An Assessment of the Reproducibility of Free Wave Reflection Data using Guided Wave Data as a Benchmark.

F C Smith†, N M Ridler∗

† Defence Research Agency (Malvern)
∗ National Physical Laboratory (Malvern)

1 Introduction

Simple free wave reflection and transmission measurement systems have been used for a number of years to characterize the materials used in radar applications. Until recently, free wave S-parameter measurement techniques were comparatively basic. Measurement calibration rarely went beyond the level of scalar response correction, nor was it always recognized that free wave measurement techniques violated the transmission line assumptions which underpin S-parameter measurements. With the arrival of more sophisticated uses for free wave reflection and transmission data, however, a greater emphasis on developing methods of reducing free wave measurement uncertainty has become necessary. Although the sources of correctable error in guided media are quite different from those in unguided media, the same calibration equations can be used irrespective of the medium of propagation [1]. Sophisticated calibration schemes reduce the effects of some error sources, but there is a large body of anecdotal evidence which still suggests that free wave S-parameter data remain significantly less accurate than their guided wave counterparts.

There are two fundamental problems which have kept free wave scattering parameter measurements out of mainstream metrology. Firstly, many of the measurement systems in current use have been developed in materials science laboratories rather than in microwave measurement laboratories. Secondly, the lack of nationally recognized reference materials has prevented estimates being made of the absolute error in measured data. Data taken in any of the UK free wave measurement laboratories cannot be compared quantitatively, and even qualitative comparison can sometimes lead to erroneous conclusions.

In an attempt to impose some order upon the methodology of free wave scattering parameter measurements, the Defence Research Agency at Malvern organized a measurement intercomparison involving all the UK laboratories who routinely make free wave reflection measurements. The results of this intercomparison have been published [2]. In the present paper, we undertake further studies on the intercomparison data to examine the commonly held belief that the reproducibility of free wave data is significantly poorer than the reproducibility of data taken in guided media. In 1993, the UK network analyzer users' group ANAMET organized a measurement intercomparison of type-N coaxial line terminations [3]. The ANAMET type-N intercomparison data provide a suitable benchmark from which the dispersion observed in free wave one-port reflection data can be judged. Both intercomparisons encompass the intermediate microwave frequency band (2 GHz to 18 GHz), and the mismatches of the test load impedances are similar.

Automatic network analyzers (ANAs) were used in both intercomparisons to record reflection data [2],[3]. The principal differences in reproducibility are therefore caused by the different propagating media apparatus and the different calibration procedures.
2 Dispersion in One-Port Free Wave Data

Lack of standardization in the ‘front-end’ apparatus is the principal cause of dispersion in free wave S-parameter data. The most common one-port measurement devices consist of a bistatic antenna arrangement with transmit and receive antennas mounted on a radial positioner. The angular displacement between the antennas is twice the required measurement angle. Calibration is effected at the measurement reference plane, which is positioned at the centre of rotation of the radial positioner. Measurement errors occur because the arrangement of antenna and sample is unable to provide an approximation to the ideal infinite sample and infinite planewave. These extremes are necessary if one-port data are to be correctly interpreted as a transmission line voltage reflection coefficient.

The ‘front-end’ components, which vary greatly between laboratories, are the measurement environment, the transmit and receive antennas, and the radial positioner. The measurement environments used in the UK are all non-reflecting; most are anechoic chambers, but a few of the measurement systems exploit large open areas to minimise coupling to the environment. Many laboratories choose to use broadband horn antennas with a 3-4 octave frequency range; however, a mix of standard gain and ‘home-made’ horns are also quite common. The radial positioners exhibit the greatest degree of variation in measurement equipment between laboratories. There is inevitably a corresponding variation between the errors in measurement angle settings.

All UK laboratories use the one-port error model as a basis for eliminating source match, directivity and tracking errors [4]. The extent of error correction in the UK, however, varies between three term error correction and one term response correction. Experimental and signal processing methods are often used to eliminate errors which are not removed by calibration. Signal processing brings into play a broad range of esoteric factors which can further increase the dispersion in data.

On a basic level, the measurement quantity $S_{11}$ ought to be independent of the equipment used to measure it. The special features of free wave measurements, however, cause the apparent reflectivity of a sample to be related to the specific configuration used at the ‘front-end’.

3 Dispersion in One-Port Coaxial Line Data

To understand the causes of dispersion in measurements of one-port items in coaxial line it is necessary to investigate the sources of error in the measurement process. Errors are traditionally categorised as either random or systematic, depending on their physical nature. For example, the electrical noise inherent in the measuring instrument is a good example of a random error component contributing to the dispersion in the instrument’s indications. Systematic error components are often caused by invalid assumptions in the characteristics of the calibration artefacts. For example, it is common to assume that a “matched” load standard used in a three-term one-port calibration technique produces zero reflection, i.e., is perfect. This error will introduce a systematic error in all subsequent results obtained using the calibrated instrument.

A third component of error is caused by the imperfect coupling between test item and measuring instrument. This source of error straddles the random/systematic error divide because it includes the lack of perfect connection repeatability, which is random in nature, and the presence of a junction impedance, which is systematic in nature.

The composite effect of the random errors present in a measuring system can be observed easily by a suitable repeatability assessment on the system. Systematic errors, by their very nature, are
inherently more difficult to detect. An indication of their presence can be obtained by examining reproducibility statistics obtained from a measurement intercomparison exercise, since such an exercise goes some way towards effectively randomising the systematic components. Repeatability and reproducibility statistics can then be compared directly as quantitative indicators of random and systematic errors, respectively.

The ANAMET type-N VSWR intercomparison showed the reproducibility statistics to be nominally an order of magnitude larger than the repeatability statistics, indicating that systematic errors dominated the random errors in the measurements. For the type of connector used in the intercomparison (50 ohm, type-N), the effects of junction impedance are usually relatively small. It was therefore assumed that the dominant cause for dispersion in the coaxial line data was the calibration of the measuring instruments.

4 The Free Wave and Coaxial Line Measurement Intercomparisons

Five square planar samples were chosen as test samples for the free wave intercomparison [3]. Each sample had a side dimension of 300mm. Samples 1 - 4 were four-parameter metal-backed resonant absorbing materials with differing frequency characteristics; it was assumed that the metal backing plates were Perfect Electrical Conductors (PECs). Sample 5 was an unbacked single layer of PTFE whose dielectric constant had been characterized on an open resonator. The frequencies and incidence angles at which data were recorded were 2 GHz to 18 GHz and 0°, 40° and 60° respectively. The nominal normal incidence angle varied across participating laboratories from 0° to 10°. Of the two possible incident polarization states, parallel polarization only was measured. Because of the presence of the polarization (Brewster) angle, the polarization and angular measurement conditions gave a broad range of reflection values across the measured frequency bandwidth.

Three pairs of terminations with nominal VSWRs of 1.05, 1.2 and 1.5 were chosen as the test items for the ANAMET VSWR intercomparison. Each pair of items had one fitted with a male and one fitted with a female type-N connector.

The repeatability and reproducibility [5] of free wave and coaxial line data were calculated to enable quantitative comparison between the data taken in the two media. Calculations were effected using the methods described in [3]. Ten laboratories took part in the free wave intercomparison and six in the coaxial line intercomparison.

The reflection coefficients of the N-type coaxial line terminations were approximately constant over the 2 to 18 GHz measurement band. The reflectivities of the planar free wave samples, however, were not. Direct broadband comparisons of repeatability are therefore not possible. Instead, free wave and coaxial line data are compared at frequencies and reflectivities which coincide. The free wave samples used for the comparison are samples 1,2,3 and 5 (cf [2]) measured at normal incidence. Free wave normal incidence data exhibit the lowest levels of dispersion. The following data have been chosen to illustrate the extent of the differences between results obtained in the two media; other coaxial terminations and other free wave samples used in the intercomparisons will give rise to slightly different numerical values. The overall picture, however, remains unchanged.

Table 1 shows the inter-laboratory reproducibility for a nominal line termination of VSWR=1.5 (|S_11| ≈ −14dB). Table 2 shows the inter-laboratory reproducibility for a nominal line termination of VSWR=1.2 (|S_11| ≈ −21dB).
Table 1: Comparison between the reproducibility of inter-laboratory data taken in free space and coaxial line. The numerical values show the results at one standard deviation. VSWR of load = 1.5 (nominal).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Frequency (GHz)</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>N/A</td>
<td>0.0126</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0608</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>N/A</td>
<td>0.0225</td>
<td>0.0462</td>
<td>0.0465</td>
<td>0.0504</td>
<td>0.0479</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.0425</td>
<td>0.0496</td>
<td>0.0393</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Female N-type Load</td>
<td></td>
<td>0.0117</td>
<td>0.0096</td>
<td>0.0064</td>
<td>0.0114</td>
<td>0.0196</td>
<td>0.0237</td>
</tr>
</tbody>
</table>

Table 2: Comparison between the reproducibility of inter-laboratory data taken in free space and coaxial line. The numerical values show the results at one standard deviation. VSWR of load = 1.2 (nominal).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Frequency (GHz)</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.0331</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.0009</td>
<td>0.0012</td>
<td>0.0013</td>
<td>0.00070</td>
<td>N/A</td>
</tr>
<tr>
<td>Female N-type Load</td>
<td></td>
<td>0.0045</td>
<td>0.0058</td>
<td>0.0053</td>
<td>0.0046</td>
<td>0.0073</td>
</tr>
</tbody>
</table>

The repeatability of each free wave and coaxial sample was investigated at DRA Malvern and NPL Malvern respectively. Due to incidence angle considerations, there are many fewer points where frequency and reflectivity data coincide to enable comparison between the two media. Similar rather than coincident points are therefore chosen to examine repeatability. Table 3 compares the repeatability data from metal backed, unbacked and coaxial samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>VSWR</th>
<th>Angle</th>
<th>Frequency (GHz)</th>
<th>Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.5</td>
<td>0°</td>
<td>6.24</td>
<td>0.0035</td>
</tr>
<tr>
<td>5</td>
<td>1.05</td>
<td>60°</td>
<td>5.28</td>
<td>0.000046</td>
</tr>
<tr>
<td>Female N-type load</td>
<td></td>
<td>1.5</td>
<td>N/A</td>
<td>7.00</td>
</tr>
<tr>
<td>Female N-type load</td>
<td></td>
<td>1.05</td>
<td>N/A</td>
<td>7.00</td>
</tr>
</tbody>
</table>

Table 3: Comparison between the repeatability of free space and coaxial line VSWR data taken at DRA Malvern and NPL Malvern respectively. The numerical values show the results at one standard deviation.

Normal incidence free wave data are used in Tables 1 and 2. The inter-laboratory data exhibit greater dispersion as the incidence angle increases. The effect is complicated by the angular dependence of reflectivity; however, the trend in dispersion is still observable. Table 4 displays the reproducibility of free wave sample 1 data as a function of the incidence angle at 11 GHz.

<table>
<thead>
<tr>
<th>Reproducibility</th>
<th>0°</th>
<th>40°</th>
<th>60°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0126</td>
<td>0.0265</td>
<td>0.0939</td>
</tr>
</tbody>
</table>

Table 4: Comparison between the reproducibility of free space VSWR data taken at 11 GHz and various incidence angles. The numerical values show the results at one standard deviation. The
frequency is chosen to minimize the effects of VSWR variations.

5 Discussion and Conclusions

A fundamental feature common to both intercomparisons is the relationship between inter-laboratory dispersion data and frequency; as frequency increases so does the reproducibility standard deviation. For coaxially guided waves this effect is due principally to an increase in the systematic error components discussed earlier. For example, in general, the match of a near-matched termination degrades as the frequency increases. In the presence of a "matched-load" assumption, this leads to a systematic error in the measuring instrument which will increase with frequency. (Systematic errors due to junction impedance will also, in general, increase with frequency.) In free space, effects due to the electrical dimensions of the 'front-end' apparatus contribute significantly to the variations of reproducibility with respect to frequency. At low frequencies, the broadband horn antennas are electrically small; comparatively little variation therefore exists in the antennas' radiation patterns and the illumination distribution across each sample does not vary greatly between laboratories. The differences in horn dimensions become electrically significant at high frequencies; the horn main beam and sidelobes are then virtually unique to each laboratory. The increased diversity in antenna characteristics will contribute to the dispersion in inter-laboratory data. Similar effects are caused by the radial positioners and supporting structures. In traversing the 2 to 18 GHz band, the electrical dimensions of these structures move from being electrically small to being electrically large and significant. The variation in construction of the positioners and supporting structures will therefore also contribute to the high frequency dispersion in data.

Free wave samples 1 to 4 were absorbing materials backed with a PEC. To facilitate material parameter measurements, the samples and backing plates used for the intercomparison were not permanently joined; the temporary joining mechanism used prevented a perfect sample/PEC interface from being achieved. The presence of small unrepeatably distributed air gaps (< 0.01mm) can cause an increase in the dispersion of free wave reflection data.

Similar values for the reproducibility of free wave and guided wave data are obtained only (1) when the sample/PEC interface uncertainty and the effects caused by the 'front-end' apparatus are removed, or (2) when the measurement frequency is low enough to mask the effects of different measurement apparatus. Condition (1) is achieved in the sample 5 repeatability data in Table 3. This is a rare instance where reproducibility is similar in guided and unguided reflection data. A combination of conditions (1) and (2) is pertinent to sample 5 in Table 2. The reproducibility of sample 5 data is seen to compare favourably with the guided wave data taken at the same frequency and at a similar VSWR. The favourable comparison, however, is caused by the apparent similarity of measurement systems at low frequencies, and therefore cannot be exploited for broadband applications. It should also be recalled that Tables 1 and 2 use free wave data taken at normal incidence. Table 4 shows that reproducibility of free wave data will become poorer at wider incidence angles.

It has been shown that dispersion in reflection data is significantly higher in free space than in coaxially guided systems. The dispersion is reduced under very specific conditions, but for arbitrary samples and measurement bands the reproducibility of free wave data is hampered by the broad range of 'front-end' apparatus. Improvements to the free wave measurement apparatus are unlikely significantly to improve the quality of free wave data. Alternative free wave methodologies are therefore sought. In recent years, Gaussian beam quasi-optical systems have been used at intermediate microwave frequencies. These systems first used lensed conical horns to focus energy on to the test and calibration samples [6]. Lensed systems have provided an improvement on the unfo-
cused free wave approach, but the modal purity of the Gaussian beam at intermediate frequencies is poor. Lenses also have the disadvantage of causing large impedance transitions whose effects are not always eliminated by calibration. A new technique has recently been investigated based on the use of reflecting focusing elements to form the Gaussian beam [7]. A bistatic mirror arrangement, designed to operate at intermediate microwave frequencies, is also being developed at DRA. The bistatic mirror arrangement is intrinsically superior to the lens system. It is anticipated that these new methodologies will give rise to free wave repeatability and reproducibility data comparable to the data obtained from general purpose guiding components; the estimated error in measured data should also improve.

References


