Bi-Lateral Comparison between NIS-Egypt and NMISA-South Africa for the Calibration of an Optical Time Domain Reflectometer

Osama Terra, Mariesa Nel, Hatem Hussein

Abstract—Calibration of Optical Time Domain Reflectometer (OTDR) has a crucial role for the accurate determination of fault locations and the accurate calculation of loss budget of long-haul optical fibre links during installation and repair. A comparison has been made between the Egyptian National Institute for Standards (NIS-Egypt) and the National Metrology institute of South Africa (NMISA-South Africa) for the calibration of an OTDR. The distance and the attenuation scales of a transfer OTDR have been calibrated by both institutes using their standards according to the standard IEC 61746-1 (2009). The results of this comparison have been compiled in this report.

Keywords—OTDR calibration, recirculating loop, concatenated method, standard fibre.

I. INTRODUCTION

OTDRs are widely used as a diagnostic tool during the installation and repair of optical fibre networks. Their purpose is to detect fault in locations and to measure loss along optical fibre links. Therefore, a regular calibration for OTDRs is required to assure the stated accuracy in attenuation and distance measurements. Several methods are proposed for the calibration of OTDRs [1], [2]. In this report, a comparison has been made between NIS-Egypt and NMISA-South Africa for the calibration of OTDRs by calibrating the distance and attenuation scales of a transfer OTDR and comparing the calibration results. The calibrations are performed according to the standard IEC 61746-1 (2009) [1].

II. BACKGROUND ON OTDR CALIBRATION

A. Distance Scale Calibration

The goal of the distance scale calibration is to find the location offset (ΔL₀) and the distance scale deviation (ΔSₙ) of an OTDR [1]. The parameters (ΔL₀, ΔSₙ) are the intercept and the slope, respectively, of the curve plotted between the location errors of the OTDR measurements (Lₒtdrⱼ - Lᵣᵢⱼ) and the well-known lengths of the reference fibre (Lᵣᵢⱼ). That’s to say:

ΔL₀ = (Lₒtdr - Lᵣ)ᵢ (at L = 0),

ΔSₙ = (Lₒtdrᵢ - Lᵣᵢ) / Lᵣᵢ (1)

where, Λ \( \Delta L_o \) is the thermo-optic coefficient for silica fibres which is about \( 1 \times 10^{-5} \) [4].

In this report, two methods will be used for the calibration of OTDR, namely, the recirculating loop method which is implemented by NIS and the concatenated method which is implemented by NMISA.

1. Recirculating Loop Method

The recirculating delay line, which is displayed in Fig. 1 (a), places a number of reflective features on the OTDR display, as shown in Fig. 1 (b). Using the reference values of the fibre length, measured at NIS, for the lead-in fibre \( L_a \) and the delay-line \( L_b \), the series of reference locations can be described by:

\[
L_{ref,i} = L_a + i \cdot L_b
\]

The guide to the expression of the uncertainty in measurements (GUM) is used to calculate the uncertainties [3]. The uncertainties in the location offset and the distance scale deviation are described by:

\[
u(L_a) = \sqrt{\left(\frac{\delta L_{Adrr}}{L_{Adrr}}\right)^2 + \left(\frac{\delta L_{Areff}}{L_{Areff}}\right)^2}, \quad u(\Delta S_L) = \sqrt{\left(\frac{\delta S_{Adrr}}{L_{Adrr}}\right)^2 + \left(\frac{\delta S_{Bref}}{L_{Bref}}\right)^2}
\]

where, \( \delta L_{Adrr}, \delta L_{Areff} \), \( \delta S_{Adrr}, \delta S_{Bref} \), are the absolute and relative uncertainties in the measured and the reference lead-in fibre lengths. Optical fibre length is sensitive to temperature changes. Uncertainty contribution due to temperature changes must be included in uncertainty budget. If the OTDR is calibrated at any other temperature than the one at which it was measured, the following relation must be applied to compensate for the temperature induced length changes:

\[
\delta L = \frac{\Delta N}{\Delta T_{emp}} L
\]

Osama Terra is with the National Institute of Standard (NIS), Tersa St. Haram, code: 12211, P. O. Box: 136 Giza, Egypt.

Mariesa Nel is with the National Metrology Institute of South Africa (NMISA), Lynnwood Ridge, Pretoria, South Africa.

Hatem Hussein is with the National Institute of Standard (NIS), Tersa St. Haram, code: 12211, P. O. Box: 136 Giza, Egypt.
Concatenated Fibre Method

A lead in fibre of 1 km is used and the standard fibre is approximately 10 km long. The short lengths that were used for the concatenated fibre were in increments of 30 cm. 30 cm, 60 cm and 1.2 m fibre lengths were used in combination to perform the measurements. The incremental fibre lengths must be shorter than the distance sampling interval of the OTDR. A measurement set-up diagram is given in Fig. 2.

\[ L_{\text{ref}} = \frac{c T_{\text{std}}}{n} \]

where, \( L_{\text{ref}} \) which represents the physical length of the standard fibre; \( L_{\text{OTDR}} \) is the distance as measured by the OTDR; \( \langle L_{\text{OTDR}} \rangle \) is the average of \( L_{\text{OTDR}} \) as realised with different incremental fibres. \( n \) is the group refractive index as set on the OTDR; \( c = 299 \, 792 \, 458 \, \text{m/s} \) is the speed of light in vacuum; \( T_{\text{ref}} \) is the time-of-flight of a light pulse through the fibre; \( L_{\text{OTDR}} \) is a location as measured by the OTDR; \( L_{\text{LeadIn}} \) is the length of a lead-in fibre, lead-in patch cords and incremental fibre(s).

B. Loss Scale

The goal of an OTDR attenuation scale calibration is to find the attenuation scale deviation, \( \Delta A \), using (3):

\[ \Delta A = \frac{A_{\text{OTDR}} - A_{\text{ref}}}{A_{\text{ref}}} \]  

where, \( A_{\text{OTDR}} \) is the attenuation measured by the OTDR and \( A_{\text{ref}} \) is the reference attenuation. The standard reference fibre method is implemented to calibrate the attenuation scale of the OTDR according to the IEC 61746-1 (2009) standard [1]. The calibrated fibre standard is connected to the OTDR through a set of lead-in fibres. The lead-in fibres places the fibre standard at different positions (\( A_{\text{OTDR},i} \)) along the OTDR backscatter trace. A variable attenuator is used to move the fibre at different attenuation levels. The attenuation scale deviation, \( \Delta A \), is determined for the operating wavelengths of the OTDR at 1310 nm and 1550 nm. The calibration set-up is shown in Fig. 3.

FIG. 3 OTDR calibration using fibre standard method

The major contributors to the uncertainty in the attenuation scale deviation, \( \Delta A \), are the standard reference fibre and the statistical uncertainty of the measurement. The wavelengths of the OTDR lasers are measured using an optical spectrum analyser with an accuracy better than \( \pm 0.05 \, \text{nm} \) and were found to be (1547.7 nm and 1312.2 nm). The uncertainty in the OTDR attenuation scale calibration due to wavelength is neglected since the wavelength is accurately measured. The uncertainty of the attenuation scale deviation is described by (7):

\[ u(\Delta A) = \sqrt{\left(\frac{\delta A_{\text{OTDR}}}{A_{\text{OTDR}}}\right)^2 + \left(\frac{\delta A_{\text{ref}}}{A_{\text{ref}}}\right)^2} \]  

III. REFERENCE STANDARDS

A. Distance Standards

NIS uses a recirculating loop (RL) that purchased from the NPL. The RL consists of a lead-in fibre of \( \approx 2.2 \, \text{km} \) and a fibre...
loop of ≈ 12.4 km, to calibrate the distance scale of the OTDR. The RL has been calibrated at NIS using the time-of-flight technique with reference to a time interval counter [5]. In order to complete the traceability chain to the SI unit of time, the counter is calibrated at the time and frequency laboratory at NIS. The results are shown in Table I.

TABLE I
CALIBRATION RESULTS OF THE RECURRENT ARTEFACT (AT 23°C) FOR NIS LABORATORY

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Wavelength/nn</th>
<th>Time-of-flight/ns</th>
<th>Uncertainty/ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-in</td>
<td>1310</td>
<td>10826.46</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>1556</td>
<td>10831.00</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Loop</td>
<td>1310</td>
<td>67619.04</td>
<td>± 1.5</td>
</tr>
<tr>
<td></td>
<td>1556</td>
<td>67646.00</td>
<td>± 1.5</td>
</tr>
</tbody>
</table>

NMISA, South Africa calibrated the OTDR using the concatenated fibre method. A standard length of fibre was used for the calibration as well as short lengths of fibre. The standard length fibre was purchased from NPL, Single-Mode (Corning SMF-28), additionally; it is calibrated at NMISA with a delay generator that is referenced to the Caesium atomic clock. The RL has been calibrated at NIS using the time-of-flight method. A standard length of fibre was used to calibrate the distance scale of the OTDR.

B. Attenuation Standards

NIS uses a fibre spool with length of about 10.2 km to calibrate the OTDR. The spectral attenuation of the fibre spool has been measured at NIS using the cutback technique. A wide range external-cavity tuneable diode laser source (1500 nm to 1630 nm) and a distributed feedback, DFB, laser at 1310 nm are used for the cutback technique. In-house traceability to SI unit of power is performed using a calibrated power meter. The artefact used by NMISA as the standard for the calibration of the OTDR attenuation scale is a fibre from NPL, National Physical Laboratory. The fibre was calibrated in 2005 for attenuation coefficient uniformity. The single mode fibre is about 10.3 km long and is fitted with FC/APC connectors, it is fitted into a box to minimise environmental changes.

IV. TRANSFER ARTEFACT (OTDR)

A Yokogawa AQ1200 OTDR which has a distance range > 200 km with accuracy of ± 1.5 m and dynamic range of 32 dB with accuracy of ± 0.05 dB/dB is used as a transfer standard. The OTDR uses two lasers operating at wavelengths 1310 nm and 1550 nm to measure the distance of a fibre.

V. RESULTS

A. Distance Scale Calibration

The following OTDR setting are chosen before starting the measurement: pulse width of 3 ns, group refractive index n =1.46 (for 1310 and 1550 nm), and 1 minute averaging time. The calibration results are given in Table III.

TABLE II
RESULTS OF OPTICAL DELAY LINE CALIBRATION FOR THE NMISA LABORATORY (AT 24.3°C)

<table>
<thead>
<tr>
<th>Wavelength/nn</th>
<th>Time-of-flight/ns</th>
<th>Uncertainty/ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>1315</td>
<td>49930.1</td>
<td>1.2</td>
</tr>
<tr>
<td>1559</td>
<td>49951.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The major contributors to the distance scale deviation (ΔSL) and to the location offset (ΔL0) are the reference fibre length and the temperature variations. The combined uncertainty is found by adding in quadrature this contribution to the statistical uncertainty from the measurements. The expanded uncertainty at 95% can be calculated by multiplying the combined uncertainty by 2.17 for infinite degree of freedom (OTDR averages several measurements over one minute).

B. Attenuation Scale Calibration

The OTDR is used to measure the attenuation standard uses a pulse width of 5 µm over 1 minute. The calibration results of the OTDR attenuation scale deviation, ΔSA, at NIS and NMISA are shown in Table IV.

TABLE III
CALIBRATION RESULTS FROM NIS AND NMISA

<table>
<thead>
<tr>
<th>Wavelength/nn</th>
<th>Parameter</th>
<th>NIS Value</th>
<th>Uncertainty (dB/dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1310 nm</td>
<td>Location offset</td>
<td>0.54 m</td>
<td>±0.49 m</td>
</tr>
<tr>
<td></td>
<td>Distance scale deviation</td>
<td>±0.94×10⁻⁵</td>
<td>±3.90×10⁻⁵</td>
</tr>
<tr>
<td>1550 nm</td>
<td>Location offset</td>
<td>0.26 m</td>
<td>±0.45 m</td>
</tr>
<tr>
<td></td>
<td>Distance scale deviation</td>
<td>±1.79×10⁻⁵</td>
<td>±4.19×10⁻⁵</td>
</tr>
</tbody>
</table>

C. Comparison of Results

A comparison between the results for both institutes, NIS and NMISA, for location offset and distance scale deviation at 1310 nm and 1550 nm is shown in Figs. 4 and 5.

D. Normalized Error (En)

The normalized Error (En) is calculated for the parameter (X) according to (8):

$$E_n(X) = \frac{X_{NIS} - X_{NMISA}}{\sqrt{(U(X_{NIS})^2 + U(X_{NMISA})^2)}}$$  (8)

where X is (ΔL0, ΔSL, ΔSA, ΔS). Table V shows the normalized error for these parameters.
The results obtained for attenuation scale deviation at 1310 nm and 1550 nm are shown in Fig. 6.
VI. Conclusion

A bi-lateral comparison between NIS-Egypt and NMISA-South Africa has been conducted. A transfer OTDR has been calibrated by both institutes, NIS and NMISA, for the distance and the attenuation scales using their respective standards according to the IEC standard 61746-1 (2009). Good agreement is found between the results from both institutes which lie within the uncertainty limits of the OTDR.

ACKNOWLEDGMENT

The author would like to thank the Science and Technology Development Fund (STDF) for supporting and funding this research and the accreditation process under the umbrella of center of excellence projects-laboratory accreditation.

REFERENCES