Evaluation of OTDR Calibration Technique and use for Optical Fibre Uniformity Measurements

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ABSTRACT

A 'Golden Fibre' calibration artefact has been used to calibrate a range of OTDRs which in turn have been used to make measurements on a standard telecom fibre and a non-uniform fibre. The results have enabled the calibration technique to be evaluated. Test definitions for fibre uniformity have been assessed and values of mode-field-diameter and cut-off wavelength have been calculated from the measured relative backscatter parameter and compared with discrete measurements of these parameters.

INTRODUCTION

Several OTDR calibration techniques have been under discussion within the International Electrotechnical Commission's Technical Committee 86, Working Group 4 [1]; these comprise both active and passive methods. A passive 'Golden Fibre' calibration artefact was used in this study to allow the OTDR to be calibrated under similar conditions to those which measurements are made.

Thirteen organisations used the 'Golden Fibre' calibration artefact to calibrate their OTDR and then measure a standard telecom fibre and a highly non-uniform fibre. The results have enabled the calibration technique and a number of fibre uniformity tests to be evaluated.

'GOLDEN FIBRE'

This 12.9 km fibre was selected as having the greatest uniformity from a group of telecommunication fibres conforming to ITU-T Rec. G652 [3], the fibres being measured on an OTDR which had previously been calibrated for the linearity of its response. It was wound on a standard 15 cm diameter reel at a tension of 60 g. The fibre was subjected to environmental and vibration tests and the attenuation was shown to be stable. The total loss of the fibre was measured by the cut-back technique [4] over the wavelength range 1200 to 1600 nm with a typical uncertainty of 0.0013 dB/km. The loss showed no directional dependence to within the noise level and difference in attenuation coefficient between the central 4 km section and the average for the whole length was <0.0015 dB/km. The optical length was measured with an uncertainty better than ± 0.2 m using a time-of-flight technique.

TEST FIBRES

In addition to the 'Golden Fibre' (Fibre 1), two test fibres were circulated to participants; a typical telecom fibre 12 km long (Fibre 2) conforming to ITU/TS G652[3] and a specially prepared, highly non-uniform fibre 10 km long (Fibre 3). The attenuation and length of these fibres were also measured. All the fibres were subjected to environmental tests.

CALIBRATION

All calibrations and measurements were carried out as described in draft IEC TC86 document, Section 7.1 [1] at both 1300 and 1550 nm with a pulse width of 1 μs. A group index of 1.46 was assumed. The central 4 km section of the 'Golden Fibre' was used as the reference loss to calibrate

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the OTDR loss scale. The calibration was carried out at ~0.5 dB increments from the maximum received power. The calibration was performed at distances of 7.0 and 19.6 km using different lead-in fibres. The loss scale deviation, $\Delta S_A(F)$, and its uncertainty were calculated following the IEC procedures.

Although one OTDR had a maximum loss deviation of 0.15 dB/dB, the loss deviations were generally close to or less than ± 0.05 dB/dB. With few exceptions, all participants report a loss scale calibration uncertainty of 0.01 dB/dB or less.

The distance scale was checked using the method of IEC TC86 [1]. With the exception of 2 OTDRs, the distance scale deviation, ΔS_L, was less than 1 m in 10 km and the distance scale offset, ΔL_0, less than 3.3 m.

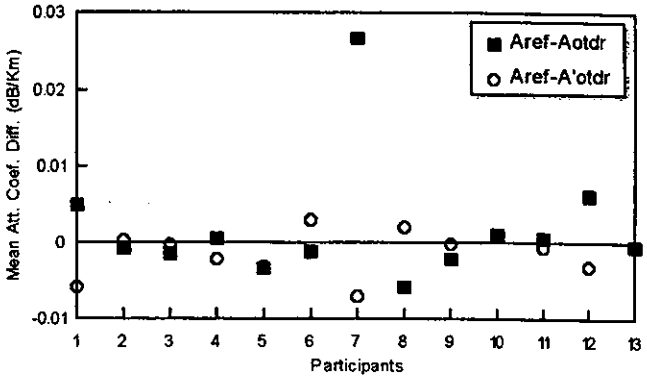


Figure 1 Difference between measured and corrected attenuation coefficients of Fibre 2 and A_{ref} at 1300nm

CALIBRATION VERIFICATION

The mean attenuation coefficient of Fibre 2, A_{OTDR} (dB/km) was determined at 1300 and 1550 nm from measurements at both ends of the fibre and with nominal 0, 2, 4 and 6 dB attenuation inserted between the fibre and the OTDR. The measured data were corrected using the loss calibration data to obtain A'_{OTDR}. The 'true' attenuation coefficient A_{ref} for the operating wavelength of the OTDR was obtained from the cut-back attenuation data. The difference between A_{ref} and the mean measured attenuation coefficient, A_{OTDR}, and between the corrected mean attenuation coefficient, A'_{OTDR}, were calculated.

The results at 1300 nm are shown in Figure 1. The calibration procedure is effective if $|A_{ref} - A'_{OTDR}| < |A_{ref} - A_{OTDR}|$. The rms mean $\langle(A_{ref} - A_{OTDR})^2\rangle^{1/2}$ is 0.0087 dB/km and the rms mean $\langle(A_{ref} - A'_{OTDR})^2\rangle^{1/2}$ is 0.0033 dB/km. The standard deviation of A_{OTDR} and A'_{OTDR} at 1300 nm determined from data at attenuation levels of 0, 2, 4 and 6 dB are compared in Figure 2.

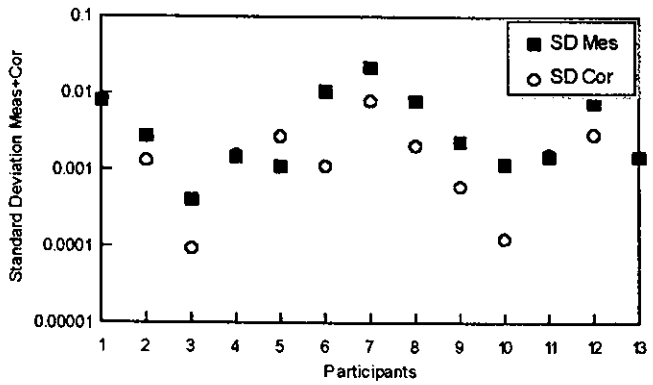


Figure 2 Standard deviation of measured and corrected attenuation coefficients of Fibre 2 at 1300nm

These results and similar ones at 1550 nm show that the 'Golden Fibre' calibration techniques is effective on a range of OTDRs and that attenuation coefficients of fibres 10 km long can be measured with an uncertainty of 0.003 dB/km; limited largely by the uncertainty in the calibration fibre itself. Loss scale calibration improves the linearity by a factor of 2 to 3.

ATTENUATION UNIFORMITY

A number of draft specifications for attenuation uniformity have been discussed within ETSI and test methods for these specifications have been proposed within CECC/WG28 [2]. Each method requires OTDR measurements to be made from both ends of the fibre, and the trace to be divided into 2 km segments at 1 km intervals.

The three proposed definitions of the fibre's attenuation uniformity parameter, X_a, are given by; half the difference between the maximum and minimum segments attenuation coefficients, $(\alpha_{max} - \alpha_{min})/2$, the maximum difference between a segment attenuation coefficient and the average attenuation coefficient for the whole fibre length, $(\alpha_{max} - \alpha_{ave})$, and the RMS deviation of each segment's attenuation coefficient from the average attenuation coefficient, $\Delta\alpha_{RMS}$. These three definitions for all participants' measurements on Fibre 2 at 1300 nm are compared in Figure 3.

Although all participants identified the fibre as having α_{min} and α_{max} towards the two ends respectively, the values of $(\alpha_{max} - \alpha_{min})$ ranged from 0.008 to 0.03 dB/km with a mean of 0.017±0.007 dB/km. This is a significant spread of results, however if the extreme results (i.e. participants 1, 2, 6 and 11) are ignored then the remainder are more tightly grouped with the standard deviation being about 16% of the mean. The ratios of $\Delta\alpha_{RMS}$ to $(\alpha_{max} - \alpha_{min})/2$ and of $(\alpha_{max} - \alpha_{ave})$ to $(\alpha_{max} - \alpha_{min})/2$ are 0.61±0.05 and 1.15±0.1 respectively. The same ratios are observed for measurements at 1550 nm, and also for measurements made on Fibre 3.

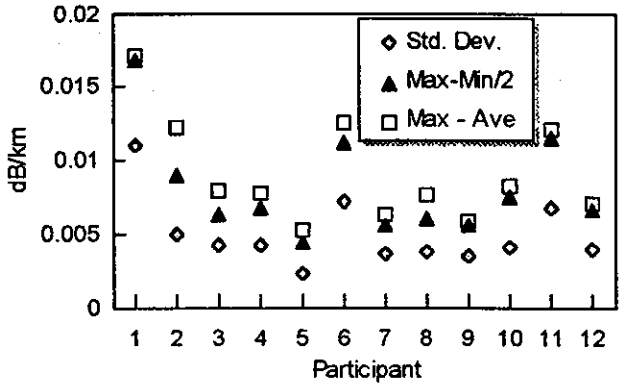


Figure 3 Comparison of proposed test methods for attenuation uniformity at 1300nm

The three proposed definitions appear to be essentially equivalent and differ only by a constant. However Fibres 2 and 3 do not show large fluctuations in attenuation, but rather a slight increase of about 0.01-0.02 dB/km from one end to the other. This would lead to a theoretical ratio of $\Delta\alpha_{RMS}$ to $(\alpha_{max} - \alpha_{min})/2$ and of $(\alpha_{max} - \alpha_{ave})$ to $(\alpha_{max} - \alpha_{min})/2$ of 0.58 and 1.00 respectively.

DETERMINATION OF FIBRE PARAMETERS FROM BACKSCATTER DATA

The backscatter parameter of a single-mode optical fibre, B, is the fraction of forward transmitted power scattered and re-guided backward in the fibre.

$$B = 0.115\, S v_g \alpha_s \tau \qquad \text{where} \quad S = \frac{3}{2n^2\omega_0^2(2\pi/\lambda)^2} .$$

Where v_g is the group velocity, α_s is the scattering loss, τ the OTDR pulse width, n the refractive index, ω_0 the mode field radius and λ the OTDR wavelength. τ and λ are fixed properties of the OTDR thus variations in the backscatter parameter are due to variations in fibre parameters. If v_g, α_s and n are assumed fixed then $B \propto 1/\omega_0^2 = 1/MFD^2$. It is therefore important to correlate backscatter non-uniformity with variations in mode-field diameter and cut-off wavelength in order to evaluate the effectiveness of the backscatter technique to monitor the uniformity of these parameters for QA purposes. In order to undertake this investigation, the backscatter of Fibre 3 was measured and

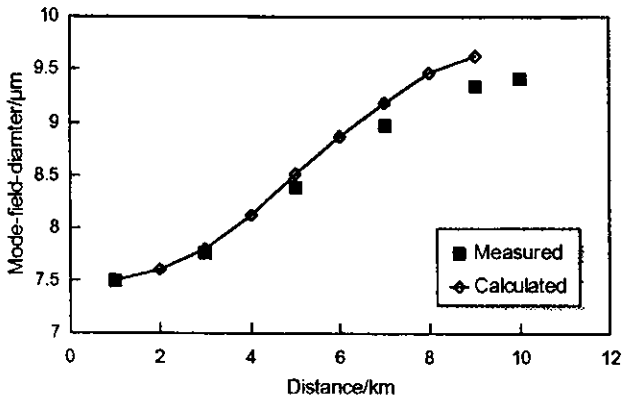


Figure 4 Measured and calculated mode-field-diameter at 1300nm

then the fibre was cut into 6 sections and the mode-field-diameter and cut-off wavelength at the ends of each section were determined using the ITU recommended test methods [4]. The mode-field diameter was calculated from the measured backscatter parameter at position z using

$$MFD(z) = MFD(1).10^{\frac{B(z)-B(1)}{20}}$$

and the reference value of MFD(1) at 1 km. The measured mode-field diameter values are compared with the values calculated from the backscatter profiles [5] in Figure 4.

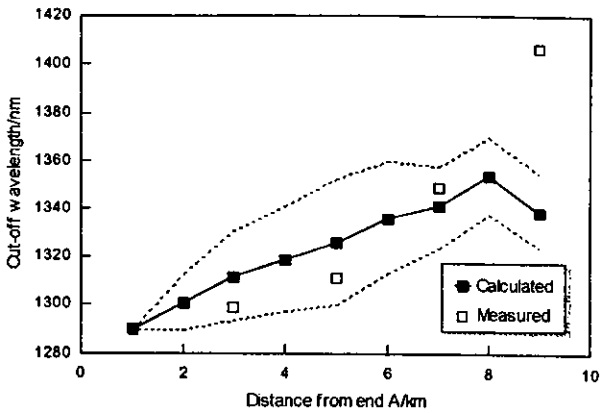


Figure 5 Comparison of calculated and measured cut-off wavelength. Dotted lines are 1σ uncertainty.

The backscatter profiles at two wavelengths allow the calculation of the fibre cut-off wavelength, λ_c. Empirically [6]

$$\omega(\lambda,z) = 0.065 + 0.434\left[\frac{\lambda}{\lambda_c}(z)\right]^{1.5} + 0.0149\left[\frac{\lambda}{\lambda_c}(z)\right]^{6} \text{ and } B(\lambda_2,z)-B(\lambda_1,z) = 20\,LOG\left[\frac{\omega(\lambda_2,1).\omega(\lambda_1,z)}{\omega(\lambda_1,1).\omega(\lambda_2,z)}\right]$$

The wavelengths for the ensemble average of OTDR's were used with $\lambda_c(1)$ to calculate a table of $B(\lambda_2) - B(\lambda_1)$ for a range of other cut-off wavelengths. The table was used to estimate λ_c from the difference in the measured backscatter profiles at 1310 and 1550 nm. The measured cut-off wavelength is compared to the values calculated from the backscatter profiles in Figure 5.

An error of 4% is observed between the calculated and measured MFD at 10 km. A maximum error of 16 nm is observed between the calculated and measured cut-off wavelength (excluding the value at 9 km where the fibre is bi-moded at the OTDR measurement wavelength).

CONCLUSION

OTDR loss scales can be calibrated to better than 0.01 dB/dB using a 'Golden Fibre' calibration artefact. The distance scale can be calibrated to better than 1 m in 10 km. Attenuation coefficients over lengths of 10 km can be determined with an uncertainty less than 0.003 dB/km using calibrated OTDRs. Comparison of the various proposed test methods for fibre attenuation uniformity demonstrates that they are equivalent although there is a significant scatter in results between OTDRs which may be due to polarisation effects. The mode-field-diameter and cut-off wavelength calculated from the measured relative backscatter parameter are compared with discrete measurements of these parameters. Results show that OTDRs can effectively monitor the uniformity of these parameters for QA purposes.

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REFERENCES

[1] International Electrotechnical Commission Draft Standard, TC86, 86(Secretariat)49, 'Calibration of optical time domain reflectometers'.
[2] CECC, Working Group 28, Draft specification on test methods for Longitudinal Uniformity. To be published.
[3] ITU-T, Recommendation G.652, 'Characteristics of single-mode optical fibre cable'.
[4] ITU-T, Recommendation G.650, 'Definition and test methods for the relevant parameters of single mode fibre'.
[5] P. Di Vita and V. Rossi, 'Backscattering measurements in optical fibres: separation of power decay from imperfection contribution', Elect. Letts., Vol. 15, no. 15, p467, 1979.
[6] K.W. Kowaliuk and J. Ferner, 'A technique to estimate the cut-off wavelength profile in single mode fibres using a switchable dual wavelength OTDR', Symposium on Optical Fibre Measurements, Boulder (USA), 1994.