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

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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 (ΔL_o) and the distance scale deviation (ΔS_L) of an OTDR [1]. The parameters (ΔL_o , ΔS_L) are the intercept and the slope, respectively, of the curve plotted between the location errors of the OTDR measurements ($L_{otdr,i} - L_{ref,i}$) and the well-known lengths of the reference fibre ($L_{ref,i}$). That's to say:

$$\Delta L_o = \left(< L_{otdr} > - L_{ref}\right)_{(at\ L=0)} \ , \quad \Delta S_L = \frac{< L_{otdr} > - L_{ref}}{L_{ref}} \quad (1)$$

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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 ($\boldsymbol{L_a}$) and the delay-line ($\boldsymbol{L_b}$), the series of reference locations can be described by (2):

$$L_{ref,i} = L_a + i \, . \, L_b \quad (2)$$

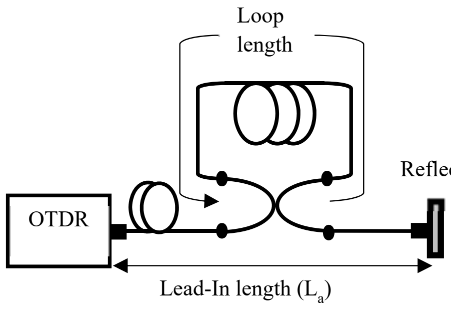
The guide to the expression of the uncertainty in measurements (GUM) is used to calculate the uncertainties [3]. The uncertainties in the location offset and the distance scale deviation are described by:

$$u(L_o) = \sqrt{(\delta L_{Aotdr})^2 + \left(\delta L_{Aref}\right)^2}, u(\Delta S_L) = \sqrt{\left(\frac{\delta L_{Botdr}}{L_{Botdr}}\right)^2 + \left(\frac{\delta L_{Bref}}{\mathrm{Bref}}\right)^2} \quad (3)$$

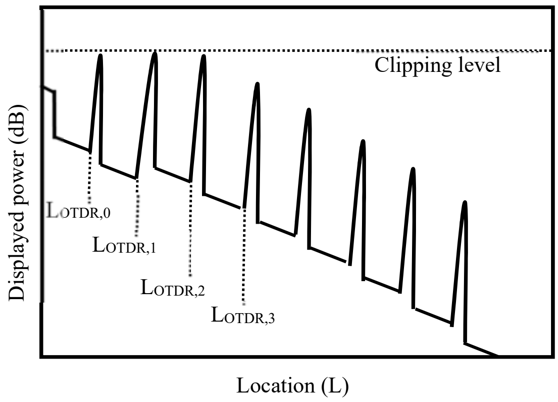
where, ($\delta L_{Aotdr}, \delta L_{Aref}$), ($\frac{\delta L_{Botdr}}{L_{Botdr}}, \frac{\delta L_{Bref}}{L_{Bref}}$): are the absolute and relative uncertainties in the measured and the reference lead-in fibre lengths. Optical fibre length is sensitive to temperature changes. Uncertainty contribution 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:

$$\delta L = \frac{\delta N}{\delta Temp} \delta Temp \ L \quad (4)$$

where, $\frac{\delta N}{\delta Temp}$, is the thermo-optic coefficient for silica fibres which is about 1×10^{-5} [4].



(a)



(b)

Fig. 1 (a) The recirculating delay-line (b) OTDR trace produced by a recirculating delay-line

2. 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.

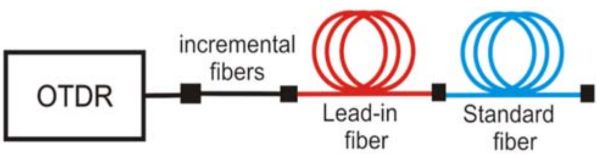


Fig. 2 Setup for calibration of an OTDR for the concatenated fibre method

The distance scale deviation, ΔS_L, and location offset, ΔL_o, of the OTDR are calculated as:

$$\Delta S_L = \frac{\langle L_{OTDR} \rangle}{L_{ref}} - 1, \Delta L_o = \langle L_{OTDR} - (1+\Delta S_L)(L_{ref} + L_{Lead\,In}) \rangle \quad (5)$$

where, $L_{ref} = \frac{cT_{std}}{n}$ which represents the physical length of the standard fibre; L_{OTDR} is the distance as measured by the OTDR; $\langle L_{OTDR} \rangle$ is the average of L_{OTDR} as realised with different incremental fibres. n is the group refractive index as set on the OTDR; c = 299 792 458 m·s^{-1} is the speed of light in vacuum; T_{ref} is the time-of-flight of a light pulse through the fibre; L_{OTDR} is a location as measured by the OTDR; L_{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, ΔS_A, using (3):

$$\Delta S_A = \frac{A_{otdr} - A_{ref}}{A_{ref}} \quad (6)$$

where, A_{otdr} is the attenuation measured by the OTDR and A_{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 ($A_{otdr,i}$) along the OTDR backscatter trace. A variable attenuator is used to move the fibre at different attenuation levels. The attenuation scale deviation, ΔS_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.

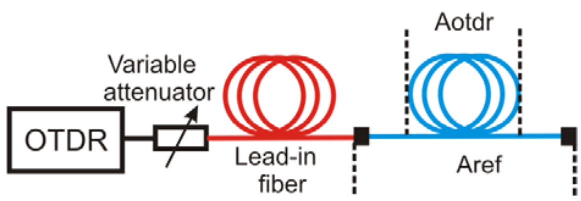


Fig. 3 OTDR calibration using fibre standard method

The major contributors to the uncertainty in the attenuation scale deviation, ΔS_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 ± 0.05 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):

$$u(\Delta S_A) = \sqrt{\left(\frac{\delta A_{otdr}}{A_{otdr}}\right)^2 + \left(\frac{\delta A_{ref}}{A_{ref}}\right)^2} \quad (7)$$

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 ≈ 2.2 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 RECIRCULATING ARTEFACT (AT 23°C) FOR NIS LABORATORY

Fibre	Wavelength/nm	Time-of-flight/ns	Uncertainty/ns
Lead-in	1310	10826.46	± 0.5
	1556	10831.00	± 0.5
Loop	1310	67619.04	± 1.5
	1556	67646.00	± 1.5

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 results of the time delay measurements are shown in Table II.

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

Wavelength/nm	Time-of-flight/ns	Uncertainty/ns
1315	49 930.1	1.2
1559	49 951.5	1.2

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 to1630 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 III
CALIBRATION RESULTS FROM NIS AND NMISA

Wavelength	Parameter		**NIS**	**NMISA**
1310 nm	Location offset	Value	0.54 m	0.65 m
		Uncertainty	±0.49 m	±0.7 m
	Distance scale deviation	Value	0.94×10^{-5}	-0.60×10^{-5}
		Uncertainty	$\pm5.2\times10^{-5}$	$\pm3.90\times10^{-5}$
1550 nm	Location offset	Value	0.26 m	1.02 m
		Uncertainty	±0.45 m	±0.67 m
	Distance scale deviation	Value	1.87×10^{-5}	-0.55×10^{-5}
		Uncertainty	$\pm5\times10^{-5}$	$\pm4\times10^{-5}$

The major contributors to the distance scale deviation (ΔS_L) and to the location offset (ΔL_o) 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, ΔS_A, at NIS and NMISA are shown in Table IV.

TABLE IV
ATTENUATION SCALE DEVIATION CALIBRATION RESULTS AT NIS AND NMISA

Institute	Wavelength	ΔS_A (dB/dB)	Uncertainty (dB/dB)
NIS	1313 nm	-0.030	± 0.032
	1548 nm	-0.033	± 0.032
NMISA	1313 nm	-0.028	± 0.025
	1348 nm	-0.005	± 0.028

C. Comparison of Results

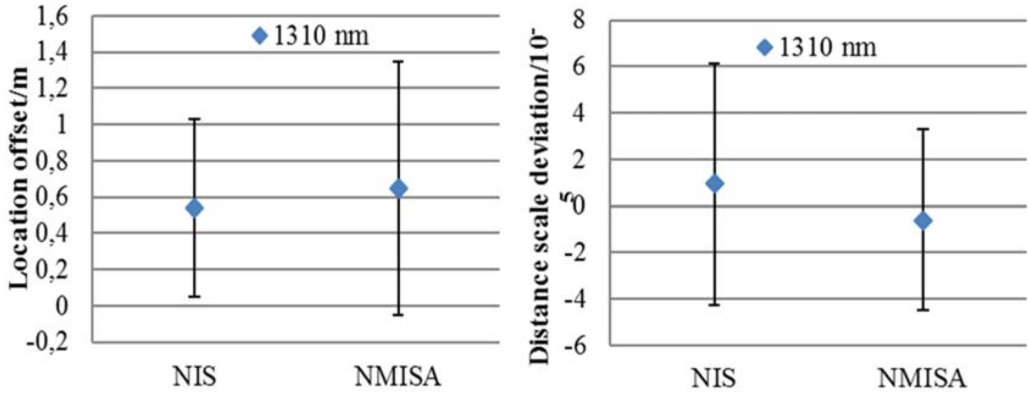
A comparison between the results for both institutes, NIS and NMISA, for location offset and distance scale deviation at 1310 nm and 1550 nm is shown in Figs. 4 and 5.

D. Normalized Error (E_n)

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

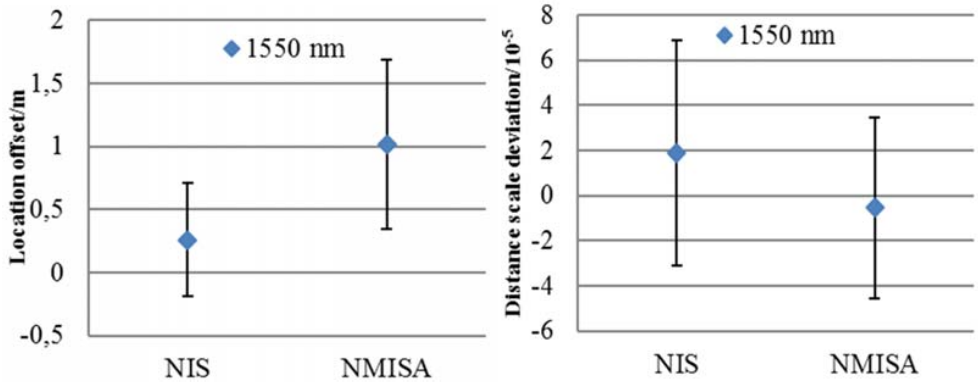
$$E_n(\mathrm{X}) = \frac{X_{NIS} - X_{NMISA}}{\sqrt{(U(\mathrm{X}_{NIS})^2 + U(X_{NMISA})^2)}} \quad (8)$$

where X is ($\Delta L_0, \Delta S_L, \Delta S_A$). Table V shows the normalized error for these parameters.



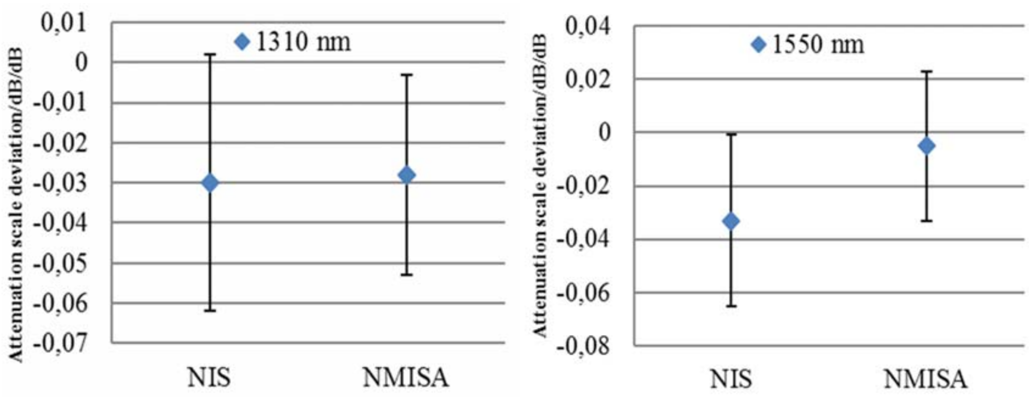
(a) (b)

Fig. 4 Comparison between NIS and NMISA at 1310 nm for (a) location offset (b) distance scale deviation



(a) (b)

Fig. 5 Comparison between NIS and NMISA at 1550 nm for (a) location offset (b) distance scale deviation



(a) (b)

Fig. 6 Comparison of the attenuation scale calibration between NIS and NMISA at (a) 1310 nm and (b) 1550 nm

The results obtained for attenuation scale deviation at 1310 nm and 1550 nm are shown in Fig. 6.

TABLE V
E_N VALUES FOR (ΔL_0, ΔS_L, ΔS_A)

Wavelength	Parameter	Normalized Error
1310 nm	ΔL_o	0.13
	ΔS_L	0.24
	ΔS_A	0.05
1550 nm	ΔL_o	0.94
	ΔS_L	0.83
	ΔS_A	0.65

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.

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