Comparison Between Two National Metrology Institutes of Diameters and Characteristic Impedance of Coaxial Air Lines

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Abstract—This paper summarizes a bilateral comparison of the measurements of the diameters of two precision coaxial air lines with a line size of 3.5 mm. These mechanical measurements were independently made by two national metrology institutes, i.e., the National Metrology Institute of Japan (NMIJ) and the National Physical Laboratory (NPL). The laboratories also calculated the characteristic impedance of each air line based on the measured diameter values. The difference between the characteristic impedances calculated by the two laboratories for both lines was less than 0.020 Ω. The uncertainty of this difference, at a 95% level of confidence for each line, was 0.084 and 0.307 Ω.

Index Terms—Characteristic impedance, comparison of measurements, national impedance standards, precision coaxial air lines.

I. INTRODUCTION

Precision air dielectric coaxial transmission lines (which are often referred to as air lines) can be very useful as references or standards for impedance measurement at radio and microwave frequencies [2]–[4]. These lines are also known as unsupported air lines since they do not contain any dielectric support beads to hold the center conductor inside the outer conductor. Instead, the center conductor is held by the test ports of the measuring instrument (or other components) to which it is connected during use. The absence of support beads means that the properties of the lines more closely conform to the ideal properties of such lines.

To use an air line as a reference device, it is usually necessary to know the characteristic impedance of the line. For example, a value of the characteristic impedance is required when the line is assumed to have a defined value of impedance (e.g., during a vector network analyzer (VNA) calibration scheme, such as thru–reflect–line [5], or during postcalibration residual error assessments [6]).

At the levels of accuracy required by today’s end users, it is important to consider the departure of the line’s characteristics from ideal values. This usually involves establishing estimates for the input quantities to the models for the line’s characteristics. This involves determining the dimensional and material properties of the conductors of the line. The determination of the material properties (i.e., the conductivity or, equivalently, resistivity) of the conductors of lines has been described elsewhere [7]. The determination of the dimensional properties (i.e., the diameters) of the conductors of the lines is done using mechanical measurement techniques (e.g., air-gauging [8] and laser-gauging [9] techniques). Since the lines are unsupported, they come as two separate parts so that both the center and outer conductors can separately be accessed.

Several national metrology institutes (NMIs) have developed dimensional metrology capabilities using air- and laser-gauging techniques specifically for measuring unsupported air lines. However, to date, to the authors’ knowledge, there has been no comparison of measurements made by NMIs for this type of measurement that has been reported in the literature. This is the motivation for this work: to undertake and report on a comparison of the dimensional measurements of air lines made at two NMIs, i.e., the National Metrology Institute of Japan (NMIJ) and U.K.’s National Physical Laboratory (NPL). This comparison was carried out between December 2006 and June 2007 and involved measurements of the diameters of two precision unsupported coaxial air lines with a line size of 3.5 mm [10], specifically the internal diameter of the outer conductor and the diameter of the center conductor. From these measured values, a mechanically derived characteristic impedance value was determined and compared. (At the same time, some time-domain measurements using VNAs were also performed on these lines. These measurements have been reported elsewhere [11].) The mechanically derived value for the characteristic impedance $Z_{\text{mech}}$ of the line is determined using

$$Z_{\text{mech}} = \frac{1}{2\pi} \sqrt{\mu / \varepsilon} \ln \left( \frac{d_2}{d_1} \right) \approx 59.939 \, 045 \times \ln \left( \frac{d_2}{d_1} \right) \quad (1)$$

where

- $d_1$ diameter of the center conductor;
- $d_2$ internal diameter of the outer conductor;
- $\varepsilon_0$ permittivity of free space (exactly defined as $8.854 \, 187 \, 817 \ldots \times 10^{-12} \, \text{F} \cdot \text{m}^{-1}$);
- $\mu_0$ permeability of free space.

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μ_0 \text{ permeability of free space (exactly defined as } 4\pi \times 10^{-7} \text{ H} \cdot \text{m}^{-1}).

Measurements of d_1 and d_2 of both lines were independently made at NMIJ and NPL. Average values and uncertainties for d_1, d_2, and Z_{mech} were then calculated. (The conductors’ loss effect, due to nonzero resistivity, was not included in the Z_{mech} calculation in this comparison.) The comparison also involved establishing the degree of equivalence of the measurements. Thus, the comparison gives an indication of the reliability of such measurements at both NMIs.

II. TRAVELING STANDARD

This comparison was carried out using two precision coaxial air lines. The identification of each line is described in Table I. The lines were of the same physical type, as described here.

1) insertable (i.e., with a male connector at one end and a female connector at the other end);
2) unsupported (i.e., containing no dielectric support beads to hold the center conductor in place);
3) nominal characteristic impedance of 50 Ω;
4) line size of 3.5 mm, nominal outer conductor internal diameter d_2 of 3.500 mm, and nominal center conductor diameter d_1 of 1.5199 mm [10];
5) fitted with LPC-3.5 precision coaxial connectors [10];
6) nominal length of 75 mm.

The main difference between the lines related to the center conductor of the female connectors is given as follows: The line belonging to NMIJ (referred to here as the NMIJ line) used a slotted contact, whereas the line from NPL (i.e., the NPL line) used a slotless contact, whereas the line from NPL (i.e., the NMIJ line) used a slotted female socket [13]. For this reason, the values of d_1 and d_2 for a section measuring approximately 0.5 mm of the line from both connector ends were ignored in this comparison.

Incidentally, the NMIJ line had very good longitudinal diameter uniformity for d_1 and d_2, except at the male end, as shown in Fig. 1(b) and (d).

III. MECHANICAL MEASUREMENT SYSTEM

NPL measured the maximum and minimum values of d_1 and d_2 along the length of both air lines using an air-gauging measurement system (AGMS) [14]. All these values had an estimated uncertainty (at a 95% level of confidence) of 1.0 μm. In addition, a laser-gauging measurement system (LGMS) was used to measure d_1 for the oversized section on the NPL line. The value of d_1 obtained by the LGMS had an uncertainty of 1.8 μm. The difference between d_1 measurements made by the AGMS and LGMS for the main section of the NPL line was less than or equal to 0.5 μm, which is well within the uncertainties for both of these measurement systems. These methods provide traceability to U.K. national standards of length (i.e., to the SI base unit meter) using calibrated plug and ring gauge standards.

NMIJ measured d_1 and d_2 along the length of each air line using an AGMS and LGMS [15]. All these values had an estimated uncertainty (at a 95% level of confidence) of 1.0 μm. These measurements were traceable to NMIJ’s national standards of length via calibrated ring and pin gauge reference standards. In addition, a 3-D coordinate measuring machine (3DCMM) was used to measure d_2 near both ends of the lines, as shown in Fig. 2. For these measurements, the ends of the lines were connected to the adapters, because the diameters at the connector interfaces can become deformed during connection [15]. A major source of uncertainty comes from the uncertainty in the reference values for the ring and pin gauge standards. A further major source of uncertainty is due to the influence of the shape of the conductor at both ends.

The uncertainty for the diameter measurements made by both NMIs was determined at a 95% level of confidence using a coverage factor k of 2 since the effective degrees of freedom for these measurements were relatively large (i.e., > 1000). The major uncertainty source in the diameter measurements at NMIJ and NPL was the uncertainty of the calibration value of the reference gauges [14], [15].

IV. UNCERTAINTY CALCULATION OF Z_{mech}

The calculation of the expanded uncertainty of Z_{mech}, i.e., U(Z_{mech}), was performed by following the methods given in [16]. The value of U(Z_{mech}) was calculated from (1) as (2), shown at the bottom of the page, where u(d_1), u(d_2), and u(ε_r) are the standard uncertainties in d_1, d_2, and ε_r, respectively. |∂Z_{mech}/∂d_1|, |∂Z_{mech}/∂d_2|, and |∂Z_{mech}/∂ε_r| are the sensitivity coefficients of each parameter with values of d_1 and d_2 for a section measuring approximately 0.5 mm of the line from both connector ends.

\[
U(Z_{mech}) = k \sqrt{\left( \frac{\partial Z_{mech}}{\partial d_1} \cdot u(d_1) \right)^2 + \left( \frac{\partial Z_{mech}}{\partial d_2} \cdot u(d_2) \right)^2 + \left( \frac{\partial Z_{mech}}{\partial \varepsilon_r} \cdot u(\varepsilon_r) \right)^2}
\]  

(2)

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Fig. 1. Measurement results, with uncertainties, made by NMIJ for (a) \(d_1\) of the NPL line, (b) \(d_1\) of the NMIJ line, (c) \(d_2\) of the NPL line, and (d) \(d_2\) of the NMIJ line. (Black solid line) Calibration value. (Gray dotted line) Uncertainty limit from the calibration value.

Fig. 2. Results of \(d_2\) measurements, made by NMIJ’s 3DCMM for the (a) female and (b) male ends of the NPL line and the (c) female and (d) male ends of the NMIJ line. The regions labeled “3DCMM” and “AGMS” were the results made by 3DCMM and AGMS, respectively. (Black line) Calibration value. (Gray line) Uncertainty in the calibration value.

59.939045/\(d_1\), 59.939045/\(d_2\), and \(Z_{\text{mech}}/\varepsilon_r\), respectively. The coverage factor \(k\) is 2 in this case.

The range for \(\varepsilon_r\), based on the laboratory environmental conditions of atmospheric pressure = (1013.25 ± 40) hPa, temperature = (23 ± 1) °C, and relative humidity = (50 ± 20)%, has been given in [12] as 0.000 078. Therefore, the standard uncertainty in \(\varepsilon_r\) can be established in the usual way, i.e., \(u(\varepsilon_r) = 0.000078/\sqrt{3} = 0.000045\).

At NPL, the values of \(d_1\) and \(d_2\) were used to determine the maximum and minimum values of \(Z_{\text{mech}}\) as follows:

\[
Z_{\text{mech(max)}} = 59.939045 \times \ln \left(\frac{d_2(\text{max})}{d_1(\text{min})}\right) \tag{3}
\]

\[
Z_{\text{mech(min)}} = 59.939045 \times \ln \left(\frac{d_2(\text{min})}{d_1(\text{max})}\right) \tag{4}
\]

where the symbols (max) and (min), which are shown as subscripts, are used to denote the maximum and minimum values of \(d_1\), \(d_2\), and \(Z_{\text{mech}}\), respectively. NPL estimated the expanded uncertainties for the maximum and minimum values of \(Z_{\text{mech}}\) using (2).

NMIJ calculated the values and uncertainties of \(Z_{\text{mech}}\) at each lengthwise location using the values of \(d_1\) and \(d_2\) at the same lengthwise location based on (1) and (2). After calculation, the maximum and minimum values of \(Z_{\text{mech}}\) were determined from all the values of \(Z_{\text{mech}}\) calculated at different points along the lengths of the air lines.

V. DATA ANALYSIS

For this comparison, the comparison parameters (i.e., the average values of \(d_1\), \(d_2\), and \(Z_{\text{mech}}\)) were chosen as the midpoint of the interval between the observed maximum and minimum values for each parameter. The midpoint (mid) and
uncertainty in the midpoint \( U(\text{mid}) \) for each parameter were determined as follows:

\[
U(\text{mid}) = \frac{(\text{max}) + (\text{min})}{2}.
\]

(5)

The difference \( \Delta_{\text{mid}} \) from the midpoint is

\[
\Delta_{\text{mid}} = \frac{(\text{max}) - (\text{min})}{2}.
\]

(6)

The \( \Delta_{\text{mid}} \) values give an indication of the quality of the line in terms of the uniformity of \( d_1, d_2, \) and \( Z_{\text{mech}}. \) The expanded uncertainty in the midpoint (at a 95% level of confidence) is given as follows:

\[
U(\text{mid}) = k \sqrt{\left(\frac{u(\text{max})}{2}\right)^2 + \left(\frac{u(\text{min})}{2}\right)^2 + \left(\frac{\Delta_{\text{mid}}}{\sqrt{3}}\right)^2}
\]

(7)

where \( u(\text{max}) \) and \( u(\text{min}) \) are the standard uncertainties in the maximum and minimum values, and \( \Delta_{\text{mid}}/\sqrt{3} \) is assumed to be the standard uncertainty for \( \Delta_{\text{mid}}, \) assuming a uniform distribution for \( \Delta_{\text{mid}}. \) The sensitivity coefficients are \( 1/2 \) for \( u(\text{max}) \) and \( u(\text{min}), \) and \( 1 \) for \( \Delta_{\text{mid}}/\sqrt{3}. \) The coverage factor \( k \) is related to the effective degree of freedom \( \nu_{\text{eff}}. \) In this case, \( \nu_{\text{eff}} \) is

\[
\nu_{\text{eff}} = \frac{u^4(\text{mid})}{\frac{u^4(\text{max})}{\nu_{\text{max}}} + \frac{u^4(\text{min})}{\nu_{\text{min}}} + \left(\frac{\Delta_{\text{mid}}/\sqrt{3}}{\nu_{\text{mid}}}\right)^2}
\]

(8)

where \( u(\text{mid}) \) is the standard uncertainty in the midpoint; \( u_{\text{max}} \) and \( u_{\text{min}} \) are the degrees of freedom for the maximum and minimum values, respectively; and, \( \nu_{\Delta_{\text{mid}}} \) is the degrees of freedom for the difference from the midpoint. (In this case, \( \nu_{\Delta_{\text{mid}}} \) is infinite since it is assumed that \( \Delta_{\text{mid}} \) is characterized by a uniform distribution.)

The midpoint, expanded uncertainty (at a 95% level of confidence), \( k, \) and \( \nu_{\text{eff}} \) were calculated for the \( d_1, d_2, \) and \( Z_{\text{mech}} \) measurements made by NMIJ and NPL of each air line. In this case, all calculated values of \( \nu_{\text{eff}} \) were relatively large; thus, a value of \( k = 2 \) was used throughout the analysis.

VI. COMPARISON METHOD

The degree of equivalence between the results obtained by NPL and NMIJ is quantitatively expressed by two terms: 1) the difference between the midpoint values of NMIJ and NPL \( \Delta \) and 2) the uncertainty of this difference at a 95% level of confidence \( U(\Delta). \) For each measurand, these were calculated as follows [17]:

\[
\Delta = |\text{NPL}_{\text{(mid)}} - \text{NMIJ}_{\text{(mid)}}|
\]

(9)

\[
U(\Delta) = k \sqrt{u^2(\text{NPL}) + u^2(\text{NMIJ})}
\]

(10)

where \( \text{NPL}_{\text{(mid)}} \) and \( \text{NMIJ}_{\text{(mid)}} \) are the midpoint values determined by NPL and NMIJ, respectively, and \( u(\text{NPL}) \) and \( u(\text{NMIJ}) \) are the associated standard uncertainties in these midpoint values. The coverage factor \( k \) is chosen based on the value of the degrees of freedom for the comparison \( v_{\text{com}} \) obtained from the following:

\[
v_{\text{com}} = \frac{u^4(\Delta)}{u^4(\text{NPL}) + u^4(\text{NMIJ})}
\]

(11)

where \( v_{\text{NPL}} \) and \( v_{\text{NMIJ}} \) are the degrees of freedom for NPL's and NMIJ's midpoint values, respectively.

The values of \( \Delta, U(\Delta), k, \) and \( v_{\text{com}} \) were calculated for the midpoint values of \( d_1, d_2, \) and \( Z_{\text{mech}} \) made by both NMIs. The calculated values of \( v_{\text{com}} \) for \( d_1, d_2, \) and \( Z_{\text{mech}} \) were relatively large, and therefore, a value of \( k = 2 \) was used in this comparison.

VII. RESULT

A. Center Conductor Diameter Measurement

Fig. 3 shows the maximum, minimum, and midpoint values of \( d_1 \) obtained by NMIJ and NPL, with the error bars representing the expanded uncertainties. The expanded uncertainty in the maximum and minimum values of \( d_1 \) obtained using the AGMSS at both NMIJ and NPL ranged from 0.7 to 1.2 \( \mu \)m. The expanded uncertainty for \( d_1 \) obtained by NPL using the LGMS for the oversized section of the NPL line was 1.8 \( \mu \)m. For the NMIJ line, the uncertainties in the maximum and minimum values were almost the same as \( \Delta_{\text{mid}} \) because of the good longitudinal diameter uniformity of this line. However, the value of \( \Delta_{\text{mid}} \) dominated the value of \( U(\text{mid}) \) for the NPL line. Thus, the midpoint value and \( U(\text{mid}) \) for \( d_1 \) for the NMIJ line provides a better representation of the measurement capabilities of both NMIs.

B. Outer Conductor Diameter Measurement

Fig. 4 shows the maximum, minimum, and midpoint values of \( d_2 \) obtained by NMIJ and NPL, with the error bars representing the expanded uncertainties. The uncertainties for the measurements of \( d_2 \) at the both NMIs were approximately 1.0 \( \mu \)m, except for the measurements made near the ends of the lines, where it was found that the outer conductors became slightly smaller and were no longer cylindrical in shape. In addition, the larger uncertainties at NMIJ included the influence of the connector’s shape and the method of measurement (using a
Fig. 4. Results of $d_2$ measurements at NMIJ and NPL for the (a) NPL and (b) NMIJ lines.

Fig. 5. Results of $Z_{\text{mech}}$ calculations at NMIJ and NPL for the (a) NPL and (b) NMIJ lines.

However, the maximum and minimum values of $d_2$ obtained by both NMIs indicated good agreement, i.e., to within 0.5 μm. Thus, the difference between the midpoint values for both lines was less than or equal to 0.4 μm. In this measurement, the influence of the shape of the NPL line compared with that of the NMIJ line caused the value of $\Delta_{\text{mid}}$ for the NPL line to be approximately twice the value of $\Delta_{\text{mid}}$ for the NMIJ line. Therefore, as before, the midpoint value and $U \left( \Delta \right)$ for $d_2$ for the NMIJ line provide a better representation of the measurement capabilities of both NMIs.

C. Characteristic Impedance Determination

Fig. 5 shows the maximum, minimum, and midpoint values for $Z_{\text{mech}}$ determined by NMIJ and NPL, with the error bars representing the expanded uncertainties. For both maximum and minimum values, there is good agreement between NMIJ and NPL. The uncertainties of $Z_{\text{mech}}$ were less than 0.057 Ω, except for the minimum values obtained by NPL for the NPL line. This was because the minimum value of $Z_{\text{mech}}$ for the NPL line was calculated using the $d_1$ obtained using the LGMS, which has a larger uncertainty, as previously described. The midpoint values determined by both NMIs agreed with each other to within 0.018 Ω. The expanded uncertainty in the midpoint value for the NPL line was larger than that for the NMIJ line due to the discontinuity on the center conductor of the NPL line. In this case, the uncertainty was dominated by the shape of the air line.

TABLE II

<table>
<thead>
<tr>
<th>Comparison parameters</th>
<th>NPL</th>
<th>NMIJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$ (μm)</td>
<td>Δ</td>
<td>U(Δ)</td>
</tr>
<tr>
<td>0.0</td>
<td>0.72</td>
<td>0.5</td>
</tr>
<tr>
<td>0.3</td>
<td>2.05</td>
<td>0.3</td>
</tr>
<tr>
<td>$Z_{\text{mech}}$ (Ω)</td>
<td>0.008</td>
<td>0.018</td>
</tr>
<tr>
<td>$Z_{\text{mech}}$ in line section (Ω)</td>
<td>0.013</td>
<td>0.084</td>
</tr>
</tbody>
</table>

For purposes of comparing the measurement capabilities of the two NMIs, the value of $Z_{\text{mech}}$ for the main section of the line (i.e., ignoring the center conductor discontinuity and the shape around the connector ends) was also determined and compared between both NMIs. These results are shown in Fig. 6. For the maximum and minimum values, the maximum difference between both NMIs was approximately 0.05 Ω, i.e., about twice the difference in $Z_{\text{mech}}$, as shown in Fig. 6. This was because NMIJ and NPL used slightly different calculation methods, as described in Section IV. The midpoint values include the influence of the calculation methods used to determine the maximum and minimum values for both NMIs. However, the midpoint values of $Z_{\text{mech}}$ for the main section of line were close to 50 Ω for both lines, and the uncertainties were less than 0.1 Ω.

D. Degrees of Equivalence

Table II summarizes the comparison results in terms of $\Delta$ and $U(\Delta)$ values for all these measurands. The values of $\Delta$ were less than or equal to 0.5 μm for all diameter measurements. The values of $U(\Delta)$ for the diameter measurements were generally less than 3.0 μm, except for the measurements of $d_1$ for the NPL line. In spite of the NPL line containing a center conductor discontinuity, the value of $\Delta$ for $d_3$ was 0.0 μm, which represents an excellent agreement between the NMIs.

Furthermore, the values of $\Delta$ for $Z_{\text{mech}}$ were less than 0.020 Ω for both lines and were considerably less than the associated $U(\Delta)$ values. The values of $U(\Delta)$ were less than 0.090 Ω for the main section of the line in both air lines. Of particular note is the value of $\Delta = 0.001$ Ω for the main section of the line for the NMIJ line.
This result, i.e., for the NMIJ line that exhibited very good longitudinal diameter uniformity, indicates very good agreement between the NMIs.

VIII. CONCLUSION

This paper has shown that the results obtained by NMIJ and NPL for the mechanical determinations of two precision coaxial air lines were equivalent to within the expected uncertainties for these measurements. This comparison indicated that a calculation of $Z_{\text{mech}}$ made by NMIJ and NPL agreed to within 1 m$\Omega$ for the NMIJ line that exhibited very good longitudinal diameter uniformity.

With regard to establishing the degree of equivalence for these measurands, all the values of $\Delta$ were less than the expanded uncertainties for both NMIs for all the comparison parameters, thus validating these calibration and measurement capabilities.

Finally, it is worth noting that, to the best of the authors’ knowledge, this is the first time that a comparison of this type of measurement has been undertaken, certainly by NMIs. It is therefore very encouraging that the comparison yielded such good agreement. This level of agreement provides very valuable underpinning measurement quality assurance for these types of measurands, which are fundamental to establishing traceability to SI for a wide range on measurements made at microwave frequencies.

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