Comparing Internet-Enabled VNA Measurements with Primary National Standards

Andrew G. Morgan‡, Ian C. Instone‡, Nick M. Ridler‡ and Richard P. Thompson‡

‡National Physical Laboratory, Teddington, England, UK
‡Agilent Technologies, South Queensferry, Scotland, UK

Abstract — This paper presents a comparison of measurements made between an Internet-enabled measurement facility and two primary national standard facilities. On this occasion, the client for the Internet-enabled facility was Agilent Technologies, South Queensferry, Scotland, and the UK’s National Physical Laboratory (NPL) operated the primary national standard facilities. Both Internet-enabled and national standard facilities performed measurements of reflection coefficient and attenuation (i.e. S-parameters) at frequencies ranging from 0.5 GHz to 26.5 GHz of coaxial devices fitted with precision 3.5 mm connectors.

Index Terms — Internet-enabled metrology, vector network analysis, microwave impedance measurement, national standards, measurement traceability.

I. INTRODUCTION

The NPL Internet-enabled measurement service for Vector Network Analysers (VNAs) [1] has now been in continuous operation since the beginning of 2001. During this time, clients of the system have been able to achieve measurements of a comparable accuracy to UK national standards by connecting to the Internet and performing NPL-style calibrations and measurements at their own premises. This service makes extensive use of the Internet to fully control a VNA, situated at a location remote to NPL, to perform measurements at RF and microwave frequencies.

This Internet-enabled Primary Impedance Measurement System (iPIMMS) [1] is based on the concept of devolving the national standard capability direct to the client end-user, thus enabling primary national standard accuracy to be achieved wherever, and whenever, it is needed.

This paper presents a test of these concepts through the use of a measurement comparison exercise involving Internet-enabled measurement facilities at Agilent Technologies, South Queensferry, Scotland, and primary national standard facilities maintained and operated by NPL. The comparison focuses on measurements of voltage reflection coefficient (VRC) and attenuation (or, equivalently, complex S-parameters) made at microwave frequencies. The primary national standard measurement facilities involved are VNA-based impedance systems [2, 3] as well as precision attenuation systems employing voltage ratio principles [4].

Section II of this paper describes the principles involved in using Internet-enabled facilities to achieve traceability for measurements made at any geographical location. Section III discusses the evaluation of the uncertainties of measurements made using the national standard and Internet-enabled VNA facilities. Section IV presents the details of the measurement comparison exercise that forms the main topic of this paper. Section V presents the results of the comparison exercise, while sections VI and VII present observations and conclusions on the comparison exercise.

II. WHY INTERNET-ENABLED MEASUREMENTS?

A. Classical traceability

For many years, the reliability of nearly all measurements has been established using the concept of traceability. The term "traceability", in this context, is defined as [5] 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 often called a "traceability chain" and this chain can consist of many links, extending across several different organizations and measurement laboratories, from end-user to primary national standard.

Each link in the traceability chain represents a "comparison of measurement". For example this concept can be applied to measurements made of products on a manufacturing production line that are compared with
measurements made of a calibrated device (or, 'working' standard) using the same test equipment. Measurements of working standards are then compared with measurements of the manufacturing facility’s primary standards. These primary standards are periodically sent to an accredited measurement laboratory\(^2\) where they are compared against accredited working standards. These working standards are in turn periodically compared with primary standards at the accredited laboratory. Finally, these primary standards are sent for comparison against standards held by a National Metrology Institute (NMI), such as NIST\(^3\) in the USA, or NPL in the UK. This traceability chain therefore links measurements made on the manufacturing production line with national standards held by NMIs.

Within each tier of this traceability hierarchy (comprising manufacturing facility, accredited laboratory and NMI), there may be several internal links in the traceability chain, e.g. between each organization’s working and primary standards. In addition, the NMI has the responsibility of linking the primary national standards for each measurement quantity to the SI Base Units (i.e. mass, length, time, etc).

The above process is illustrated in Figure 1. All stages in the process (i.e. all the 'links' in the traceability chain) must be in place for measurement traceability to be established at the manufacturing facility. Measurements made within this framework can then be compared meaningfully with other similar such measurements regardless of other circumstances (such as where, or when, the measurements were made). Therefore, this traceability process plays a vital role in enabling successful trade between organizations and between nations by establishing a common understanding of measurement quantities and their values.

A disadvantage with this process is that it can be both costly and time-consuming to establish that all links in a traceability chain are operating successfully. This is usually achieved through regular testing and maintenance of all the links in the traceability chain. A further potential disadvantage relates to the propagation of uncertainty of measurement through the traceability chain. In most instances, each level of a traceability hierarchy (e.g. as shown in Figure 1) not only ‘inherits’ its traceability from the level above, but also the uncertainty in the measurements. This uncertainty is then combined with ‘local’ uncertainty contributions\(^4\) generated at each link in the traceability chain. This means that as one moves through the traceability hierarchy, from national standard to end-user, the size of the quoted uncertainty for a particular measurement quantity tends to increase due to the need to combine inherited with local uncertainty contributions. Therefore, the more links in the traceability chain, the greater the difference in uncertainty between national standard and end-user.

### B. Contemporary traceability issues

The classical traceability process works well when the different tiers in the traceability hierarchy can be realized to the necessary degree of accuracy (or uncertainty). Historically this has been achieved, for example, by using measuring instruments and measurement techniques, each appropriate for the particular level within the traceability hierarchy. For example at the production line level, this choice may be based on factors such as reliability, user friendliness and cost-effectiveness. However, as one moves up the traceability hierarchy, accuracy and sophistication of the measurement technique become more important with less reliance being placed on user friendliness. Finally, at national standard level, the main concern is usually the achievable accuracy of the measurements and this has often led to specialized measuring instrumentation and methods being developed capable of achieving the required accuracy.

However, in recent years, measuring instruments and measurement methods suitable for use at all levels of the traceability hierarchy have become increasingly more common. This has largely been due to good instrument design and the use of techniques such as computer corrected measurement strategies that have enabled the requirements of all users to be incorporated into

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\(2\) This is a laboratory that has been accredited against standards such as ISO 17025, ISO Guide 25, ANSI/NCSL Z540-1-1994, etc.


\(4\) These ‘local’ uncertainty contributions are due to effects such as random and systematic errors generated within the operating procedures of the laboratory at the specific level of the traceability chain. For example, these might be random errors due to environmental effects or systematic errors due to uncertainties in local working standards and instrumentation.
instrument designs. An example of such instrumentation is the VNA, which finds application in nearly all measurement environments from the manufacturing production line to national standards laboratory. Similarly, VNA calibration schemes and references standards are equally available to all involved in the traceability process.

This situation has led to classical traceability mechanisms becoming burdensome and impractical in areas of measurement where common instrumentation (such as the VNA) is found at all levels of the traceability hierarchy. This is because, for classical traceability mechanisms to be appropriate, each level in the traceability hierarchy should offer greater accuracy (or lower uncertainty) than the level below it. This is difficult to achieve when all levels are using similar instrumentation capable of achieving the same degree of accuracy.

C. Internet-enabled traceability

In recognition of the fact that VNAs can be used to provide measurements at all levels of the traceability hierarchy and also that Internet connections are readily available at all locations around the world, it was decided to exploit this situation by greatly streamlining the traceability process. The resulting system of Internet-enabled measurement traceability works by using the same instrumentation and measurement method used to achieve the primary national standards at any level of the traceability hierarchy.

This means that any level of the traceability hierarchy can achieve the same accuracy (i.e. uncertainty) of measurement as was previously only available at the national standard level. Under this new scheme, the number of links in the traceability chain is effectively reduced to the minimum of just one (i.e. this being the link back to the SI Base Units). In the case of a primary standard VNA measurement system this link is to the metre, i.e. the unit of length, used for the dimensional measurements characterizing the transmission lines that act as the VNA’s reference standards.

The availability of national standard measurement accuracy on production lines of manufacturing facilities means that products can be tested more effectively and very close to specification limits with minimum concern for the effects of uncertainty in the measurements. Similar benefits can also be found at the intermediate levels in the previously used classical traceability hierarchies (e.g. within the accredited laboratories).

III. Evaluating VNA Uncertainty

Both the national standard and Internet-enabled VNA systems are operated in essentially the same way. Either a TRL [6] or LRL [7] technique is used to calibrate the VNA. Both these techniques use a transmission line (or lines) as the primary reference standard(s). The calibration process is repeated several times so that variability due to random errors in the overall process can be evaluated using statistical techniques. These random errors are due to physical effects that occur during the overall measurement process, such as: electrical noise in the instrumentation; connection repeatability of both calibration and measurement devices; flexing of test port cables; and, ambient environmental effects (e.g. temperature fluctuations).

The main sources of systematic errors (remaining after calibration) in the VNA measurements are: lack of exact knowledge of the dimensions of the calibration standards (i.e. the uncertainty in the dimensional measurements used to characterize the transmission line standards); detector non-linearity effects; isolation (i.e. cross-talk) between the test ports; and, mismatches occurring between the test ports and the devices being measured. The uncertainty in determining the dimensions of coaxial line standards is evaluated following the methods given in [8]. The other systematic errors, listed above, are evaluated using techniques given in [10].

The overall uncertainty of measurement is established by combining the uncertainty contributions due to all the above effects. The methods used to do this are based on international guidelines [11] adapted to be suitable for complex-valued quantities (i.e. the measured S-parameters) [12]. The same approach is applied to both national standard and Internet-enabled VNA systems. This process is illustrated in Figure 2.

IV. Comparison Details

Both national standard and Internet-enabled VNA systems chose to use the TRL calibration scheme with lines of nominally the same lengths. In this case, three lengths of line were chosen to provide suitable calibration performance at all frequencies from 0.5 GHz to 26.5 GHz. These lengths were: 75 mm for measurements below 1.5 GHz; 16 mm for the measurements from 1.5 GHz to 7 GHz; and, 4 mm for the measurements above 7 GHz.

5 An equivalent approach [9] is used for measurements made in rectangular waveguide.
6 It is not a requirement that lines should be of the same length. Rather, on this occasion, these line lengths are ones that are found in certain commercially available calibration kits.
The comparison exercise used two devices fitted with precision 3.5 mm connectors: a 40 dB attenuator; and, a female one-port device constructed using a 3 dB attenuator with a short-circuit attached to the male end. The 40 dB attenuator was chosen to provide both low values of VRC (at both male and female test ports) and a substantial amount of attenuation between the test ports. The one-port device was chosen to provide a significant mismatch (i.e. a nominal linear VRC magnitude of the order of 0.5).

The items were measured with NPL’s primary national standard VNA facility [2, 3] at 0.5 GHz to 26.5 GHz in 0.5 GHz steps. An averaging factor of 512 for calibration and measurement is traditionally employed by NPL when using this system, although maximum averaging (4096) was employed in measuring the 40 dB attenuator (due to the significant amount of attenuation inherent in this device).

The items were then sent to Agilent Technologies, South Queensferry, where they were measured using the Internet-enabled VNA facility, iPIMMS [1]. The VNA was calibrated at the same frequencies but with an averaging factor of 1024 for both calibration and measurement (as chosen by the client at the Agilent site). Both Agilent Technologies and NPL used 8510 series VNAs for the measurements.

An additional comparison involved using the UK primary national attenuation standard facilities to measure the 40 dB attenuator at three selected frequencies (1 GHz, 10 GHz and 18 GHz) using a voltage ratio technique [4].

### V. Results

#### A. Comparing Internet-enabled VNA measurements with national standard VNA measurements

Figures 3 to 5 show a comparison between the results obtained by the Internet-enabled VNA facility and the primary national standard VNA facility.

The error bars on all these graphs represent the expanded uncertainty of measurement at an estimated level of confidence of 95%. In addition, the measured values for the Internet-enabled VNA results have been offset slightly so that they can be seen more clearly in the graphs.
for the nominal 40 dB attenuator at 1 GHz, 10 GHz and 18 GHz. Each of these Tables also includes a row showing the difference between the two measured values. Once again, the displayed uncertainty is an expanded uncertainty at an estimated level of confidence of 95%.

Table 1. Measurements of attenuation at 1 GHz

<table>
<thead>
<tr>
<th></th>
<th>Attenuation (dB)</th>
<th>Uncertainty (dB)</th>
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<tbody>
<tr>
<td>Internet-enabled VNA</td>
<td>39.849</td>
<td>0.016</td>
</tr>
<tr>
<td>National attenuation standards</td>
<td>39.850</td>
<td>0.007</td>
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<tr>
<td>Difference</td>
<td>0.001</td>
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</table>

Table 2. Measurements of attenuation at 10 GHz

<table>
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<th>Attenuation (dB)</th>
<th>Uncertainty (dB)</th>
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</thead>
<tbody>
<tr>
<td>Internet-enabled VNA</td>
<td>40.091</td>
<td>0.064</td>
</tr>
<tr>
<td>National attenuation standards</td>
<td>40.073</td>
<td>0.007</td>
</tr>
<tr>
<td>Difference</td>
<td>0.018</td>
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</table>

Table 3. Measurements of attenuation at 18 GHz

<table>
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<th>Attenuation (dB)</th>
<th>Uncertainty (dB)</th>
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<tbody>
<tr>
<td>Internet-enabled VNA</td>
<td>40.332</td>
<td>0.119</td>
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<tr>
<td>National attenuation standards</td>
<td>40.406</td>
<td>0.010</td>
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<tr>
<td>Difference</td>
<td>0.074</td>
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</table>

VI. OBSERVATIONS

The graphs presented in Figures 3 to 5 clearly show good agreement between the Internet-enabled VNA measurements and those obtained using the primary national standard VNA facilities. This agreement between the two systems is demonstrated by there being only small differences between the measured mean values (in the context of the uncertainties of measurement) and the relatively similar sizes of the uncertainties for the measurements at each frequency. This is encouraging in that it demonstrates that the Internet-enabled VNA facility is successfully emulating the performance capabilities of the primary national standard VNA facility. This effectively validates the concept of devolving the national standard capability to a remote end-user client through the use of the Internet.

B. Comparing Internet-enabled VNA measurements with national attenuation standard measurements

Tables 1 to 3 show a comparison of the $S_{21}$ results obtained using the Internet-enabled VNA (converted to decibels using expressions given in [13]) with results obtained using the national attenuation standard facilities.

It is also worth stating that the measured phase of all the S-parameters also showed very good agreement between the two measurement systems.
The results in Tables 1 to 3 show that the Internet-enabled VNA capability also shows good agreement with the primary national attenuation standard facility. This provides increased confidence in the Internet-enabled VNA measurements in that the attenuation system measurements are based on entirely different, independent, measurement methods. Such independence of measurements can provide a valuable tool for unmasking any hidden systematic errors that may be present in a measurement system. It is therefore reassuring that, on this occasion, no such ‘hidden’ measurement errors have been exposed in these systems.

VII. CONCLUSIONS

The Internet-enabled VNA facility (iPIMMS) has shown very good agreement with two different primary national standard measurement capabilities operated by NPL. In both cases, the Internet-enabled facility has achieved results that agree with the national standards to within the stated uncertainty of measurement – this uncertainty itself being comparable with the primary national standard VNA facilities. This clearly demonstrates that a measurement at a national standards level of accuracy can be successfully realized by clients remote to NPL through the use of the Internet as part of the measurement process. The authenticity of the achieved measurements has been further demonstrated by way of comparison with an entirely different type of measurement facility – the primary national attenuation standard system.

ACKNOWLEDGEMENT

The work described in this paper was funded by the National Measurement System Directorate of the UK government’s Department of Trade and Industry.

REFERENCES


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Note that the attenuation facilities are more time consuming to operate and therefore only three selected frequencies were used during this comparison exercise. However, in general, the ‘quality’ of attenuation measurement made by these facilities is superior in that the achieved uncertainties of measurement are smaller than those obtained using VNA-based systems.