Traceability via the Internet for Microwave Measurements Using Vector Network Analyzers

Richard A. Dudley and Nick M. Ridler

***Abstract*—The Internet has been utilized to provide highly efficient and cost-effective measurement services using vector network analyzers (VNAs). Remote calibration and measurement using VNAs from two of the leading instrument manufacturers has been achieved with direct access to primary national measurement standards and procedures, via the Internet, for microwave frequencies in the range 45 MHz to 110 GHz.**

***Index Terms*—Internet calibration, internet-enabled metrology, microwave measurements, network analyzer calibration, traceability using the internet, vector network analyzer (VNA).**

I. INTRODUCTION

REGULAR instrument calibration is an essential part of today's quality-driven measurement environment, and a link to a national or international standard should be present. Achieving traceability requires a laboratory to periodically send their standards to be calibrated at a National Measurement Institute (NMI), acquiring a certificate and correction values. The standards are measured under carefully controlled conditions at the NMI, but there is no guarantee that these conditions will be reproduced when the standards are used at the remote laboratory. Furthermore, in some cases, the value of the standards can be affected by transport, leading to an uncertainty component, which is difficult to assess.

The downtime experienced by laboratories fulfilling calibration schedules can be extremely disruptive and costly while the equipment is away. On the equipment's return, system checks, paperwork, and the update of soft or hard calibration figures compound the delays. A calibration laboratory or NMI that provides a highly efficient service, minimizing clients' downtime and recommissioning time, will have a clear advantage and has originated the search for calibration services, which can be executed remotely.

The implementation of "remote calibrations" using the Internet as a data transmission medium is rapidly emerging as a solution to all of the transportation, environmental, downtime, and cost issues with current calibration schemes. Additional benefits emerge in the dissemination of measurement techniques and good practice equally to all laboratories.

The use of the Internet to assist in metrology was launched primarily at IMTC 1999, where systems offering video conferencing and remote monitoring [1], [2] to assist the interaction between NMIs and secondary laboratories were presented. The interactive control of instrumentation via the Internet has been addressed by O'Dowd *et al.* [3] and is now becoming a feature of software packages such as LabVIEW.

At the National Physical Laboratory (NPL), U.K., we have combined the technology of remote monitoring, remote control and NMI calibration techniques for VNAs to provide a service allowing calibration and device measurement, with traceability to primary national impedance standards [4]. Within this paper, the details of the new service are presented, beginning with issues of traceability, followed by a discussion of the service implementation and testing for the Internet calibration of VNAs.

II. TRACEABILITY OVER THE INTERNET

Traceability of measurements is a requirement for both existing international accreditation standards [5] and quality management standards [6]. Traceability is defined [7] as the "property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties." The unbroken chain of comparisons is called a "traceability chain."

In the field of VNA measurements, traceability has been established traditionally through the physical transfer of a series of reference artifacts. Typically, a laboratory requiring traceability sends electrical reference artifacts (attenuators, matched and mismatched transmission lines) to an NMI where the devices are evaluated electrically, in terms of reflection and transmission coefficient measurements, and a certificate of calibration is issued. The laboratory then calibrates their own VNA (using standards assumed to be perfect) and measures the electrical reference artifacts. The results achieved by the laboratory are verified by comparison with the values supplied by the NMI on the certificate of calibration. The closeness of agreement between the two data sets indicates the validity of the uncertainty of measurement quoted by the laboratory—the laboratory having previously evaluated the uncertainty of measurement for their own system.

Since VNAs can provide measurements over a wide range of frequencies and a wide range of nominal values, the laboratory is required to verify the system's performance under these wide-ranging conditions. To do this, the certificate of calibration supplied by the NMI often contains results at several hundred different frequencies for each of typically between four to six devices with different characteristics. The electrical behavior of these devices at RF and microwave frequencies is subject to drift with time, due to changes such as environmental conditions, so

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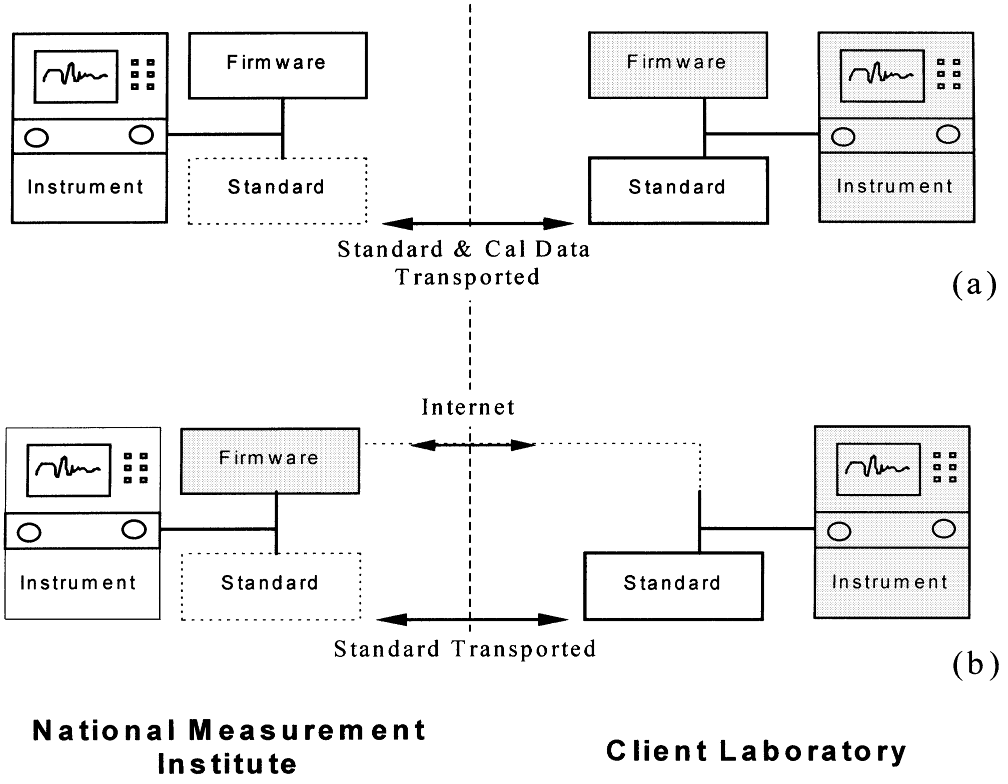

Fig. 1. Basic components of a measurement system: calibration artifacts, instrument, and control firmware. In (a), conventional traceability situation is shown, while in (b), the differences of an Internet calibration are shown.

that recalibration of each device is recommended at intervals of typically 12 months.

A system termed the primary impedance measurement system [4] (PIMMS) has been developed at NPL to address the calibration of VNAs. PIMMS utilizes a commercial VNA controlled by an external computer over a GPIB connection, overriding the firmware calibration procedure. Algorithms for calibration, measurement, and uncertainty evaluation are implemented within PIMMS using NPL constructed code.

Neglecting the intricacies, PIMMS can be simplified to three basic components: the calibration artifacts, instrumentation, and instrument firmware [Fig. 1(a)]. Therefore, the move to an Internet system can be achieved by allowing the NPL PIMMS software to control secondary laboratory VNAs, with a knowledge of the calibration artifacts and VNA performance [see Fig. 1(b)]. We have termed this new Internet version of PIMMS as $\imath$PIMMS.

III. UNCERTAINTY OF MEASUREMENT

NPL's $\imath$PIMMS facility removes the need for the electrical reference artifacts to be sent periodically to NPL for calibration. Instead, the *standards* used by a client laboratory to calibrate their VNA (previously assumed to be perfect) are measured directly by NPL. These standards are lengths of precision transmission line that are used to realize thru-reflect-line (TRL) [8] and line-reflect-line (LRL) [9] calibration schemes on the VNA. In the coaxial line, these standards are unsupported reference air lines of an appropriate length,[1] whereas in the waveguide, nominal 1/4-wavelength sections of air-filled waveguide are used.

The measurements made by NPL on these standards are the dimensions of the standards leading to a direct assessment of the overall quality of the standard. This enables the uncertainty of measurement to be traced directly back to dimensional measurements (i.e. the SI base unit, the meter), avoiding the need for the electrical calibration of the verification artifacts. This reduces the traceability chain between the electrical measurements made by the client laboratory and the SI base units to the minimum, i.e., a chain with only one link. This, then, prevents the usual broadening of uncertainty intervals due to moving through a traceability chain, from national standard to end-user—the size of the uncertainties achieved by the client laboratory being the same as those achieved at NPL.

In the case of standards in the coaxial line, the dimensional measurements made by NPL are of the diameters of the inner and outer conductors of the line. These measurements are made, for example, using an air-gauging measurement system [10]. These values are used to establish the characteristic impedance, Z_0, of the line using the following expression:

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{b}{a}\right) \approx 59.939\,04 \times \ln\left(\frac{b}{a}\right) \qquad (1)$$

where

b diameter of outer conductor;
a diameter of inner conductor;

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[1] For example, an air line with a nominal length of 7 mm can be used to realize TRL calibrations over a frequency range from 1 to 18 GHz.

ε	$\varepsilon_0\varepsilon_{\mathrm{r}}$;
ε_0	$8.854\,187\,817\ldots \times 10^{-12}$ F.m^{-1} (defined);
ε_{r}	1.000 649 (for 'standard' air at a temperature of 23 °C, 50% relative humidity and 1013.25 hPa atmospheric pressure) [11];
μ	$\mu_0\mu_{\mathrm{r}}$;
μ_0	$4\pi \times 10^{-7}$ H.m^{-1} (exact);
μ_{r}	1.000 000.

The reflection coefficient Γ caused by the line's Z_0 departing from the ideal value of characteristic impedance, Z, (e.g. 50 Ω), is given by

$$\Gamma = \frac{Z - Z_0}{Z + Z_0}. \tag{2}$$

Γ is then treated as a component to the uncertainty of reflection measurements made using iPIMMS. Similarly, Γ provides an estimate of the mismatch uncertainty [12] for the transmission measurements. An additional contribution to the uncertainty in the reflection measurements (and mismatch uncertainties for transmission measurements) is due to the need to determine the loss in the coaxial line. This loss causes the characteristic impedance of the line to depart from its lossless value, and can be significant particularly at lower RF [13]. Impedance renormalization techniques based on measurements of the line's propagation constant, similar to those discussed in [14], are employed to ensure a frequency-independent value for the characteristic impedance.

In the case of rectangular waveguide transmission line standards, the dimensions of the waveguide apertures are used to establish the quality of the line using expressions given in [15]. For example, for small departures from the ideal dimensions for the width of a waveguide aperture, the following Γ is generated:

$$|\Gamma| \approx \frac{1}{8}\left(\frac{\lambda_g}{w}\right)^2 \frac{|\delta w|}{w} \tag{3}$$

(to first order in δw), where w is the ideal width of the waveguide, δw is the difference between the measured and ideal width for the waveguide, and λ_g is the guide wavelength given by

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{2w}\right)^2}} \tag{4}$$

where

λ	$c/(f\sqrt{\varepsilon_r})$;
c	speed of electromagnetic radiation in vacuo;
f	frequency.

(Note that the maximum $|\Gamma|$ occurs when the frequency is a minimum).

Similarly, for small departures from the ideal dimensions for the height of a waveguide aperture, the following Γ is generated:

$$|\Gamma| \approx \frac{|\delta h|}{2h} \tag{5}$$

(to first order in δh), where h is the ideal height of the waveguide and δh is the difference between the measured and ideal height for the waveguide.

As with the coaxial line standards, the waveguide Γs are treated as components to the uncertainty of the reflection measurements and as mismatch uncertainties for transmission measurements.

The recalibration interval for the dimensional measurements made by NPL of the line standards (both coaxial and waveguide) is recommended at intervals of typically three years. This compares favorably with the 12-month recalibration intervals used previously to establish traceability for these measurements by the conventional route.

In addition to the uncertainty due to tolerances in the line standards used to calibrate the VNA, the characteristics of the client's VNA test set—in particular, the linearity and isolation between the test ports—also affect the uncertainty in the transmission measurements. The linearity is established from VNA measurements, made by the client, of a step attenuator. These measurements are compared with calibrated values derived beforehand by NPL using primary national standard attenuation measurement facilities [16]. The step attenuator is sent from NPL to the client laboratory so that the VNA measurements are made by the client in their own laboratory. The test set isolation is evaluated by the client laboratory by observing the measured transmission between the VNAs two test ports when terminated with low reflecting loads.

Finally, both reflection and transmission measurements are affected by random errors in the measurement process. The causes of these errors include: the connection repeatability of both the calibration and measurement artifacts, electrical noise present on the signals detected by the VNA, any cable flexing while making the measurements, and fluctuations in the laboratory environmental conditions. The effects of all the random errors on the measurement process are evaluated *in-situ* by repeating, a number of times, the connection of both calibration and measurement artifacts. Under normal circumstances, a client will repeat the process typically between six to eight times to achieve a realistic determination of the size of the random errors affecting the measurements.

The data for each customer line and test set are stored in a database within iPIMMS, so that when a given client logs-on to the service, the appropriate data for their equipment is up-loaded from the database. Measurements are then corrected directly at the client's premises, by sending commands and controls over the Internet, using the dimensional data and test set data stored in the database. This enables very efficient uncertainty intervals to be established based on the client's own primary reference standards and equipment. The iPIMMS calculation routines evaluate the uncertainty in the client's measurements using internationally accepted methods [17].

A typical uncertainty budget showing the principal components to the overall uncertainty of measurement for iPIMMS is shown in Table I. This budget corresponds to a measurement of the reflection and transmission coefficients at 18 GHz of a nominal 20-dB attenuator fitted with 7-mm precision coaxial connectors. (Note that, in determining the overall uncertainty in the reflection coefficient measurements, the uncertainties due to the conductors' loss and the conductors' diameters are assumed correlated, and so these terms are summed during the combination process).

TABLE I
TYPICAL UNCERTAINTY BUDGET FOR A MEASUREMENT MADE USING *i*PIMMS ON A NOMINAL 20-dB ATTENUATOR, AT 18 GHz

Component of uncertainty	Linear reflection coefficient standard uncertainty	Linear transmission coefficient standard uncertainty
Repeatability	0.00033	0.000 049
Conductors' loss	0.00016	N/A
Conductors' diameters	0.00080	N/A
Isolation	N/A	0.000 037
Linearity	N/A	0.000 065
Mismatch	N/A	0.000 005
Overall combined standard uncertainty	0.0010	0.000 090

IV. *i*PIMMS APPROACH TO CALIBRATION

The Internet approach effectively extends the GPIB connection between the local control computer of PIMMS and the VNA, across the Internet, to a client's control computer and VNA. When a secondary laboratory now requires a measurement at the highest level of accuracy, it logs on to the appropriate NPL web page,[2] which then guides them through the measurement process while initializing and controlling the measurement system. NPL firmware controls the measurement hardware, interprets the data, corrects it using the database of calibration data, and evaluates the uncertainty of measurement. This method not only reduces the amount of work required by the secondary laboratory but also ensures that the latest procedures are followed. This method has the ability to shrink the hierarchy of a measurement laboratory's traceability chain to a single link with the national or international standards available.

While on-line, the client enters the required measurement parameters and is offered options based on the knowledge NPL has about the client's equipment. From this point, the entire measurement process is controlled automatically by the NPL web-server, and the need for clients to provide their own uncertainty budget is removed.

V. *i*PIMMS TECHNOLOGY

Selecting the appropriate software to allow two-way communication between an NPL server and a remote laboratory, while maintaining data security, overcoming company firewalls and running at an acceptable speed, presents significant challenges. Several options are available, of which Java, ActiveX, and VB script are three technologies used by NPL to implement the *i*PIMMS system. The NPL server hosts the core PIMMS software, compiled from Visual Basic source code into a common gateway interface (CGI) executable file with the addition of code to structure the processes of calibration and measurement. During a client measurement run, an exchange between the *i*PIMMS-CGI and the client's web browser using simple "form" entry fields, both visible and hidden, controls the client's options.

The final code segment is the use of Microsoft ActiveX components—effectively, applications that run inside an Internet Explorer window and have access to all the computer's functionality, but primarily GPIB, RS232 and USB. The ActiveX component downloads on each new client session and thus requires no user installment and takes care of upgrades. Once running, the ActiveX component has the same functionality as any other program operating on the client's computer, but once the measurement is completed, the control can force data back to the server using the Internet connection. The server CGI then returns with the next sequence which may be another ActiveX component or a standard web page.

Data flow between server and client, which includes both measurement data and GPIB controls to the VNA, is performed in a secure manner using a secure sockets layer (SSL), ensuring that data integrity is maintained in both directions. During measurement, raw data is stored on the client's machine and only transferred across the Internet on completion of a calibration. Typically, the packet of data transferred is below ten kilobytes, and hence even a very slow Internet connection can be utilized. The method of data transfer uses standard web browser communication ports, reducing a client's liaison with service providers and computer services. If a client can currently browse the Internet and complete web-forms, then the NPL *i*PIMMS service will be easily accessible.

The *i*PIMMS system contains features one would associate with any standard data acquisition software, allowing data files to be catalogued and viewed, recalculated, measurement runs to be suspended or added to, and so on. The data is stored on the NPL server, which is backed up on a regular basis, but can optionally be downloaded to the client's local PC for use in records or calibration certificates.

Following extensive field trials with a remote laboratory, BAE SYSTEMS, the U.K.'s first commercial Internet calibration service, has been established for two of the leading instrument manufacturers, with a third under construction. The *i*PIMMS calibration and measurement service received its official launch in February 2001 at BAE SYSTEMS' headquarters in London.

In the period since the launch of *i*PIMMS, it has remained reliable, and has suffered no malicious attacks or loss of service due to hardware or software failure. The number of regis-

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[2] Details can be found at http://www.internetcalibrations.com

tered users increases on a monthly basis, and NPL's commitment to the service continues with recent upgrades enabling multiline calibration for coaxial measurements over very broad bandwidths.

VI. CONCLUSION

NPL's Internet calibration of VNAs is unique, and in February 2001 became the U.K.'s first calibration service to offer measurement traceability to national standards simply by connecting to the Internet. NPL regards the system as a pioneer to a series of future services to be offered in other areas of metrology. A full system demonstration along with the hardware and software requirements can be found at www.internetcalibrations.com.

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REFERENCES

[1] P. S. Filipski and N. M. Oldham, "SIMnet—a collaborative tool for metrology in the Americas," in *Proc. 16th IEEE Instrum. Meas. Tech. Conf.*, vol. 2, May 1999, pp. 623–625.

[2] K. B. Lee and R. D. Schneeman, "Distributed measurement and control based on the IEEE 1451 smart transducer interface standards," in *Proc. 16th IEEE Instrum. Meas. Tech. Conf.*, vol. 2, May 1999, pp. 608–613.

[3] R. O'Dowd, D. Maxwell, T. Farrell, and J. Dunne, "Remote characterization of optoelectronic devices over the internet," in *Proc. 4th Opt. Fiber Meas. Conf.*, Oct. 1997, pp. 155–158.

[4] N. M. Ridler, "A review of existing national measurement standards for RF and microwave impedance parameters in the UK," *IEE Colloq. Dig.*, no. 99/008, pp. 6/1–6/6, Feb. 1999.

[5] ISO/IEC 17 025, "General Requirements for the Competence of Testing and Calibration Laboratories, " 1st ed., International Organization for Standardization, 1999.

[6] ISO 9001, "Quality Management Systems—Requirements," 3rd ed., International Organization for Standardization, 2000.

[7] ISO, International Vocabulary of Basic and General Terms in Metrology, 2nd ed., International Organization for Standardization, 1993.

[8] G. F. Engen and C. A. Hoer, "Thru-reflect-line: an improved techniques for calibrating the dual six-port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 987–993, Dec. 1979.

[9] C. A. Hoer and G. F. Engen, "On-line accuracy assessment for the dual six-port ANA: extension to nonmating connectors," *IEEE Trans. Instrum. Meas.*, vol. IM-36, pp. 524–529, June 1987.

[10] J. P. Ide, "Traceability for Radio Frequency Coaxial Line Standards," NPL Report DES 114, July 1992.

[11] N. M. Ridler and J. C. Medley, "An Uncertainty Budget for VHF and UHF Reflectometers," NPL Report DES 120, May 1992.

[12] I. A. Harris and F. L. Warner, "Re-examination of mismatch uncertainty when measuring microwave power and attenuation," *Proc. Inst. Elect. Eng. H*, vol. 128, no. 1, pp. 35–41, February 1981.

[13] W. C. Daywitt, "First-order symmetric modes for a slightly lossy coaxial transmission line," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 11, pp. 1644–1651, Nov. 1990.

[14] R. B. Marks and D. F. Williams, "Characteristic impedance determination using propagation constant measurement," *IEEE Microwave Guided Wave Lett.*, vol. 1, pp. 141–143, June 1991.

[15] D. J. Bannister, E. J. Griffin, and T. E. Hodgetts, "On the Dimensional Tolerances of Rectangular Waveguide for Reflectometry at Millimetric Wavelengths," NPL Report DES 95, Sept. 1989.

[16] F. L. Warner, P. Herman, and P. Cummings, "Recent improvements to the UK national microwave attenuation standards," *IEEE Trans. Instru. Meas.*, vol. IM-32, no. 1, pp. 33–37, Mar. 1983.

[17] *Guide to the Expression of Uncertainty in Measurement*, 1st ed: International Organization for Standardization, 1993.

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