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Automation of Measurements in the dclf Laboratory of the CSIR NML

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Abstract

At the end of 2005 it was decided that a number of measurements performed in the dc Low Frequency (dclf) Laboratory of the CSIR National Metrology Laboratory (CSIR NML) could benefit from automation. The measurements identified were typically highly repetitive, and being performed using measuring instruments that can be connected to a computer with relatively little effort.

A number of commercial instrumentation automation software packages were evaluated, but these packages were found to be too expensive for the purposes of a National Metrology Institute, given the programming experience available to the dclf laboratory. The software packages described in this paper were all written in Borland Delphi. To date, the following measurements were automated: calibration of digital multimeters up to 6.5 digits; capacitance measurements of a single standard capacitor and decade capacitors; and ac power measurements of single and three phase sources and meters.

The following measurements are in the process of being automated: RLC measurements (inductance, resistance, and capacitance); ac-dc difference measurements and resistor calibration result analysis. The approach followed, software structure, validation and implementation of the software will be discussed. As these software packages automatically calculate the uncertainty of measurement, some time will be spent on the algorithms used for this purpose.

1. Introduction

The CSIR NML is the custodian of the national measurement standards for South Africa. In the dc Low Frequency (dclf) laboratory of the CSIR NML the following parameters are maintained: dc voltage, dc resistance, impedance, ac/dc difference, ac power and energy.

Many of these measurements are performed using very modern measuring equipment, the result of extensive capital investment in recent years. These measurements are still performed in a mostly manual fashion, using manpower that could be applied much more efficiently.

Given the nature of most of these instruments and measurement, it is easy to see how the laboratory could benefit from automation. A cost / benefit analysis showed that the benefit in manpower savings far outweigh the cost of software development. This lead to the automation tasks reported here.

2. Software strategy

Having decided that automation of the measurement systems in the dclf laboratory was a priority, a strategy to achieve this objective in the most efficient way was formed. This included the evaluation of commercial measurement automation software packages, interface strategies, and other factors. It was found that the commercial software available for the task was prohibitively expensive, weighed up against the high level programming language experience available to the laboratory. Even the most advanced of these packages still requires the setting up of measurement or calibration files, and post processing of the measurement data.

Once the decision was taken not to use a commercial measurement package, a choice had to be made between the two packages that had the most experience available in the laboratory. These were National Instruments Labview™, and Borland Delphi. Although Labview™ has many usable features available as pre-packaged virtual instrument (vi) modules, the choice was made to use Delphi as Labview™ does not have the powerful low level control possibilities of Delphi. A quick “showdown” programming exercise in the laboratory adequately proved this point.

The next step in the project was to decide which measurement to automate first. Part of the first project included the development of a common interface for the automation software to be implemented. This will enable the metrologists in the laboratory to easily familiarise themselves with the different automated measurement systems.

The strategy also included a common structure to the software, common data output structures, and common validation strategies. A common documentation and version control system is used for the software. The validation is performed by comparing results obtained using the software with results obtained using the manual methods. Validation of uncertainty calculations are performed by comparing software outputs with manually calculated values using the same inputs. All possible scenarios are evaluated during validation, as far as this is possible. The detailed validation report is then filed with the software.

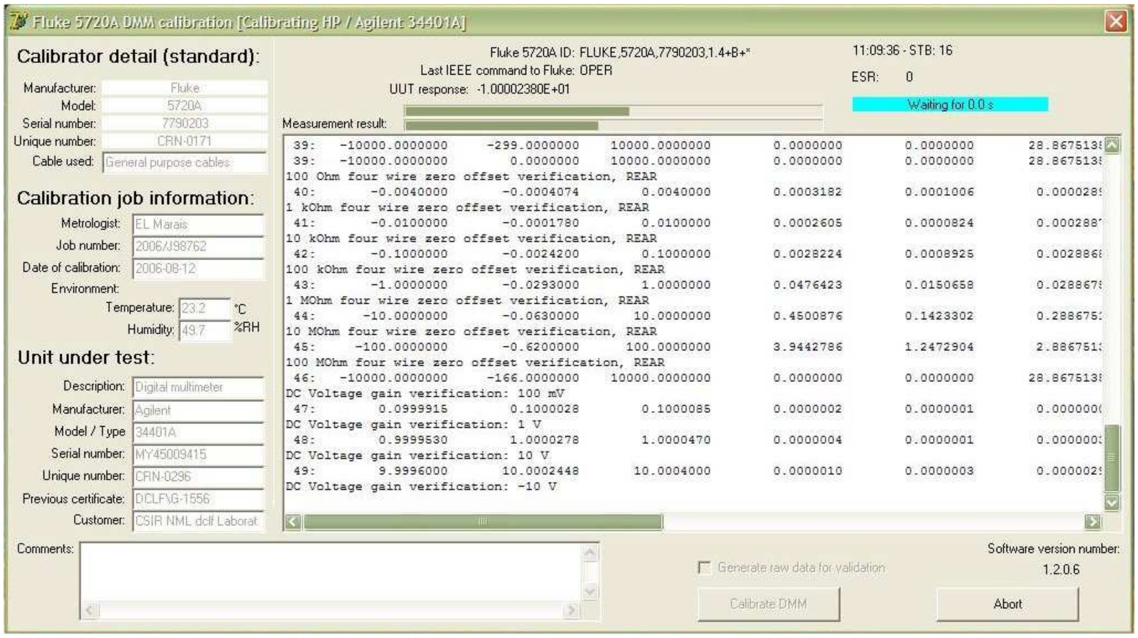
There is no paperwork associated with any of the developed software packages; all information is available from within the software. Part of the strategy also includes training of laboratory personnel in the use of the software, and active participation in testing and using the software.

3. Work to date

3.1. Multimeter calibration.

The first software package to be written was for the calibration of multimeters. The software was written very generally to interpret a text file containing calibration instructions. The software can at present only perform calibration of meters having General Purpose Interface Bus (HPIB) interfaces, but it is planned to include serial interfaced instruments (RS232, USB, etc.), and manually controlled instruments in future. The interface for this package is shown in figure 2, the physical measurement setup in figure 2, an extract of a calibration file in figure 3, and an extract from a results file in figure 4.

For this software package, a pseudo-language was developed for interpretation of calibration commands. It can contain comments, instructions to the user of the software, calibration commands, wait commands (for stabilisation after connection changes) and GPIB instructions for the instrument under calibration. This significantly reduces the complexity of the main calibration program, and allows exceptional flexibility. It also allows for the easy modification of a calibration sequence for special purposes. The use of the software removes the influence of the operator from the calibration, thus improving the measurement uncertainties.



Calibrator detail (standard):
Manufacturer: Fluke
Model: 5720A
Serial number: 7790203
Unique number: CRN-0171
Cable used: General purpose cables

Calibration job information:
Metrologist: EL Marais
Job number: 2006/J98762
Date of calibration: 2006-08-12
Environment:
Temperature: 23.2 °C
Humidity: 49.7 %RH

Unit under test:
Description: Digital multimeter
Manufacturer: Agilent
Model / Type 34401A
Serial number: MY45009415
Unique number: CRN-0296
Previous certificate: DCLF\G-1556
Customer: CSIR NML dclf Laborat

Comments:

Fluke 5720A ID: FLUKE,5720A,7790203,1.4+B+*
Last IEEE command to Fluke: OPER
UUT response: -1.00002380E+01
11:09:36 - STB: 16
ESR: 0

Measurement result:

```
 39:   -10000.0000000     -299.0000000    10000.0000000        0.0000000        0.0000000        28.867513
 39:   -10000.0000000        0.0000000    10000.0000000        0.0000000        0.0000000        28.867513
100 Ohm four wire zero offset verification, REAR
 40:       -0.0040000       -0.0004074        0.0040000        0.0003182        0.0001006         0.000028
1 kOhm four wire zero offset verification, REAR
 41:       -0.0100000       -0.0001780        0.0100000        0.0002605        0.0000824         0.000288
10 kOhm four wire zero offset verification, REAR
 42:       -0.1000000       -0.0024200        0.1000000        0.0028224        0.0008925         0.002886
100 kOhm four wire zero offset verification, REAR
 43:       -1.0000000       -0.0293000        1.0000000        0.0476423        0.0150658         0.028867
1 MOhm four wire zero offset verification, REAR
 44:      -10.0000000       -0.0630000       10.0000000        0.4500876        0.1423302         0.288675
10 MOhm four wire zero offset verification, REAR
 45:     -100.0000000       -0.6200000      100.0000000        3.9442786        1.2472904         2.886751
100 MOhm four wire zero offset verification, REAR
 46:   -10000.0000000     -166.0000000    10000.0000000        0.0000000        0.0000000        28.867513
DC Voltage gain verification: 100 mV
 47:        0.0999915        0.1000028        0.1000085        0.0000002        0.0000001         0.000000
DC Voltage gain verification: 1 V
 48:        0.9999530        1.0000278        1.0000470        0.0000004        0.0000001         0.000000
DC Voltage gain verification: 10 V
 49:        9.9996000       10.0002448       10.0004000        0.0000010        0.0000003         0.000002
DC Voltage gain verification: -10 V
```

Software version number:
1.2.0.6

Figure 1: Multimeter calibration interface.

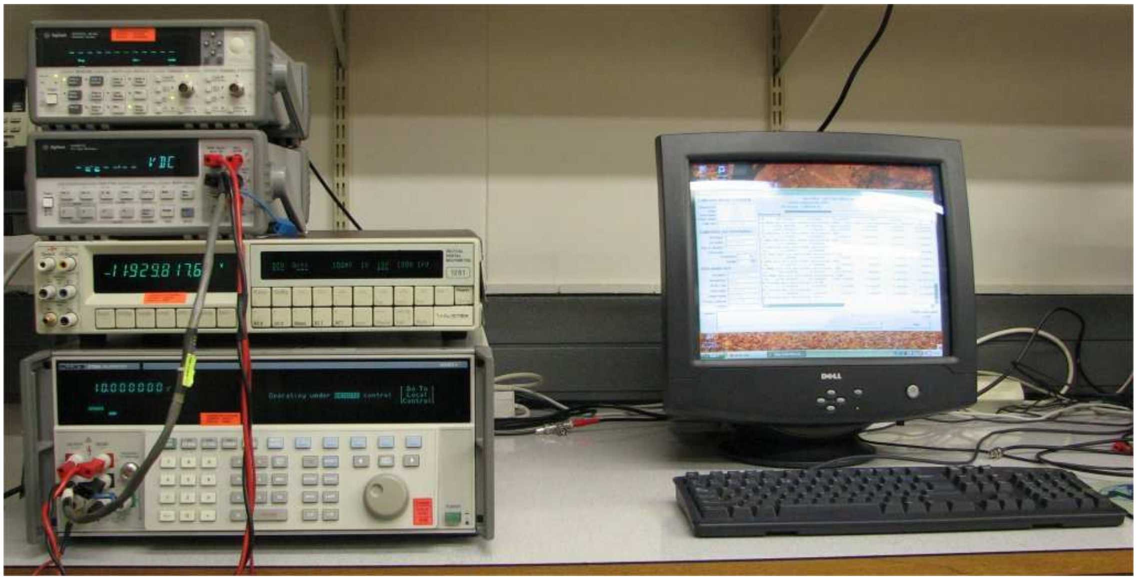
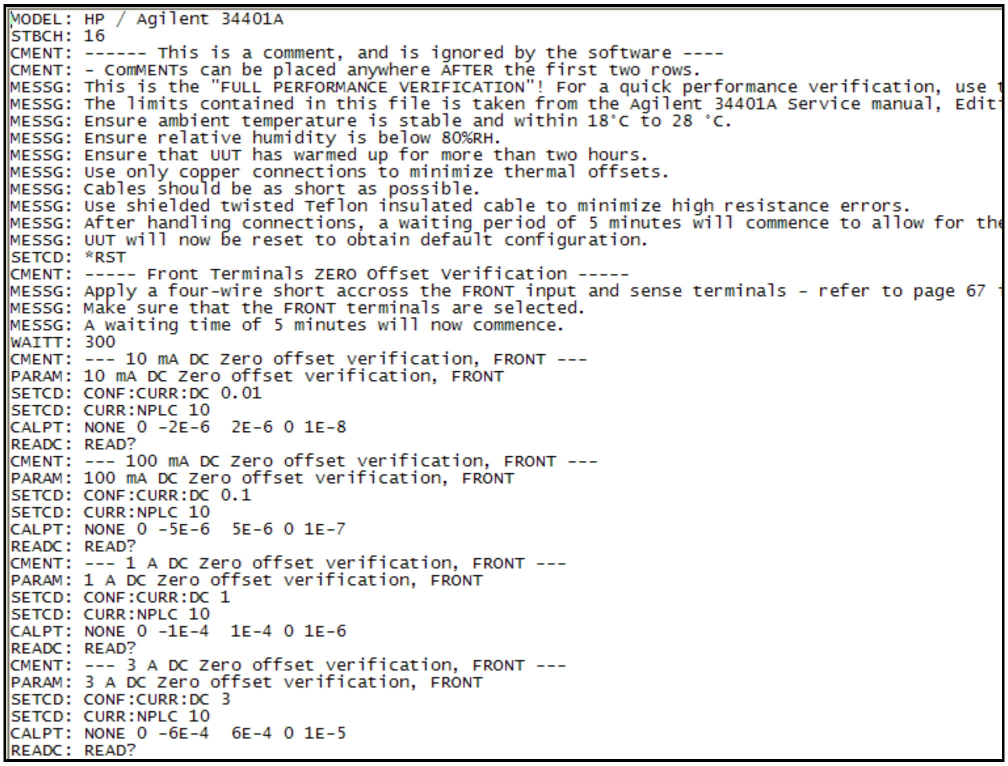
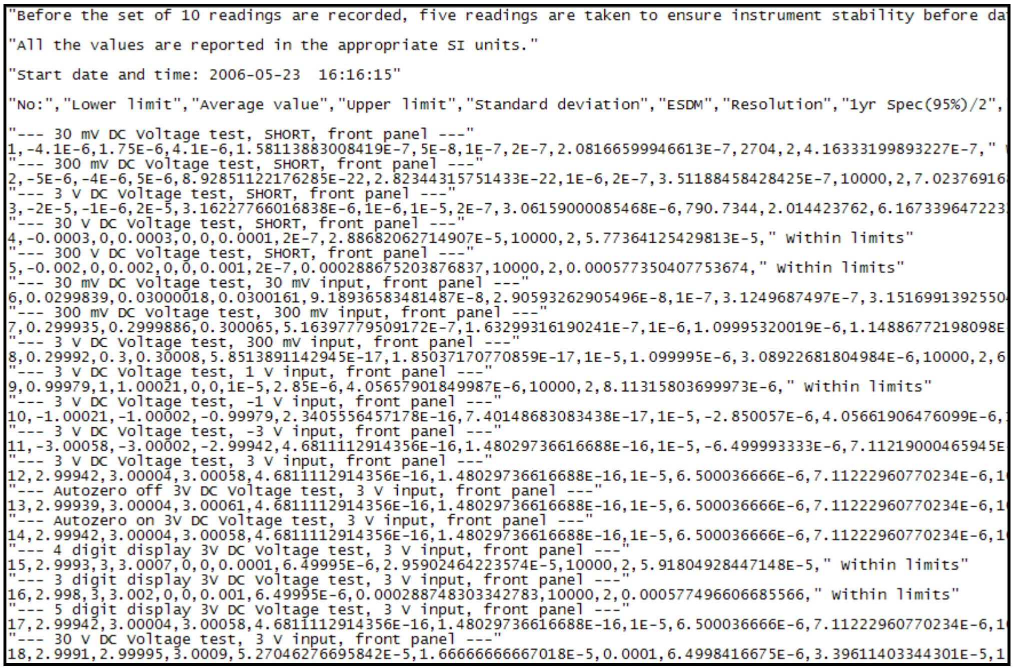


Figure 2: DMM calibration system setup.



```
MODEL: HP / Agilent 34401A
STBCH: 16
CMENT: ------ This is a comment, and is ignored by the software ----
CMENT: - CoMMENTS can be placed anywhere AFTER the first two rows.
MESSG: This is the "FULL PERFORMANCE VERIFICATION"! For a quick performance verification, use
MESSG: The limits contained in this file is taken from the Agilent 34401A Service manual, Edit
MESSG: Ensure ambient temperature is stable and within 18°C to 28 °C.
MESSG: Ensure relative humidity is below 80%RH.
MESSG: Ensure that UUT has warmed up for more than two hours.
MESSG: Use only copper connections to minimize thermal offsets.
MESSG: Cables should be as short as possible.
MESSG: Use shielded twisted Teflon insulated cable to minimize high resistance errors.
MESSG: After handling connections, a waiting period of 5 minutes will commence to allow for th
MESSG: UUT will now be reset to obtain default configuration.
SETCD: *RST
CMENT: ----- Front Terminals ZERO Offset Verification -----
MESSG: Apply a four-wire short accross the FRONT input and sense terminals - refer to page 67
MESSG: Make sure that the FRONT terminals are selected.
MESSG: A waiting time of 5 minutes will now commence.
WAITT: 300
CMENT: --- 10 mA DC Zero offset verification, FRONT ---
PARAM: 10 mA DC Zero offset verification, FRONT
SETCD: CONF:CURR:DC 0.01
SETCD: CURR:NPLC 10
CALPT: NONE 0 -2E-6  2E-6 0 1E-8
READC: READ?
CMENT: --- 100 mA DC Zero offset verification, FRONT ---
PARAM: 100 mA DC Zero offset verification, FRONT
SETCD: CONF:CURR:DC 0.1
SETCD: CURR:NPLC 10
CALPT: NONE 0 -5E-6  5E-6 0 1E-7
READC: READ?
CMENT: --- 1 A DC Zero offset verification, FRONT ---
PARAM: 1 A DC Zero offset verification, FRONT
SETCD: CONF:CURR:DC 1
SETCD: CURR:NPLC 10
CALPT: NONE 0 -1E-4  1E-4 0 1E-6
READC: READ?
CMENT: --- 3 A DC Zero offset verification, FRONT ---
PARAM: 3 A DC Zero offset verification, FRONT
SETCD: CONF:CURR:DC 3
SETCD: CURR:NPLC 10
CALPT: NONE 0 -6E-4  6E-4 0 1E-5
READC: READ?
```

Figure 3: Multimeter calibration file extract.



```
"Before the set of 10 readings are recorded, five readings are taken to ensure instrument stability before da

"All the values are reported in the appropriate SI units."

"Start date and time: 2006-05-23  16:16:15"

"No:","Lower limit","Average value","Upper limit","Standard deviation","ESDM","Resolution","1yr Spec(95%)/2",

"--- 30 mV DC Voltage test, SHORT, front panel ---"
1,-4.1E-6,1.75E-6,4.1E-6,1.58113883008419E-7,5E-8,1E-7,2E-7,2.08166599946613E-7,2704,2,4.16333199893227E-7,"
"--- 300 mV DC Voltage test, SHORT, front panel ---"
2,-5E-6,-4E-6,5E-6,8.92851122176285E-22,2.82344315751433E-22,1E-6,2E-7,3.51188458428425E-7,10000,2,7.02376916
"--- 3 V DC Voltage test, SHORT, front panel ---"
3,-2E-5,-1E-6,2E-5,3.16227766016838E-6,1E-6,1E-5,2E-7,3.06159000085468E-6,790.7344,2.014423762,6.167339647223
"--- 30 V DC Voltage test, SHORT, front panel ---"
4,-0.0003,0,0.0003,0,0,0.0001,2E-7,2.88682062714907E-5,10000,2,5.77364125429813E-5," within limits"
"--- 300 V DC Voltage test, SHORT, front panel ---"
5,-0.002,0,0.002,0,0,0.001,2E-7,0.000288675203876837,10000,2,0.000577350407753674," within limits"
"--- 30 mV DC Voltage test, 30 mV input, front panel ---"
6,0.0299839,0.03000018,0.0300161,9.18936583481487E-8,2.90593262905496E-8,1E-7,3.1249687497E-7,3.1516991392550
"--- 300 mV DC Voltage test, 300 mV input, front panel ---"
7,0.299935,0.2999886,0.300065,5.16397779509172E-7,1.63299316190241E-7,1E-6,1.09995320019E-6,1.14886772198098E
"--- 3 V DC Voltage test, 300 mV input, front panel ---"
8,0.29992,0.3,0.30008,5.8513891142945E-17,1.85037170770859E-17,1E-5,1.099995E-6,3.08922681804984E-6,10000,2,6
"--- 3 V DC Voltage test, 1 V input, front panel ---"
9,0.99979,1,1.00021,0,0,1E-5,2.85E-6,4.05657901849987E-6,10000,2,8.11315803699973E-6," within limits"
"--- 3 V DC Voltage test, -1 V input, front panel ---"
10,-1.00021,-1.00002,-0.99979,2.3405556457178E-16,7.40148683083438E-17,1E-5,-2.850057E-6,4.05661906476099E-6,
"--- 3 V DC Voltage test, -3 V input, front panel ---"
11,-3.00058,-3.00002,-2.99942,4.6811112914356E-16,1.48029736616688E-16,1E-5,-6.499993333E-6,7.1121900046594 5E
"--- 3 V DC Voltage test, 3 V input, front panel ---"
12,2.99942,3.00004,3.00058,4.6811112914356E-16,1.48029736616688E-16,1E-5,6.500036666E-6,7.11222960770234E-6,1
"--- Autozero off 3V DC Voltage test, 3 V input, front panel ---"
13,2.99939,3.00004,3.00061,4.6811112914356E-16,1.48029736616688E-16,1E-5,6.500036666E-6,7.11222960770234E-6,1
"--- Autozero on 3V DC Voltage test, 3 V input, front panel ---"
14,2.99942,3.00004,3.00058,4.6811112914356E-16,1.48029736616688E-16,1E-5,6.500036666E-6,7.11222960770234E-6,1
"--- 4 digit display 3V DC Voltage test, 3 V input, front panel ---"
15,2.9993,3,3.0007,0,0,0.0001,6.49995E-6,2.95902464223574E-5,10000,2,5.91804928447148E-5," within limits"
"--- 3 digit display 3V DC Voltage test, 3 V input, front panel ---"
16,2.998,3,3.002,0,0,0.001,6.49995E-6,0.000288748303342783,10000,2,0.000577496606685566," within limits"
"--- 5 digit display 3V DC Voltage test, 3 V input, front panel ---"
17,2.99942,3.00004,3.00058,4.6811112914356E-16,1.48029736616688E-16,1E-5,6.500036666E-6,7.11222960770234E-6,1
"--- 30 V DC Voltage test, 3 V input, front panel ---"
18,2.9991,2.99995,3.0009,5.27046276695842E-5,1.66666666667018E-5,0.0001,6.4998416675E-6,3.39611403344301E-5,1
```

Figure 4: Multimeter results file extract.

The high number of multimeters, especially 6.5 digit meters, received by the laboratory for calibration (mostly from internal clients), prompted the urgency of this project. The standard used for most calibrations is a Fluke model 5720A calibrator. A requirement for the calibration of higher accuracy multimeters (typically 8.5 digit meters) exists in the laboratory.

The software was adapted to enable the use of artefact standards, typically in cases where the accuracy specification of the calibrator cannot meet the accuracy requirements for the calibration of these meters.

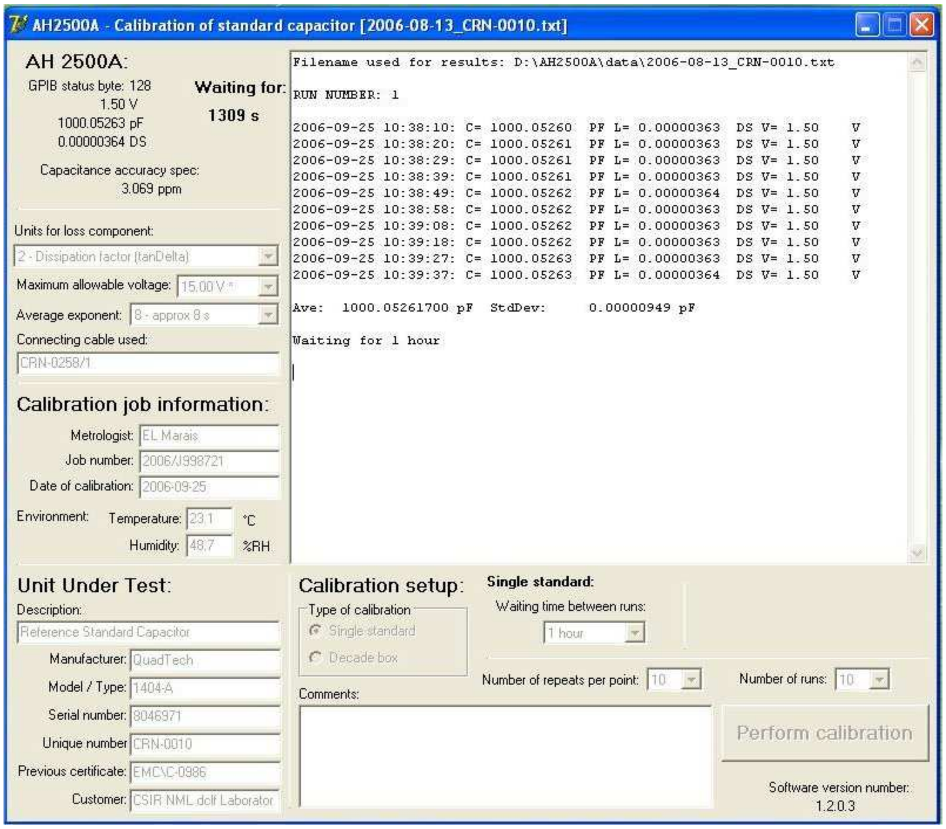
This makes the software ideal for use in a high level metrological institute.

The software currently calculates the uncertainty of measurement for each measurement point, and gives an indication whether the instrument complies with its specification. The metrologist must still transfer the measurement results to the calibration certificate. The automatic generation of calibration certificates is planned as a future project.

3.2. Capacitance calibration.

The software for calibration of capacitors is written to use the Andeen-Hagerling model 2500A high precision capacitance bridge. At present this limits the automatic calibration of capacitors to a frequency of 1 kHz. (Software for automation of the RLC digibridge is planned that will allow the automated calibration of impedance standards at other frequencies.)

Impedance was the first parameter taken over by the author at the end of 2005, and as such it was an ideal starting point for automation. The software has a similar "look and feel" as the multimeter calibration software, although the functionality is significant different. The user interface is shown in figure 5, and the physical measurement setup in figure 6. Comparison with the interface for multimeter calibration shows the similarities.



AH2500A - Calibration of standard capacitor [2006-08-13_CRN-0010.txt]

AH 2500A:

GPIB status byte: 128
1.50 V
1000.05263 pF
0.00000364 DS

Waiting for:
1309 s

Capacitance accuracy spec:
3.069 ppm

Units for loss component: 2 - Dissipation factor (tanDelta)
Maximum allowable voltage: 15.00 V *
Average exponent: 8 - approx 8 s
Connecting cable used: CRN-0258/1

Calibration job information:

Metrologist: EL Marais
Job number: 2006/J998721
Date of calibration: 2006-09-25
Environment: Temperature: 23.1 °C
Humidity: 48.7 %RH

Unit Under Test:

Description: Reference Standard Capacitor
Manufacturer: QuadTech
Model / Type: 1404-A
Serial number: 8046971
Unique number CRN-0010
Previous certificate: EMC\C-0986
Customer: CSIR NML dclf Laborator

Calibration setup:

Type of calibration
● Single standard
○ Decade box

Single standard:
Waiting time between runs: 1 hour
Number of repeats per point: 10
Number of runs: 10

Comments:

Software version number:
1.2.0.3

```
Filename used for results: D:\AH2500A\data\2006-08-13_CRN-0010.txt

RUN NUMBER: 1

2006-09-25 10:38:10: C= 1000.05260  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:38:20: C= 1000.05261  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:38:29: C= 1000.05261  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:38:39: C= 1000.05261  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:38:49: C= 1000.05262  PF L= 0.00000364  DS V= 1.50    V
2006-09-25 10:38:58: C= 1000.05262  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:39:08: C= 1000.05262  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:39:18: C= 1000.05262  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:39:27: C= 1000.05263  PF L= 0.00000363  DS V= 1.50    V
2006-09-25 10:39:37: C= 1000.05263  PF L= 0.00000364  DS V= 1.50    V

Ave:  1000.05261700 pF  StdDev:     0.00000949 pF

Waiting for 1 hour
```

Figure 5: User interface for capacitance calibration.

Figure 6: Measurement setup for capacitance calibration.

For the calibration of single capacitors, the user can choose all significant measurement parameters, such as secondary units, measurement integration time, number of measurements per set, number of repeats, and waiting time between repeats. The software calculates the statistics per set, and the statistics based on the averages per set. This allows characterisation of the unit under test for short and medium term stability, significantly improving the level of service provided to customers. The software also calculates the uncertainty of measurement. Calculation of the specification of the capacitance meter is the most involved calculation, and putting this in place took a significant amount of time.

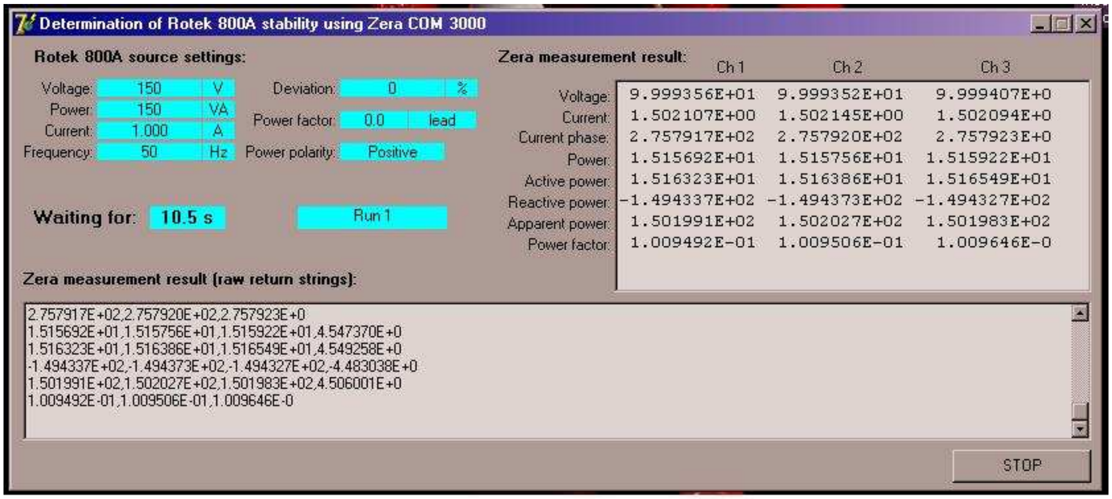
Calibration of decade devices is handled in a similar way, although presently the switches cannot be turned automatically. The user can once again choose all major parameters, such as number of decades, integration time, number of sets, and secondary parameter. The process still requires a lot of manpower, as the system must be monitored – the user still needs to switch the decade switches.

3.3. ac Power and Energy calibration.

ac Power and Energy automation software was a logical choice, given the easy automation of the power source and secondary power standard available to the laboratory. The high number of measurements required in a normal power or energy calibration also made this a good choice for automation.

The instruments currently used for calibration of customer devices are a Rotek model 800A power source and a Zera COM 3000. This software is the least mature of the three packages discussed in this paper, as can be seen from the user interface in figure 7. Figure 8 shows a typical measurement setup. The software reads a measurement instruction file, and interprets the instructions to perform the measurements.

Since a number of parameters are normally measured during the calibration of ac Power and Energy calibrations, it is possible to combine parameters during a single measurement. For this software, the data analysis and uncertainty calculations are still performed manually (it will be automated in a future project), but the volume of work for this parameter is reasonably low, so this is currently not a significant problem. An update to the specifications of the software strategy is planned to bring this software in line with the strategy, and improve its usefulness.



Rotek 800A source settings:

Voltage: 150 V
Power: 150 VA
Current: 1.000 A
Frequency: 50 Hz
Deviation: 0 %
Power factor: 0.0 lead
Power polarity: Positive

Waiting for: 10.5 s

Run 1

Zera measurement result:

	Ch 1	Ch 2	Ch 3
Voltage:	9.999356E+01	9.999352E+01	9.999407E+0
Current:	1.502107E+00	1.502145E+00	1.502094E+0
Current phase:	2.757917E+02	2.757920E+02	2.757923E+0
Power:	1.515692E+01	1.515756E+01	1.515922E+01
Active power:	1.516323E+01	1.516386E+01	1.516549E+01
Reactive power:	-1.494337E+02	-1.494373E+02	-1.494327E+02
Apparent power:	1.501991E+02	1.502027E+02	1.501983E+02
Power factor:	1.009492E-01	1.009506E-01	1.009646E-0

Zera measurement result (raw return strings):

```
2.757917E+02,2.757920E+02,2.757923E+0
1.515692E+01,1.515756E+01,1.515922E+01,4.547370E+0
1.516323E+01,1.516386E+01,1.516549E+01,4.549258E+0
-1.494337E+02,-1.494373E+02,-1.494327E+02,-4.483038E+0
1.501991E+02,1.502027E+02,1.501983E+02,4.506001E+0
1.009492E-01,1.009506E-01,1.009646E-0
```

Figure 7: ac Power and Energy software user interface.

Figure 8: ac Power measurement setup.

4. Planned work

As mentioned in the abstract, the following measurements are next in line for automation: RLC measurements (inductance, resistance, and capacitance); ac-dc difference measurements and resistor calibration result analysis.

The automation of RLC measurements were started late in 2005, but a problem was experienced with interfacing to the instrument. According to the manufacturer, this is due to the original purpose of the interface, that being the control of a sorter for component selection. This implies that the instrument acts as a controller on the GPIB bus, and since the PC normally fulfils that function, there is contention on the bus. The GPIB interface of choice used in the dclf Laboratory is the Agilent model, but according to the manufacturer of the RLC Bridge, the National Instruments interface can be configured to work with the bridge. An appropriate interface was purchased, and will be used to automate this bridge.

Measurements performed with the bridge include capacitance, inductance, ac resistance and loss. The bridge can also measure at several frequencies in the range from 12 Hz to 200 kHz. The bridge has to be OPEN and SHORT calibrated after every change in measurement configuration or frequency, so the software will have to interact with the user fairly regularly.

Currently the ac-dc difference measurements are fully automated. The software used is however very old (DOS based), and does not allow the user flexibility in setting up the measurement in an arbitrary way. The main motivation for rewriting the software is to move it to a more modern platform, and to add the required flexibility.

All resistance measurements currently performed in the laboratory are fully automated. There are two automated bridges with scanners, one for low resistance measurements (to 10 kOhm), and one for high resistance measurement (10 kOhm to 1 GOhm). An ultra-high resistance bridge is used for measurements up to 100 TOhm. All these instruments are fully automated to perform measurements, but the analysis of the measurement results are still a manual process. It is planned to fully automate this analysis, to reduce the manpower required for this task, and to improve the efficiency of resistance measurements in the laboratory.

Generating certificates is one of the most manpower intensive procedures in the laboratory. For the automated systems, performing routine measurements, this should not be the case. The automatic generation of certificates will be addressed as a future project. The most efficient way to do this will be to use the Rich Text Format (RFT) as the language for the certificates. RTF can be read by all office applications, and this protects the certificates from future changes in corporate software policy, and changes or upgrades of office applications.

The generation of certificates will be modularised. Different modules will be developed to generate the different sections of the certificate. This will be written to easily accommodate changes in certificate layouts and quality system requirements. The software will be developed using some of the simpler certificates, and will slowly be developed further to accommodate more complex measurement situations.

It is also planned to install a laboratory network, with all the measurement computers linked to one another and to a central printer. The results can then be shared, and result sheets printed centrally. A gateway machine for access to the general CSIR network will be put in place to protect the laboratory network from intrusions, and to enable the CSIR network to access the data stored on the laboratory machines securely. The gateway will also provide data backup services to the laboratory network.

Disclaimer

The use of specific manufacturers and products does not imply an endorsement of these manufacturers or products by the CSIR NML, nor does it imply that these manufacturers and products are necessarily the best suited to the applications discussed in this paper.