

Calibration of optical time-domain reflectometers (OTDR)

The European Standard EN 61746:2005 has the status of a
British Standard

ICS 33.180.01

National foreword

This British Standard is the official English language version of EN 61746:2005. It is identical with IEC 61746:2005. It supersedes BS EN 61746:2001 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee GEL/86, Fibre optics, which has the responsibility to:

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Calibration of optical time-domain reflectometers (OTDR)
(IEC 61746:2004)

Etalonnage des réflectomètres optiques
dans le domaine de temps (OTDR)
(CEI 61746:2004)

Kalibrierung optischer
Rückstreumessgeräte (OTDR)
(IEC 61746:2004)

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Foreword

The text of document 86/230/FDIS, future edition 2 of IEC 61746, prepared by IEC TC 86, Fibre optics, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61746 on 2005-02-01.

This European Standard supersedes EN 61746:2001.

Specific changes to EN 61746:2001 include the development of Clause 9, "Reflectance calibration", and the introduction of Annexes E, F and G.

The following dates were fixed:

- latest date by which the EN has to be implemented
at national level by publication of an identical
national standard or by endorsement (dop) 2005-11-01
- latest date by which the national standards conflicting
with the EN have to be withdrawn (dow) 2008-02-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61746:2005 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60825-1	NOTE	Harmonized as EN 60825-1:1994 (not modified).
IEC 60825-2	NOTE	Harmonized as EN 60825-2:2004 (not modified).
IEC 61300-3-6	NOTE	Harmonized as EN 61300-3-6:2003 (not modified).

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CALIBRATION OF OPTICAL TIME-DOMAIN REFLECTOMETERS (OTDR)

1 Scope

This International Standard provides procedures for calibrating single-mode optical time domain reflectometers (OTDR). It only covers OTDR measurement errors and uncertainties.

This standard does not cover correction of the OTDR response.

In order for an OTDR to qualify as a candidate for complete calibration using this standard, it must be equipped with the following minimum feature set:

- a) a programmable index of refraction, or equivalent parameter;
- b) the ability to present a display of a trace representation, with a logarithmic power scale and a linear distance scale;
- c) two markers/cursors, which display the loss and distance between any two points on a trace display;
- d) the ability to measure absolute distance (location) from the OTDR's zero-distance reference;
- e) the ability to measure the displayed power level relative to a reference level (for example, the clipping level).
- f) the ability to evaluate the reflectance of a reflective event.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-1 (all parts), *Optical fibres – Part 1: Measurement methods and test procedures*

IEC 60793-1-40, *Optical fibres – Part 1-40: Measurement methods and test procedures – Attenuation*

IEC 60794-1-2, *Optical fibre cables – Part 1-2: Generic specification – Basic optical cable test procedures*

IEC 61300-3-2, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-2: Examinations and measurements – Polarization dependence of attenuation in a single-mode fibre optic device*

ITU-T Recommendation G.650.1:2004, *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable*

ITU-T Recommendation G.650.2:2002, *Definitions and test methods for statistical and non-linear attributes of single-mode fibre and cable*

3 Terms, definitions and symbols

For the purposes of this document, the following definitions apply.

NOTE For more precise definitions, the references to IEC 60050-731 should be consulted.

3.1 attenuation

A
loss

optical power decrease in decibels (dB)

NOTE If P_{in} (watts) is the power entering one end of a segment of fibre and P_{out} (watts) is the power leaving the other end, then the attenuation of the segment is

$$A = 10 \log_{10} \left(\frac{P_{\text{in}}}{P_{\text{out}}} \right) \text{ dB} \quad (1)$$

[IEV 731-01-48, modified]

3.2 attenuation coefficient

α
attenuation of a fibre per unit length

[IEV 731-03-42, modified]

3.3 attenuation dead zone

for a reflective or attenuating event, the region after the event where the displayed trace deviates from the undisturbed backscatter trace by more than a given vertical distance ΔF

NOTE The attenuation dead zone will depend on the following event parameters: reflectance, loss, displayed power level and location. It may also depend on any fibre optic component in front of the event.

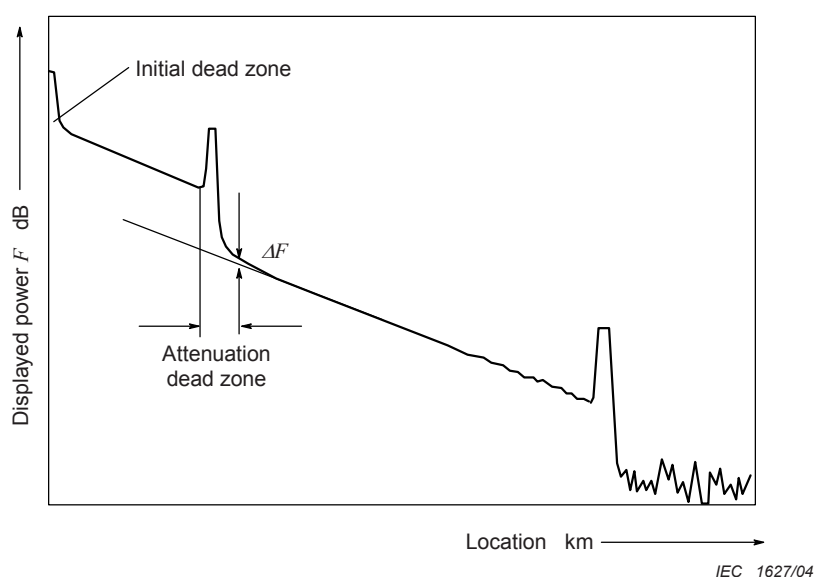


Figure 1 – Definition of attenuation dead zone

3.4**backscatter parameter** **K**

at a given point along the fibre, the backscattered propagating power per unit incident energy

NOTE 1 K is given by the following formula:

$$K = S\alpha_s \frac{v}{2} \text{ s}^{-1} \quad (2)$$

where

α_s is the scattering coefficient, e.g.; in m^{-1}

S is the backscatter capture fraction. It depends on other standard fibre parameters such as the mode field diameter in single mode fibre;

v is the group velocity, in metres per second;

$= c / N$ where c is the speed of the light in vacuum, N the group index of the fibre.

NOTE 2 See also Annex G.

3.5**backscatter coefficient** **C**

for a given pulse, the ratio of backscattered power at the input side of the fibre to the pulse input power

NOTE 1 It represents the backscatter parameter for a given pulse width. The backscatter coefficient is defined from the backscatter parameter using the following formula:

$$C(\Delta T) = K\Delta T \quad (3)$$

where ΔT is the pulse width, e.g. in seconds.

Usually the backscatter coefficient is expressed in dB for a given pulse width, ΔT .

$$C_{\text{dB}}(\Delta T) = 10 \log_{10}(K\Delta T) \quad (4)$$

NOTE 2 The pulse width, ΔT in the previous formula is used to normalise $C(\Delta T)$. Usual values for ΔT are 1 ns and 1 μs . See also Annex G.

3.6**calibration**

set of operations which establish, under specified conditions, the relationship between the values indicated by the measuring instrument and the corresponding known values of that quantity

NOTE See ISO *Guide International vocabulary of basic and general terms in metrology*.

3.7**centre wavelength** **λ_{centre}**

power-weighted mean wavelength of a light source in vacuum, in nanometres (nm)

NOTE For a continuous spectrum, the centre wavelength is defined as:

$$\lambda_{\text{centre}} = \frac{1}{P_{\text{total}}} \int p(\lambda) \lambda d\lambda \quad (5)$$

For a spectrum consisting in discrete lines, the centre wavelength is defined as:

$$\lambda_{\text{centre}} = \frac{\sum_i P_i \lambda_i}{\sum_i P_i} \quad (6)$$

where

$p(\lambda)$ is the spectral power density of the source, for example in W/nm;

λ_i is the i^{th} discrete wavelength;

P_i is the power at λ_i , for example in watts;

$P_{\text{total}} = \sum P_i$ is the total power, for example in watts.

The above integrals and summations extend over the entire spectrum of the light source.

3.8 confidence level

estimated probability that the true value of a measured quantity lies within a given expanded uncertainty

NOTE In this standard, the confidence level is standardized to 95 %. See "expanded uncertainty" for further clarification.

3.9 distance

spacing (actual or simulated) between two features in a fibre, for example in metres

3.10 distance sampling error

maximum distance error attributable to the distance between successive sample points, specified in metres

NOTE The distance sampling error is repetitive in nature; therefore, one way of quantifying this error is by its amplitude.

3.11 distance scale deviation

ΔS_L

average error of the distance scale, that is difference between the average displayed distance $\langle D_{\text{otdr}} \rangle$ and the correspondent reference distance D_{ref} divided by the reference distance, for example in m/m

NOTE 1 ΔS_L is given by the following formula:

$$\Delta S_L = \frac{\langle D_{\text{otdr}} \rangle - D_{\text{ref}}}{D_{\text{ref}}} = \frac{\langle D_{\text{otdr}} \rangle}{D_{\text{ref}}} - 1 \quad (7)$$

where $\langle D_{\text{otdr}} \rangle$ is the displayed distance between two features on a fibre (actual or simulated) averaged over at least one sample spacing

NOTE 2 It is assumed that a relatively long distance, for example 2 000 m, is used in this formula.

3.12 distance scale factor

S_L

average displayed distance divided by the correspondent reference distance

NOTE 1 S_L is given by the following formula:

$$S_L = \frac{\langle D_{\text{otdr}} \rangle}{D_{\text{ref}}} \quad (8)$$

where $\langle D_{\text{otdr}} \rangle$ is the displayed distance between two features on a fibre (actual or simulated) averaged over at least one sample spacing

NOTE 2 It is assumed that relatively long distances are used in this formula.

3.13 distance scale uncertainty

$\sigma_{\Delta S_L}$

uncertainty of the distance scale deviation, for example in m/m

NOTE 1 $\sigma_{\Delta SL}$ is given by the following formula:

$$\sigma_{\Delta SL} = \sigma \left(\frac{\langle D_{otdr} \rangle}{D_{ref}} - 1 \right) = \sigma \left(\frac{\langle D_{otdr} \rangle}{D_{ref}} \right) \quad (9)$$

NOTE 2 It is assumed that the distance is relatively long, because short distances may lead to larger uncertainties.

NOTE 3 In the above formula, $\sigma()$ is understood as the standard uncertainty of $()$.

3.14

dynamic range (one-way)

amount of fibre attenuation that causes the backscatter signal to equal the noise level

NOTE It can be represented by the difference between the extrapolated point of the backscattered trace (taken at the intercept with the power axis) and the noise level expressed in decibels, using a standard category B fibre (see IEC 60793-1)

3.15

expanded uncertainty

range of uncertainties within which the true value of the measured quantity lies, at the given confidence level

NOTE 1 For further information, see Annex D and the ISO *Guide for the expression of uncertainty in measurement*.

NOTE 2 When the distribution of uncertainties is assumed to be gaussian, and the (estimated) confidence level is 95 %, then for a large number of measurements, the standard uncertainty is defined by ± 2 times the standard deviation.

3.16

group index

N

factor by which the speed of light in vacuum has to be divided to yield the propagation velocity of light pulses in the fibre

3.17

location

L

spacing (actual or simulated) between the front panel of the OTDR and a feature in a fibre, for example in metres

3.18

location error

ΔL

displayed location of a feature L_{otdr} minus the reference location L_{ref} , for example in metres

NOTE This error is a function of the location

3.19

location offset

ΔL_0

(constant) additive term of the location error model used in this standard, for example, in metres

NOTE This is approximately equivalent to the location of the OTDR front panel connector on the instrument's distance scale (for a perfect OTDR, the location offset is zero).

3.20

location offset uncertainty

$\sigma_{\Delta L_0}$

uncertainty of the location offset expressed in metres

3.21 location readout uncertainty

$\sigma_{L_{\text{readout}}}$

uncertainty of the location measurement samples caused by both the distance sampling error and the uncertainty type A of the measurement samples, in the form of the half-width of a confidence interval, in metres

3.22 loss deviation

ΔS_A

difference between the displayed loss of a fibre component A_{otdr} and the reference loss A_{ref} , divided by the reference loss, in dB/dB

NOTE 1 ΔS_A is given by the following formula:

$$\Delta S_A = \frac{A_{\text{otdr}} - A_{\text{ref}}}{A_{\text{ref}}} \quad (10)$$

NOTE 2 The loss deviation usually depends on the displayed power level, F .

3.23 loss scale factor

S_A

(power level dependent) ratio of the displayed loss and the reference loss, in dB/dB

NOTE S_A is given by the following formula:

$$S_A = \frac{A_{\text{otdr}}}{A_{\text{ref}}} \quad (11)$$

3.24 loss uncertainty

$\sigma_{\Delta S_A}$

uncertainty of the loss deviation, in dB/dB

3.25 noise level

upper limit of a range which contains at least 98 % of all noise data points

3.26 non-linearity (of logarithmic power scale)

difference between the maximum and minimum values of the loss scale factor S_A for a given range of power levels, in dB/dB

NOTE 1 Changes of the displayed power level can be produced by changing the incident power to the component.

NOTE 2 Non-linearity is one contribution to loss deviation; it usually depends on the displayed power level and the location.

3.27 power level

a) received power level, P

power received by the OTDR's optical port

b) displayed power level, F

level displayed on the OTDR's power scale

NOTE 1 Unless otherwise specified, F is defined in relation to the clipping level (see Figure 8).

NOTE 2 Usually, the OTDR scale displays five times the logarithm of the received power, plus a constant offset.

3.28**reference distance** **D_{ref}**

distance between features in a fibre or the length of a fibre, actual or simulated, precisely determined with the help of measurement equipment other than the OTDR, usually expressed in metres

3.29**reference location** **L_{ref}**

spacing between the OTDR's front panel and a feature on the fibre, actual or simulated, precisely determined with the help of measurement equipment other than the OTDR, usually expressed in metres

3.30**reference loss** **A_{ref}**

loss of a fibre optic component, actual or simulated, precisely determined by means other than direct usage of the OTDR's power scale, in decibels

3.31**reflectance** **R**

the ratio of the reflected power (in watts), to the incident power (in watts), at a discrete location in a fibre optic component

NOTE 1 R is given by the following formula:

$$R = 10 \log_{10} \left(\frac{P_{\text{refl}}}{P_{\text{inc}}} \right) \quad (12)$$

where P_{refl} = the reflected power, e.g. in watts;

P_{inc} = the incident power, e.g. in watts;

NOTE 2 In this document, reflectance is expressed in decibels.

NOTE 3 Reflectance values are negative.

NOTE 4 For the purpose of this document, the reflectivity, ρ , is defined as the linear value of the reflectance:

$$\rho = \frac{P_{\text{refl}}}{P_{\text{inc}}} \quad (13)$$

3.32**sample spacing**

distance between two consecutive data points digitized by the OTDR, for example, in metres

NOTE Sample spacing may be obtainable from instrument set-up information. Sample spacing may depend on the measurement span and other OTDR instrument settings.

3.33**spectral width** **$\Delta\lambda_{\text{FWHM}}$**

full-width half-maximum (FWHM) spectral width of the source

NOTE 1 For a non-continuous spectrum, for example the spectrum of a Fabry-Perot type laser diode, the spectral width is defined as the FWHM of the spectral envelope, to be calculated from the RMS spectral width, $\Delta\lambda_{\text{RMS}}$:

$$\Delta\lambda_{\text{RMS}} = \left(\frac{\sum P_i \lambda_i^2}{P_{\text{total}}} - \lambda_{\text{centre}}^2 \right)^{1/2} \quad (14)$$

leading to

$$\Delta\lambda_{\text{FWHM}} = M\Delta\lambda_{\text{RMS}} \quad (15)$$

where

λ_{centre} is the centre wavelength of the laser diode in vacuum;

$P_{\text{total}} = \sum P_i$ is the total power, in watts;

P_i is the power of the i^{th} longitudinal mode;

λ_i is the wavelength of the i^{th} longitudinal mode in vacuum;

M is the multiplication factor; for a source with a gaussian envelope, $M = 2,35$; for other types of spectra, use $M = 2,35$ as well.

NOTE 2 If the laser emits at one wavelength only (single-line spectrum), it may be sufficient to specify an upper limit, for example spectral width <1 nm.

3.34

standard uncertainty

uncertainty of a measurement result expressed as a standard deviation

NOTE For further information, see Annex D and the ISO *Guide to the expression of uncertainty in measurement*.

3.35

uncertainty type A

uncertainty obtained by the statistical analysis of a series of observations

NOTE For further information, see Annex D and the ISO *Guide to the expression of uncertainty in measurement*.

3.36

uncertainty type B

uncertainty obtained by means other than the statistical analysis of a series of observations

NOTE 1 For further information, see Annex D and the ISO *Guide to the expression of uncertainty in measurement*.

NOTE 2 "Other means" may include previous measurement data, experience with, or general knowledge of, the behaviour and properties of relevant materials and instruments, manufacturers' specifications, data provided in calibration and other certificates, and uncertainties assigned to reference data taken from handbooks.

4 Calibration test requirements

4.1 Preparation

Perform all tests at an ambient room temperature of $23\text{ °C} \pm 3\text{ °C}$, with a relative humidity of $(50 \pm 20)\%$, unless otherwise specified. Give the test equipment a minimum of 2 h prior to testing to reach equilibrium with its environment. Allow the OTDR a warm-up period according to the manufacturer's instruction.

4.2 Test conditions

The test conditions usually include the following OTDR external conditions: date, temperature, humidity (non-condensing), fibre type, connector-adapter combination and use of a lead-in fibre.

Perform the calibration in accordance with the manufacturer's specifications and operating procedures. Where practical, select a range of test conditions and parameters so as to emulate the actual field operating conditions of the OTDR under test. Choose these parameters so as to optimize the OTDR's accuracy and resolution capabilities (for example, view windows, zoom features, etc.), as specified by the manufacturer's operating procedures.

The test conditions usually include the following OTDR parameters: averaging time, pulse power, pulse shape, pulse width, pulse repetition rate, sample spacing, centre wavelength, spectral width, use of optical and electronic masking. Unless otherwise specified, set the OTDR group index to exactly 1,46.

Record the conditions as specified in Clause 10.

NOTE 1 The calibration results only apply to the set of test conditions used in the calibration process.

NOTE 2 Because of the potential for hazardous radiation, be sure to establish and maintain conditions of laser safety. Refer to IEC 60825-1 and IEC 60825-2.

4.3 Traceability

Make sure that all test equipment which has a significant influence on the calibration results is calibrated in an unbroken chain to the appropriate national standard or natural physical constant. Upon request, specify this test equipment and its calibration chain(s). The recalibration period(s) shall be defined and documented.

5 Distance calibration – General

The objective of distance calibration is to determine deviations (errors) between the measured and actual distances between points on a fibre, and to characterize the uncertainties of these deviations.

An OTDR measures the location L of a feature from the point where a fibre is connected to the instrument, by measuring the round-trip transit time T for a light pulse to reach the feature and return. L is calculated from T using the speed of light in vacuum $c(2,997\,924\,58 \times 10^8 \text{ m/s})$ and the group index N of the fibre:

$$L = \frac{cT}{2N} \quad (16)$$

Errors in measuring L will result from scale errors, from offsets in the timebase of the OTDR and from errors in locating a feature relative to the timebase. Placing a marker in order to measure the location may be done manually or automatically by the instrument. The error will, generally, depend on both the marker placement method and the type of feature (for example, a point loss, a large reflection that saturates the receiver or a small reflection that does not).

Even larger errors in measuring L may result from the uncertainty in determining the fibre's group index N . The determination of N is beyond the scope of this standard. Consequently, the calibration procedures below only discuss the OTDR's ability to measure T correctly. For the purpose of this standard, a default value $N = 1,46$ is used and the uncertainty of N is considered to be 0.

5.1 Location error model

In order to characterize location errors, a specific model will be assumed that describes the behaviour of most OTDRs. Let L_{ref} be the reference location of a feature from the front panel connector of the OTDR and let L_{otdr} be the displayed location. It is assumed that the displayed location L_{otdr} , using OTDR averaging to eliminate noise, depends functionally on the reference location L_{ref} in the following way:

$$L_{\text{otdr}} = S_L \cdot L_{\text{ref}} + \Delta L_0 + f(L_{\text{ref}}) \quad (17)$$

where

S_L is the scale factor, which ideally should be 1;

ΔL_0 is the location offset, which ideally should be 0;

$f(L_{\text{ref}})$ represents the distance sampling error, which is also ideally 0. The distance sampling error is a periodic function with a mean of zero and a period equal to the distance interval between sampled points on the OTDR. As an example, if the location of a large reflection is measured by placing a marker on the first digitized point that shows an increase in signal and the position of the reflection is incremented in fine steps, then $f(L_{\text{ref}})$ may be shaped like a periodic ramp waveform.

Equation (17) is meant to characterize known errors in location measurements, but there may still be an additive uncertainty type A. This will affect both the distance measurements and the accuracy with which parameters describing the errors can be determined by the procedures below.

S_L and ΔL_0 may be determined by measuring L_{otdr} for different values of L_{ref} , then fitting a straight line to the data by the least squares method. S_L and ΔL_0 are the slope and intercept, respectively.

Equivalently, a line may be fitted to the location error function, that is the difference between L_{otdr} and L_{ref} :

$$\Delta L = L_{\text{otdr}} - L_{\text{ref}} = \Delta S_L \cdot L_{\text{ref}} + \Delta L_0 + f(L_{\text{ref}}) \quad (18)$$

where

ΔS_L is the slope, and

ΔL_0 is still the intercept, as illustrated in Figure 2.

After finding the linear approximation, the distance sampling error $f(L_{\text{ref}})$ respectively its half-amplitude $\Delta L_{\text{readout}}$ may be determined by measuring departures from the line for different values of L_{ref} . The distance sampling error amplitude ΔL_{sample} is taken as half the amplitude of $f(L_{\text{ref}})$.

In this standard, the distance sampling error amplitude ΔL_{sample} is treated as part of the location readout uncertainty type A. The stated uncertainty result thus ignores the repetitive nature of the sampling error, that is it does not distinguish between the relative contributions of the sampling error and the uncertainty type A.

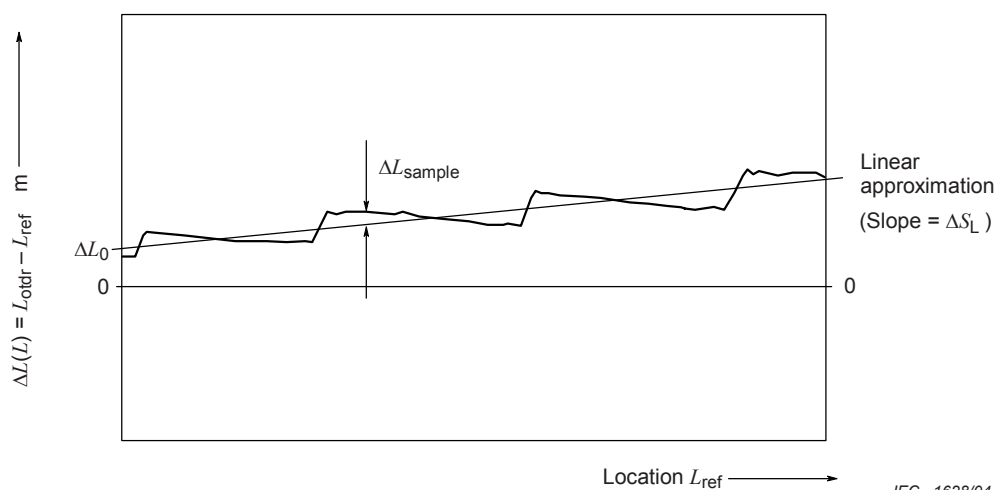


Figure 2 – Representation of the location error $\Delta L(L)$

Therefore, the result of the distance calibration shall be stated by the following parameters:

- $\Delta S_L, \sigma_{\Delta S_L}$ the distance scale deviation and its uncertainty;
- $\Delta L_0, \sigma_{\Delta L_0}$ the location offset and its uncertainty;
- $\sigma_{L_{\text{readout}}}$ the location readout uncertainty, that is the combined uncertainty due to the distance sampling error and the uncertainty type A of the measurement samples, in the form of a standard deviation.

In compliance with the "mathematical basis", divide the largest excursions from the least-squares approximation by the square root of 3 for stating $\sigma_{L_{\text{readout}}}$. Note that the uncertainty will depend on the distance, the displayed power level and the instrument settings.

5.2 Using the calibration results

The error in the location of a feature $\Delta L = L_{\text{otdr}} - L_{\text{ref}}$ can be calculated from the calibration results:

$$\Delta L = \Delta L_0 + L_{\text{ref}} \Delta S_L \quad (19)$$

with the uncertainty in ΔL given by the following formula, in which the recommended confidence level of 95 % is used:

$$\pm 2 \sigma_{\Delta L} = \pm 2 (\sigma_{\Delta L_0}^2 + L_{\text{ref}}^2 \sigma_{\Delta S_L}^2 + \sigma_{L_{\text{readout}}}^2)^{1/2} \quad (19a)$$

where the displayed location L_{otdr} can be used instead of the reference location L_{ref} without serious consequences.

Similarly, the error in the distance between two features ΔD and its uncertainty can be calculated from the following formula:

$$\Delta D = D_{\text{ref}} \Delta S_L \quad (20)$$

with uncertainty in ΔD given by the following formula:

$$\pm 2 \sigma_{\Delta D} = \pm 2 (D_{\text{ref}}^2 \sigma_{\Delta S_L}^2 + 2 \sigma_{L_{\text{readout}}}^2)^{1/2} \quad (20a)$$

where the displayed distance D_{otdr} can be used instead of the reference distance D_{ref} .

NOTE The 2 in front of $\sigma_{L_{\text{readout}}}^2$ is due to combining two uncorrelated uncertainties.

Additional uncertainties may have to be taken into account if the type of feature is different from the feature used in the calibration. Specify the type of feature as part of the calibration result.

5.3 Measuring fibre length

As indicated above, one of the methods of OTDR distance calibration is to measure fibres of known length with the OTDR. In several instances in this standard, it is required that fibre length be determined using the fibre's transit time, in contrast to a mechanical length measurement. This method is directly compatible with the measurement principle of the OTDR itself. In addition, the transit time can usually be measured with better accuracy than its mechanical length, particularly when the fibre is long. Therefore, in this standard, it is suggested that fibre transit time instead of fibre length be used whenever accuracy is important.

Measure the transit time of the fibre T_{transit} with the help, for example, of a pulse generator, a triggerable laser source, an optical-to-electrical converter (O/E converter) and a time interval counter. It is important that the laser source has approximately the same centre wavelength λ_{centre} as the test OTDR, because a difference in wavelength may result in a difference of transit time due to the chromatic dispersion of the fibre. An alternative to the laser source is using the OTDR itself to produce optical pulses; in this case, the centre wavelengths automatically coincide. Record the transit time as the difference between the arrival times with and without the fibre inserted between the laser source and the O/E converter.

When this fibre is used for OTDR distance calibrations, then the reference distance D_{ref} can be calculated by

$$D_{\text{ref}} = \frac{cT_{\text{transit}}}{N} \quad \text{m} \quad (21)$$

In this equation, use a group index N which is identical with the OTDR's group index setting. The time measurement principle makes it possible to use D_{ref} as the reference distance.

6 Distance calibration methods

Each of the three alternative calibration methods described below is capable of determining all of the necessary calibration results: location offset, distance scale deviation, and their uncertainties.

6.1 External source method

6.1.1 Short description and advantage

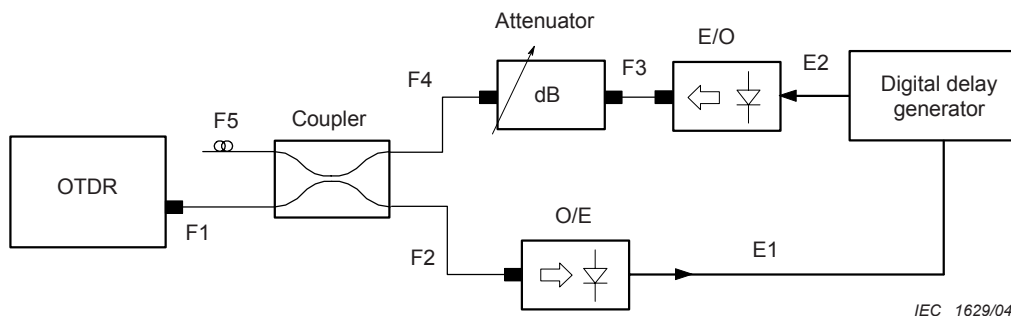
The external source method uses a calibrated time-delay generator to simulate the time delay in a fibre and an optical source to simulate the reflected or scattered signal from a fibre.

The method is well suited to automated laboratory testing under computer control. For simplicity, only reflective features are discussed in this standard. To calibrate the OTDR for features other than reflection, the pulsed E/O converter described below should be replaced by an optical source that simulates the appropriate feature.

6.1.2 Equipment

In addition to the OTDR, the measurement equipment includes, as shown in Figure 3:

- a) an optical coupler;
- b) an optical-to-electrical converter;
- c) a digital delay generator with pulse capability;
- d) an electrical to optical converter;
- e) a variable optical attenuator, for reduction of the pulse amplitude to just below the clipping level.



Key

F1, F2, F3, F4 and F5	fibres
E1 and E2	electric cables
E/O	electrical-to-optical converter
O/E	optical-to-electrical converter

**Figure 3 – Equipment for calibration of the distance scale –
External source method**

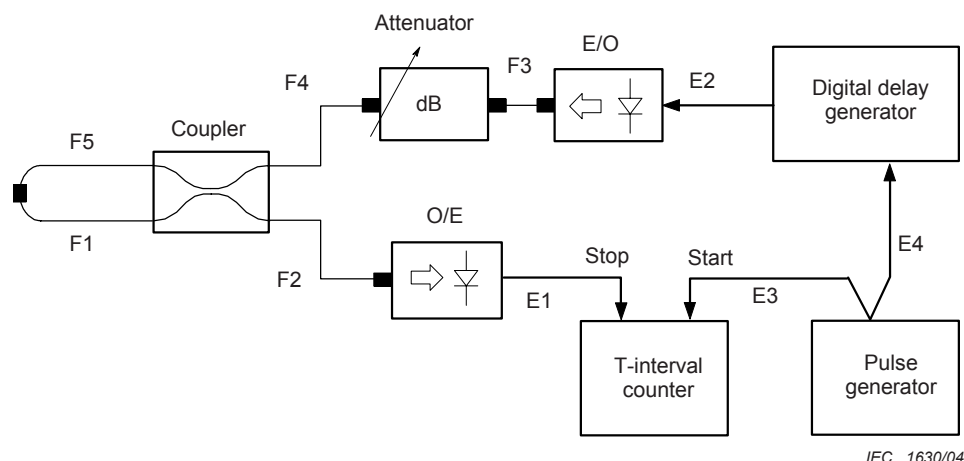
The coupler routes the OTDR signal to the O/E converter (detector). The detector triggers the delay generator, which, after a known time delay, causes an optical pulse to be generated. This pulse is then coupled back to the OTDR.

The E/O converter can be a simple pulsed laser that simulates a reflection. Constant pulse amplitude and pulse width are considered adequate to calibrate the distance scale for reflective features. However, the attenuator makes it possible to adjust the pulse amplitude based on the distance of the reflection from the front panel of the OTDR, in order to simulate the change of reflection amplitude caused by the attenuation of the fibre.

To allow accurate calibration of the set-up, fibres F1 and F5 should have the same length (see below). The circles in fibre F5 indicate fibre loops of less than 1 cm in diameter, in order to absorb reflections from the end of F5. Other optical termination methods are also acceptable.

6.1.3 Calibration of the equipment

Before using the "external source" equipment, it shall be properly calibrated. It is assumed that the digital delay generator is regularly calibrated. For computing the location offset ΔL_0 from the measured data, it is also necessary to determine the insertion delay T_{delay} of the apparatus. This can be accomplished by adding a pulse generator and a calibrated time interval counter to the equipment, as shown in Figure 4.



Key

F1, F2, F3, F4 and F5	fibres
E1, E2, E3 and E4	electric cables
E/O	electrical-to-optical converter
O/E	optical-to-electrical converter

Figure 4 – Set-up for calibrating the system insertion delay

To calibrate the insertion delay T_{delay} , proceed as follows.

Set the pulse generator to square wave, with a repetition period more than twice as long as the delay time to be measured. Use the output pulse of the pulse generator as the start pulse on the time interval counter, and to externally trigger the delay generator. Set the digital delay generator for external triggering and zero delay for the leading edge of the pulse generator signal. Set the trigger levels of the delay generator and the counter.

The external source will then generate an optical square wave which, after re-conversion to an electrical pulse, will stop the time interval counter. To ensure lowest uncertainty, the electrical cables E3 and E4 should have equal length. Also, fibres F1 and F5 should have equal lengths. Note that identical cable numbers in Figures 3 and 4 mean the same physical cables. Adjust the optical attenuator for best triggering of the time interval counter. Record the displayed time interval (between start and stop) as the insertion delay T_{delay} .

6.1.4 Measurement procedure

6.1.4.1 Preparation

Select the technique (automatic or manual) for locating the feature on the OTDR. Program the attenuator to generate the desired pulse amplitude(s). Select the pulse width on the digital delay generator, for example 10 μs .

Choose the time settings of the delay generator T_i so that the samples are distributed over a wide distance range with some randomness, to accomplish averaging over the OTDR's distance sampling interval. The first time setting should be chosen so that the pulse appears close to the front panel of the OTDR, but sufficiently out of the initial dead zone for good measurements. If the testing laboratory does not determine and analytically justify a different distance sampling scheme, one of the two schemes below shall be chosen.

- a) In the first scheme, evaluate the sample spacing D_{sample} (for the appropriate OTDR instrument setting), for example by zooming into the OTDR trace. Then calculate the corresponding delay difference of the delay generator T_{sample} using:

$$T_{\text{sample}} = \frac{2ND_{\text{sample}}}{c} \quad (22)$$

where N is the OTDR's group index setting and c is the speed of light in vacuum.

Then calculate a total number of i delay generator settings, grouped in k clusters of n settings each ($i = kn$), where each cluster uniformly covers one sample spacing. Each cluster shall have the form:

$$T_k, T_k + T_{\text{sample}}/n, T_k + 2 T_{\text{sample}}/n, \dots, T_k + (n-1) T_{\text{sample}}/n \quad (23)$$

where the number of settings in each cluster n is at least four and is the same for every cluster. The centres of the clusters are uniformly spaced, from just beyond the initial dead zone to a large distance over which the instrument is to be calibrated. The number of clusters k may be as small as two.

- b) In the second scheme, there are no clusters, and the sample spacing D_{sample} does not need to be known except very approximately. Calculate T_{sample} from equation (22). Choose the time settings so that they are uniformly spaced between the initial dead zone and a large distance and each has a random time interval added. The random intervals should have a uniform probability density in the interval $-T_1$ to T_1 , where T_1 is at least $20 T_{\text{sample}}$ but less than 10 % of the longest time delay for the tests. The number of measurements i (that is different settings) should be at least 20.

Alternatively, prior knowledge of the magnitude of the uncertainty type A and the tolerable uncertainty in the measurements may lead the testing laboratory to select a different systematic or random distance sampling scheme.

6.1.4.2 Taking the measurement results

Select the first time setting of the time T_i of the series T_1 as defined above. Record the time T_1 of the delay generator and the measured location $L_{\text{otdr},1}$ of the event on the OTDR. Proceed with the time settings as selected in 6.1.4.1. Always record the time T_i and the measured location $L_{\text{otdr},i}$. Continue until all time settings are completed.

6.1.5 Calculations and results

Following the concept of Clause 4, use the time settings to calculate i reference locations $L_{\text{ref},i}$:

$$L_{\text{ref},i} = \frac{c(T_i + T_{\text{delay}})}{2N} \quad (24)$$

where

N is the group index setting of the OTDR;

T_i are the time settings defined in 6.1.3;

T_{delay} is the calibrated insertion delay of the test equipment (see 6.1.2).

Then, use the reference locations and the displayed locations $L_{\text{otdr},i}$ to calculate the set of i location errors ΔL_i :

$$\Delta L_i = L_{\text{otdr},i} - L_{\text{ref},i} \quad (25)$$

To determine the location offset ΔL_0 and the distance scale deviation ΔS_L , fit the location error data to the simplified location error model (in which the distance sampling error is momentarily neglected):

$$\Delta L_{i, \text{model}} = \Delta S_L L_{\text{ref},i} + \Delta L_0 \quad (26)$$

Specifically, minimize the difference between the model and the data using the least-squares criterion, that is choose ΔS_L and ΔL_0 so that the summation

$$\sum_i (\Delta L_i - \Delta S_L L_{\text{ref},i} - \Delta L_0)^2 \quad (27)$$

is minimized. Record ΔL_0 and ΔS_L obtained from the approximation.

As in Figure 2, the slope of the linear approximation represents the distance scale deviation ΔS_L . The intercept with the vertical axis represents the location offset ΔL_0 . Record ΔS_L and ΔL_0 obtained from the calculation.

6.1.6 Uncertainties

A general discussion of the distance uncertainties can be found in Clause 5.

Note that the following list of uncertainties may not be complete. Additional contributions may have to be taken into account, depending on the measurement set-up and procedure. The mathematical basis given in Annex D should be used to calculate and state the uncertainties.

6.1.6.1 Distance scale uncertainty

The least-squares approximation outlined in 6.1.5 effectively uses the displayed distances between the measurement samples to calculate the distance scale deviation. It is assumed that the measurement samples near $L = 0$ and near the farthest location $L = L_{\text{max}}$ have the strongest influence on the distance scale deviation because the samples in the middle of the range have no influence on the slope of the distance error model.

Applying the standard formula for the propagation of errors to equation (9) yields the distance scale uncertainty $\sigma_{\Delta S_L}$ in which $\langle D_{\text{otdr}} \rangle \cong D_{\text{ref}}$ was used.

$$\sigma_{\Delta S_L} \cong \left[\left(\frac{\sigma_{\langle D_{\text{otdr}} \rangle}}{\langle D_{\text{otdr}} \rangle} \right)^2 + \left(\frac{\sigma_{D_{\text{ref}}}}{D_{\text{ref}}}} \right)^2 \right]^{1/2} \text{ m/km} \quad (28)$$

where

D_{otdr} is $D_{\text{ref}} \approx L_{\text{ref}}$ (for the long distances discussed here);

$\sigma_{\langle D_{\text{otdr}} \rangle}$ is the standard deviation expressing the uncertainty of the distance samples (on the basis of the location samples);

$\sigma_{\langle D_{\text{otdr}} \rangle} / \langle D_{\text{otdr}} \rangle$ represents the slope uncertainty due to inaccurate distance readout; it is equivalent to the standard deviation of $(\Delta L_i - \Delta L_{i, \text{model}})$ which includes the marker placement uncertainty and the distance sampling error; the least-squares algorithm used for the determination of ΔS_L can be used to determine $\sigma_{\langle D_{\text{otdr}} \rangle}$; if applicable, ΔL_i may be averaged over the corresponding sampling interval;

- σ_{Dref} is the uncertainty of the reference distances;
- $\sigma_{\text{Dref}}/D_{\text{ref}}$ represents the slope uncertainty caused by the digital delay generator and is equal to the relative timing uncertainty of the delay generator.

6.1.6.2 Location offset uncertainty

The location offset ΔL_0 is equal to the intercept of the least-squares approximation with the vertical axis. This intercept mostly depends on the first few samples, that is those samples which are closest to the location $L = 0$, and on the accuracy of the insertion delay T_{delay} .

The location offset uncertainty $\sigma_{\Delta L0}$ can be calculated by using the standard formula for the propagation of errors:

$$\sigma_{\Delta L0} = \left[\sigma_{\Delta L}^2 + \left(\frac{c}{2N} \right)^2 \sigma_{T_{\text{delay}}}^2 \right]^{1/2} \quad (29)$$

where

- $\sigma_{\Delta L}$ is the uncertainty of the differences between ΔL_i and the least-squares approximation near $L = 0$, which includes the marker placement uncertainty and the distance sampling error; it is equivalent to the standard deviation of $(\Delta L_i - \Delta L_{i, \text{model}})$ near $L = 0$; if applicable, ΔL_i may be averaged over the correspondent sampling interval; the least-squares algorithm used for the determination of ΔL_0 can be used to determine $\sigma_{\Delta L}$.
- $\sigma_{T_{\text{delay}}}$ is the uncertainty of the system insertion delay; the assumption is that the first-time setting will be very short or even zero, reducing the delay generator uncertainty to one of the insertion delays only.

6.1.6.3 Location readout uncertainty

As outlined in Clause 5, determine the largest difference between the location error samples ΔL_k and the least-squares approximation near $L = 0$. Then calculate the location readout uncertainty σ_{Lreadout} (which includes the distance sampling error) by dividing the largest difference by the square root of 3. Alternatively, σ_{Lreadout} can be determined either with the least-squares algorithm used for the determination of ΔS_L and ΔL_0 or with the following formula:

$$\sigma_{\text{Lreadout}} = \left[\frac{1}{n-1} \sum_{i=1}^n (\Delta L_i - \Delta L_{i, \text{model}})^2 \right]^{1/2} \quad (30)$$

6.2 Concatenated fibre method

6.2.1 Short description and advantages

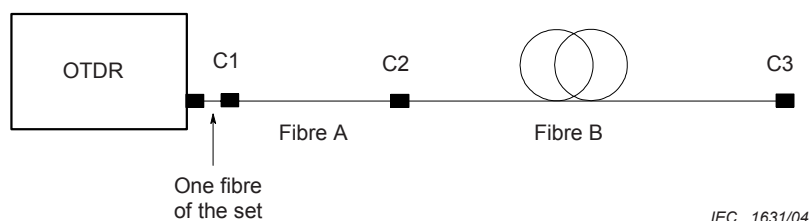
This method uses calibrated fibres with transit times precisely measured at the wavelength of the OTDR under test to calibrate the distance scale.

The method requires only connectorized lengths of fibre, and is thus both inexpensive and well suited to testing in locations where equipment such as that used in 6.1 cannot be carried. It may be viewed as a manual test method because it requires connecting and disconnecting short lengths of fibre a number of times to vary the locations of features. However, this process can be automated with optical switches, if desired.

6.2.2 Equipment

In addition to the test OTDR, the equipment includes, as shown in Figure 5:

- fibre A, to determine the location offset;
- fibre B, to determine the distance scale deviation;
- a set of incremental fibres, to determine the distance sampling error.



Key

C1, C2 and C3 optical connectors

Figure 5 – Concatenated fibres used for calibration of the distance scale

Normally these fibres will be cabled or packaged in some way for protection and connectorized for easy connection and disconnection. Alternatively, they may be used with a fibre optic switching mechanism that does not require connectors.

The requirements on these fibres are indicated below.

- Fibre A may be a simple fibre with an end reflection, or a fibre with an internal reflection or splice. Its length is not very important, as long as it puts the feature to be measured on a backscatter trace which is essentially undisturbed from the initial reflection(s) near the OTDR port. Approximately 1 km to 2 km is suggested for the fibre length or the distance to the feature.

To calibrate the fibre, measure its optical transit time T_a from the front end (to be connected to the OTDR) to the feature according to the procedure in Clause 5. If an internal feature is to be used, then the fibre shall be constructed from two segments: the first is calibrated according to Clause 5, after which it is connected or spliced to a second length. The joint will then have a calibrated location, whereas the remaining length does not need to be calibrated.

Fibre A may be split into a short jumper fibre and a length as outlined before, with connectorized ends. In this way, the incremental fibres (see below) can be inserted after the first section of fibre A without having access to the front panel of the OTDR. The reflection from the near-end connectors shall be small enough to avoid placing the feature at the end of fibre A into the dead zone of the OTDR.

This alternative may be important in automated systems.

Fibre A can also be used as a lead-in fibre for measuring the distance scale deviation with the help of fibre B.

- Fibre B shall have reflective ends, for example by using the reflections from its connectors. Because the uncertainty is reduced by making this fibre longer, it is recommended that fibre B be at least 10 km long.

To calibrate the fibre, measure its optical transit time T_b as described in Clause 5.

Caution: for a correct distance calibration, the reflections from the two ends of fibre B (connectors C2 and C3) should be approximately equal. For example, if one end produces a reflection that saturates the OTDR and the other end does not, then the difference in waveforms can lead to inaccurate distance measurements. The effect of this difference on the measured distance scale deviation will be small if the fibre is long, however.

- c) The set of incremental fibres will be used to vary the locations of the two reflections of the long fibre B by amounts less than the distance sampling interval of the OTDR. Their lengths should be selected in order to generate at least four distance increments which are evenly spaced over the distance sampling interval. As an example, if the distance sampling interval is 10 m, this can be accomplished with two fibres of lengths 2,5 m and 5 m. Separately and in combination, these can produce increments of 0 m (no fibre), 2,5 m, 5 m, and 7,5 m (both fibres). More generally, the fibres should generate length increments of

$$0, D_x, 2 D_x, \dots, (n - 1) D_x \quad (31)$$

where

$n \geq 4$, and

$n D_x$ equals the distance sampling interval of the OTDR under the conditions to be tested.

Except in unusual cases, calibrating the transit time of these fibres according to Clause 5 is unnecessary. Instead, their physical lengths should be measured. The difference between the true group index and the OTDR group index setting will be negligible on such short fibres.

6.2.3 Measurement procedures

The contribution of random noise to location error is usually small except when the displayed power level comes close to the noise limit of the instrument. Longer OTDR averaging is recommended in this case.

6.2.3.1 Preparation

Select the type of feature (in or at the end of fibre A) for which the location offset is to be determined and select the fibres accordingly. Also, establish the technique (automatic or manual) for placing the markers on the feature in fibre A and the reflective ends of fibre B.

Connect fibre A to the front of the OTDR, so that the feature at or near the far end of the fibre can be seen on the OTDR. Connect fibre B to the far end of fibre A, so that the reflections from both ends of fibre B may be seen on the OTDR.

6.2.3.2 Taking the measurements

Measure the location of the feature in fibre A with the OTDR. Record this first measured location as $L_{\text{otdr},1}$. Measure the length of fibre B with the OTDR, using the two reflections generated by this fibre. Record this first measured distance as $D_{\text{otdr},1}$.

Insert the shortest of the incremental fibres between the OTDR and the beginning of fibre A. Measure the location $L_{\text{otdr},2}$ and the distance $D_{\text{otdr},2}$. If fibre A is a split fibre, as described in 6.2.2, the incremental fibres may be inserted into the split instead of between the OTDR and the beginning.

Continue inserting successively increasing length combinations of the incremental fibres. Measure the location $L_{\text{otdr},i}$ and the distance $D_{\text{otdr},i}$ until $i = n$ and the total length of the incremental fibres is $(n - 1) D_x$.

6.2.4 Calculations and results

6.2.4.1 Distance scale deviation

Compute the distance $\langle D_{\text{otdr}} \rangle$ (the length of fibre B) as the average of the n values of $D_{\text{otdr},i}$. Then compute the distance scale deviation as

$$\Delta S_L = \frac{\langle D_{otdr} \rangle}{D_{ref}} - 1 = \frac{N \langle D_{otdr} \rangle}{CT_b} - 1 \quad (32)$$

where

D_{ref} is the reference distance;

N is the group index setting of the OTDR;

T_b is the one-way transit time for fibre B, as measured according to Clause 5.

6.2.4.2 Location offset

Let $\langle L_{otdr} \rangle$ be the average of all n values of $L_{otdr,i}$. Compute the location offset on the basis of equation (18):

$$\Delta L_0 = \langle L_{otdr} \rangle - (1 + \Delta S_L) \langle L_{ref} \rangle \quad (33)$$

$$\Delta L_0 = \langle L_{otdr} \rangle - (1 + \Delta S_L) \left(\frac{cT_a}{N} + \frac{(n-1)D_x}{2} \right)$$

where

$\langle L_{ref} \rangle$ is the average reference location corresponding to the first reflection, to be calculated with the help of the average length of the incremental fibres;

N is the group index setting of the OTDR;

T_a is the one-way transit time for fibre A, as measured according to Clause 5;

ΔS_L is the distance scale deviation as determined by the equation (32); if fibre A is sufficiently short, then the ΔS_L term can be neglected.

6.2.5 Uncertainties

A general discussion of the distance uncertainties is given in Clause 5. Note that the following list of uncertainties may not be complete. Additional contributions may have to be taken into account, depending on the measurement set-up and procedure.

The mathematical basis given in Annex D should be used to calculate and state the uncertainties.

6.2.5.1 Distance scale uncertainty

The distance scale uncertainty $\sigma_{\Delta SL}$ should be calculated with the following formula which is derived from equation (32):

$$\sigma_{\Delta SL} = \left[\left(\frac{\sigma_{D_{otdr}}}{D_{otdr}} \right)^2 + \left(\frac{\sigma_{T_b}}{T_b} \right)^2 \right]^{1/2} \text{ m/km} \quad (34)$$

where $\sigma_{D_{otdr}}$ is the uncertainty of the displayed length of fibre B, for example, as caused by the marker placement uncertainty and the distance sampling error.

The transit time uncertainty of fibre B σ_{T_b} should itself be calculated by root-sum-squaring

$\sigma_{T_b, \text{counter}}$ the transit time uncertainty of fibre B, due to the time interval counter;

$\sigma_{T_b, \lambda}$ the transit time uncertainty of fibre B, due to a difference between the wavelength used in determining the transit time and the OTDR wavelength;

$\sigma_{Tb,\Theta}$ the transit time uncertainty of fibre B, due to the temperature coefficient; typical value: 1 cm/(km °C).

6.2.5.2 Location offset uncertainty

The location offset uncertainty $\sigma_{\Delta L0}$ should be calculated from the following formula which is derived from equation (33), by neglecting the ΔS_L and the $(n-1) D_x/2$ terms:

$$\sigma_{\Delta L0} = \left[\sigma_{\text{Lotdr}}^2 + \left(\frac{c}{N} \right)^2 \sigma_{Ta}^2 \right]^{1/2} \quad (35)$$

where σ_{Lotdr} is the uncertainty of measuring the location of the feature at the end (or inside) of fibre A, that is mainly the uncertainty of the marker placement; it is assumed that the distance sampling error is effectively removed by averaging over one sampling interval.

The transit time uncertainty of fibre A σ_{Ta} should itself be calculated by root-sum-squaring:

$\sigma_{Ta, \text{counter}}$ the transit time uncertainty of fibre A, due to the time interval counter;

$\sigma_{Ta, \lambda}$ the transit time uncertainty of fibre A, due to a difference between the wavelength used in determining the transit time and the OTDR wavelength;

$\sigma_{Ta, \Theta}$ the transit time uncertainty of fibre A, due to the temperature coefficient of the transit time; typical value: 1 cm/(km °C).

6.2.5.3 Location readout uncertainty

Calculate the following two sets of data, one for the location error and one for the distance error, using the measurement samples given in 6.2.3.

$$L_{\text{otdr},i} - L_{\text{ref},i} = L_{\text{otdr},i} - \left(\frac{cT_a}{N} + iD_x \right) \quad i = 0 \text{ to } n-1 \quad (36)$$

and

$$D_{\text{otdr},i} - D_{\text{ref},i} = D_{\text{otdr},i} - \frac{cT_b}{N} \quad i = 0 \text{ to } n-1 \quad (37)$$

It is recommended that half the difference between the largest and the smallest value of the L set or the D set, whichever is the larger, be divided by the square root of 3 to calculate the location readout uncertainty σ_{Lreadout} .

6.3 Recirculating delay line method

6.3.1 Short description and advantage

The recirculating delay line method uses a calibrated loop of fibre, made with a coupler and a reflector, to generate periodic reflections.

The method is similar to the concatenated fibre method: a fibre artifact is used, and there is no need for electronic equipment. The artifact generates many calibrated distance samples; this has the potential of reducing type A uncertainties affecting the distance scale deviation.

The measurements of location offset are limited to the reflective features generated by the recirculating delay line.

6.3.2 Equipment

In addition to the test OTDR, the measurement equipment only includes a recirculating delay line manufactured and calibrated according to Annex A, as shown in Figure 6.

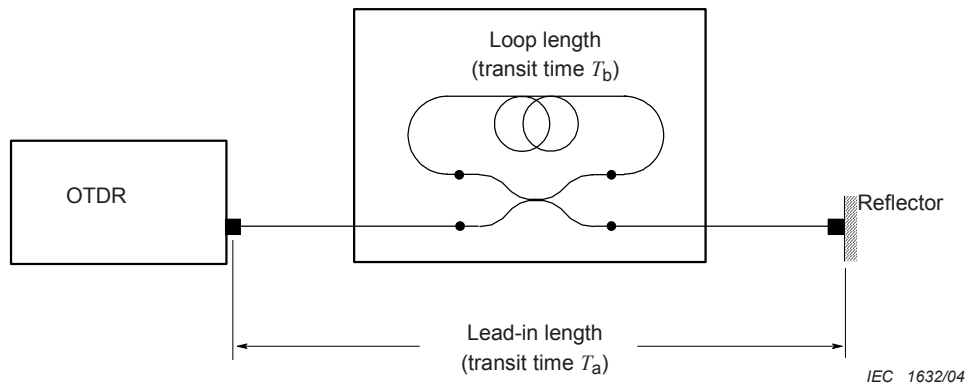


Figure 6 – Distance calibration with a recirculating delay line

The recirculating delay line places a number of reflective features on the OTDR display, as shown in Figure 7. The first feature is the one obtained from the optical pulse travelling direct to the mirror, then back direct to the OTDR. The second feature is generated by the optical pulse travelling once through the loop, then to the mirror, then back direct to the OTDR (this pulse coincides with the pulse travelling direct to the mirror, then back through the loop, then back to the OTDR). The third pulse travels through the loop twice, etc.

Accordingly, the ideal displayed locations would be

$$\begin{aligned} L_{\text{otdr},0} &= L_a \\ L_{\text{otdr},1} &= L_a + L_b/2 \\ L_{\text{otdr},2} &= L_a + L_b \quad \text{etc.} \end{aligned} \tag{38}$$

where L_a is the length of the lead-in fibre and L_b is the length of the fibre loop.

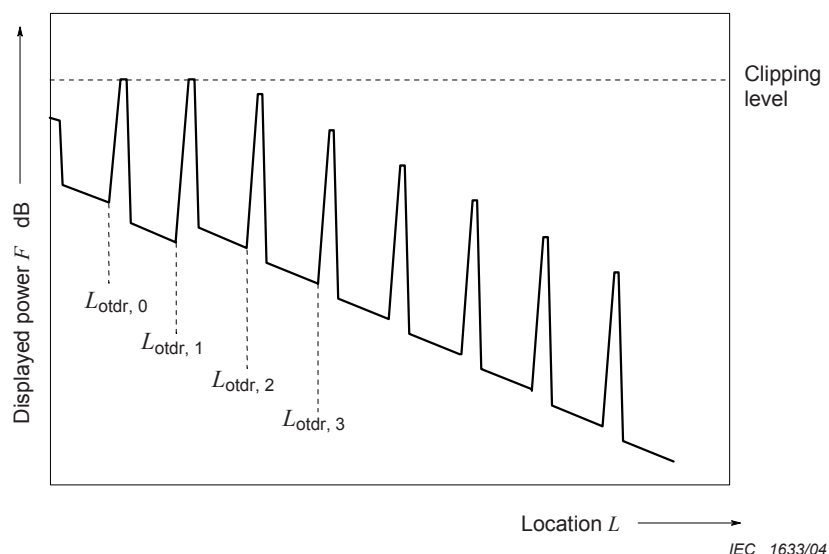


Figure 7 – OTDR trace produced by recirculating delay line

As an optional addition to the measurement set-up, it may be advantageous to use one or more incremental fibres as in 6.2.3. The need for this is reduced because the multiple reflections from the delay line are likely to generate averaging over the distance sampling interval. However, this averaging effect is not controlled and systematic control may be preferred. Using the notation of 6.2.3, it may be sufficient to let $n = 2$, so there is just one incremental fibre with length equal to half of the distance sampling interval.

6.3.3 Measurement procedure

The procedure assumes that no incremental fibres are used. If they are used, this simply increases the number of distance samples that are recorded, and it is straightforward to modify the notation and computations. The method then becomes very similar to that of 6.2, with the lead-in fibre being equivalent to fibre A and the loop length equivalent to fibre B.

6.3.3.1 Preparation

Establish the technique (automatic or manual) of placing the markers at the leading edges of the reflections from the recirculating delay line, following the manufacturer's recommendations.

Connect the recirculating delay line assembly directly to the OTDR so that the reflective features can be seen on the OTDR.

6.3.3.2 Taking the measurement results

Measure the locations of successive reflections from the recirculating delay line with the OTDR. Record these as $L_{\text{otdr},i}$, where the index i goes from 0 to k and represents the number of passes through the loop. A large number k will presumably increase the accuracy of the result, but it will be limited by loss and the noise floor of the OTDR.

6.3.4 Calculations and results

Using the calibration data of the recirculating delay line T_a and T_b the series of reference locations is: