |

# Appendix 2: Bibliography

1. *Guide to the Expression of Uncertainty in Measurement*, International Organization for Standardization, 1993, ISBN 92-67-10188-9.
2. *M3003: The Expression of Uncertainty and Confidence in Measurement*, United Kingdom Accreditation Service, 1997.
3. Rayner, D., *Initial Report on the Status of Software and Mathematics in each Metrology Area*, NPL Report CISE 18/99, February 1999.

# Appendix 3: Modelling Techniques

In this appendix we give some further detail relating to the modelling techniques (Section 3) undertaken in the Electrical area. In the following tables, a score of 1 is used to imply that the statement to the left is true (nearly) all the time, whereas a score of 5 implies the statement on the right is true (nearly) all the time. It is recognised that for certain of the questions, there can be considerable variation in the way that a score is assigned. In these cases, the score is intended to indicate an "averaged" answer across the area.

1. Are the models used in the given area of metrology typically **simple or complicated**?

| Simple | Score | Complicated |
|---|---|---|
| Simple relationship between input and output. | 3 | Pages of equations to describe the system. |
| Small number of parameters. | 3 | Large number of parameters, with complicated inter-relationships. |
| Measurement errors limited to one measured quantity. | 3 | Many variables subject to significant measurement error. |
| Measurement errors consistent with Gaussian distribution. | 4 | Non-Gaussian behaviour, outliers likely. |
| Input quantities well controlled, understood. | 2 | Inputs estimated, not all influence factors have been identified. |

2. Are the models used in the given area of metrology typically **accepted or speculative**?

| Accepted | Score | Speculative |
|---|---|---|
| Well understood physical theory accepted by all. | 3 | A number of competing models in vogue.<br>Some components modelled by empirical functions, e.g. polynomials, splines. |
| Comprehensive theory adequately taking into account all main features. | 3 | Approximations employed, terms omitted to simplify model.<br>Behaviour of some components not understood and/or ignored. |

3. Are **uncertainties** in the input quantities typically **incorporated adequately**? (This question really relates to Section 3.2 but is included here for completeness.)

| | Score | |
|---|---|---|
| All main sources of measurement uncertainty modelled. | 3 | Only some measurement errors modelled. Other quantities taken as exact. |
| Variances and correlation amongst inputs taken into account. | 4 | |

4. Are the methods of model solution typically **approximate or comprehensive**?

| Comprehensive | Score | Approximate |
|---|---|---|
| Solution method solves the computational problem posed by the model. | 3 | Approximations are employed. Some terms simplified/linearised/ignored. |
| Solution method takes into account the sources of measurement error, variances and correlation amongst the input quantities. | 3 | Easiest method of finding a solution employed. Data weighted inappropriately. |

5. Do the methods of model solution used in the given area of metrology **perform as expected**?

| Expected | Score | Exceptional |
|---|---|---|
| Solutions consistent with those predicted by theory, established by other methods. | 2 | Solutions at variance with other results. |
| Method always returns a solution. | 2 | Method produces unrealistic solutions, fails to provide a solution, crashes. |
| Rerunning the method on perturbed data/ input quantities/ produces a nearby solution. | 2 | Small changes in the input data/quantities produces large changes in the output. |
| Iterative method converges quickly. | 2 | Method can make slow progress, fail to converge. |
| Estimate of statistical uncertainties consistent with the expected measurement error, noise in the data. | 3 | Unrealistic uncertainties calculated. |

6. Are there **adequate ways to validate the model**? (This question really relates to Section 4.2 but is included here for completeness.)

| Good validation | Score | Poorly validation |
|---|---|---|
| Fit of model to the measurement data consistent with the expected measurement error. | 2 | Residual error much larger than expected, have a systematic pattern. |
| Results agree with other methods of calculation. | 2 | |
| Results agree in situations for which an analytic/reference solution exists. | 2 | Solutions at variance with other results. |
| Numerical results in accordance with predicted behaviour of the algorithm (rate of convergence). | 2 | Behaviour at variance with prediction. |