

*Measurement
Good Practice Guide*

**Calibration and Use of
Optical Time Domain
Reflectometers (OTDR)**

Brian Walker



Measurement Good Practice Guide No. 31

Calibration and Use of Optical Time Domain Reflectometers (OTDR)

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Abstract: This document describes the calibration of Optical Time Domain Reflectometers (OTDR). It also describes the principle of their operation and the performance parameters used to specify them. It gives guidance on how to use them to obtain the most accurate results and details of artefacts available to help do this.

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Calibration and Use of OTDRs

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1 Introduction

It is now over twenty-five years since the optical time domain reflectometer was first proposed [1]. During this time single-mode fibre has emerged as the dominant transmission medium for long and medium haul telecommunications. The installation of millions of kilometres of fibre in both terrestrial and undersea systems has spurred the development of OTDRs themselves and now small mini-OTDRs have a performance comparable to or better than that of laboratory instruments of only a few years ago. The uses of the OTDR has also expanded from just the measurement of attenuation and break location to include attenuation uniformity, splice loss, return loss and more recently mode field diameter, cut-off wavelength and dispersion.

In addition to standard OTDRs several other types have been developed, coherent OTDR, polarisation OTDR and sensor OTDRs. However the vast majority of OTDRs are of the standard type and this guide deals only with those. It is aimed mainly at single-mode OTDRs but many of the sections will apply to multimode as well.

2 Principles of operation

2.1 Theory of operation

The vast majority of OTDRs work by launching a pulse of light into the fibre and then measuring the intensity of light scattered back to the OTDR as a function of time after the launch. From this data the instrument determines the loss of the fibre as a function of distance.

The mechanism responsible for the scattering is known as Rayleigh scattering. It is caused by small variations in the refractive index of the fibre core which are of a size comparable to the wavelength of the light. The light is scattered in all directions but only that which is scattered back towards the OTDR and is 'captured' by the fibre will eventually reach the OTDR. About 5% of the launched light is scattered per kilometre and about 0.1% of this is captured and returned back towards the OTDR. The backscatter power returned to the OTDR, $P_{bs}(t)$, after a time t is

$$P_{bs}(t) = P_0 \Delta T K 10^{-\alpha v t / 10} \quad (1)$$

where P_0 is the launch power

ΔT is the OTDR pulse width (assumed rectangular)

K is the fibre backscatter parameter.

α is the fibre attenuation coefficient in dB/km

v is the velocity of the light in the fibre and

t is the time after the launch of the pulse into the fibre.

Light returned after time t will have originated from point at a distance L along the fibre where $L = vt/2$. The OTDR measures the round trip time and round trip loss. This is converted into a one way representation and displayed on the OTDR's screen with a vertical logarithmic scale (in dB) as

$$5 \log P_{bs}(L) = 5 \log_{10} (P_0 \Delta T K) - \alpha L \quad (2)$$

Thus, assuming K to be constant, the slope of the OTDR trace verses distance yields the attenuation coefficient α . The assumption that K does not vary along the fibre will not usually lead to large errors in the attenuation coefficient, however, it can be shown that if the fibre is measured from both ends and the average of the attenuation coefficients taken, then this is the true attenuation of the fibre even if K does vary. Further, the difference between the attenuation coefficients measurement from both ends can be used to deduce the changes in other fibre parameters such as mode field diameter.

In addition to backscatter light returned to the OTDR light can also be reflected back from connectors or from a connector air interface. The reflection from the latter is many thousand times larger than the backscatter power. This puts considerable demands on the OTDR's receiver circuitry. (This is dealt with in more detail in the section on return loss).

2.2 OTDR Block Diagram

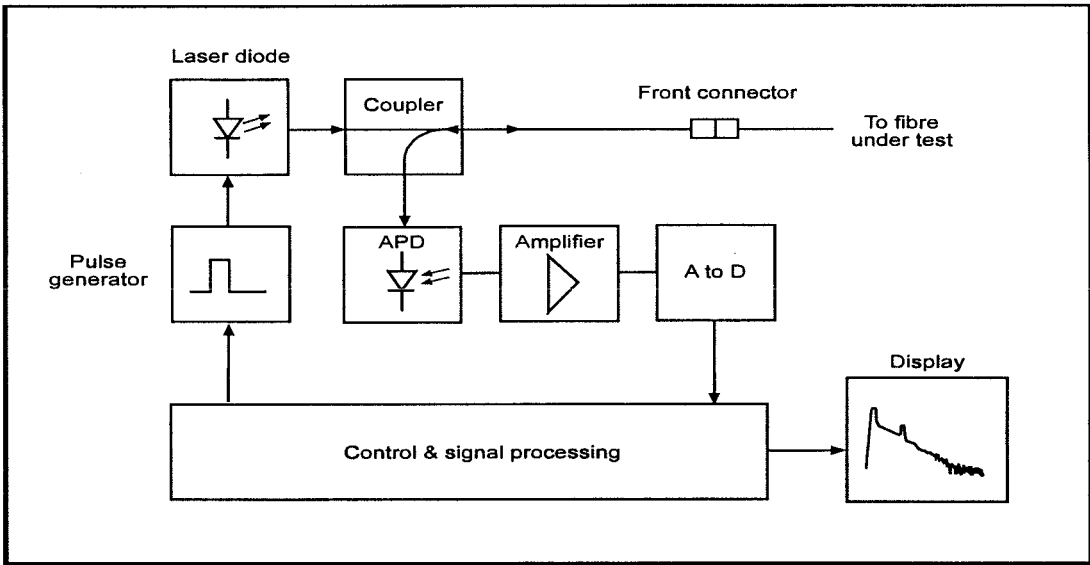


Figure 1. OTDR block diagram.

A typical OTDR set up is shown above. The signal processing unit triggers the pulse generator which drives the laser diode. This then produces a rectangular optical pulse typically 5 ns to 10 μ s wide at rates of few kilohertz. The laser output is fed via a directional coupler to the OTDR's front connector and fibre under test. The coupler may be a 50:50 coupler or alternatively a circulator or fast switch. The peak and average power of the laser are usually chosen so that the power at the OTDR's front connector is eye safe i.e. a Class I laser source. The returning optical signal is fed to a photodiode or avalanche photodiode (APD), amplified, sampled, averaged and then displayed. A typical OTDR trace is shown in Figure 2.

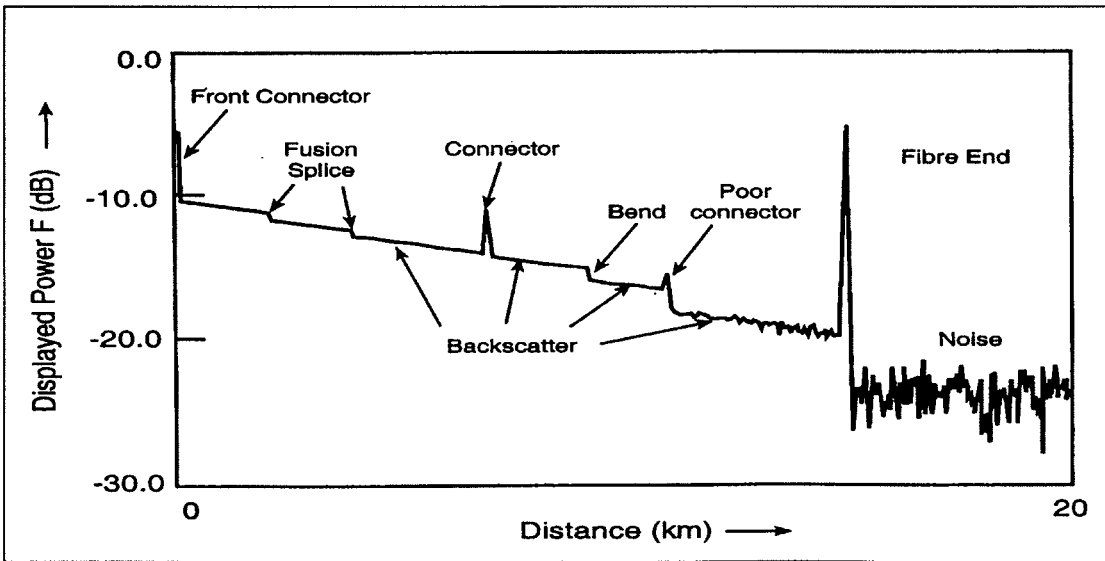


Figure 2 A typical OTDR trace.

Laser wavelengths are usually 850 and 1300 nm for multimode fibre and 1310 and 1550 nm for single-mode. Increasingly, single-mode OTDRs use additional wavelengths

such as 1625, 1410 and 1240 nm. These are either used on installed links to monitor systems carrying signals at 1310/1550 nm or for spectral modelling purposes. In the later, measurement of the fibre attenuation at four wavelengths are used to predict values at others within the 1300 and 1550 nm regions. In future it is likely that OTDRs will be produced which can be tuned to any wavelengths in the 1530 to 1580 nm range. Such OTDRs are likely to be employed on wavelength division multiplexed systems.

The backscattered signal received by the OTDR is typical more than 40 dB below the launched power. This is detected with a low noise APD or pin photodiode. Even so, for shorter pulse widths and for measurements at long distances (and consequently low returned signals), the backscatter light produces electrical signals from the detector which can be below the noise level of the detector and amplifier. To overcome this averaging is used. Each distance sample point is averaged many times and the noise, which is assumed random, averages to zero whereas the backscatter signal does not. The relation between the improvement in signal to noise ratio by going from averaging time T_1 to T_2 is equal to $10 \log (T_2 / T_1)^{1/2}$. Thus increasing the averaging time from 1 to 4 minutes decreases the noise by 3 dB. As the OTDR display one way dBs the noise level on the screen decreases by half this i.e. 1.5 dB.

Modern OTDRs can measure fibres > 100 km long. This means that the signal from the end of the fibre can be more than 40 dB down on that at the launch end. This may be too large a range to be covered by the A to D converter so some OTDRs may change other parameters whilst acquiring a trace. For example, laser power may be increased or APD gain increased when samples from the far end of the fibre are being recorded. Data acquired under these different conditions are then 'merged' to give a single trace.

3 Performance specification

The performance of the OTDR is specified by a number of parameters which should enable the user to select the instrument most suitable for a particular application. Ideally, the specifications should be presented in a standard way to make comparison of different instruments easier. Unfortunately this is not at present the case but such a standard is gradually evolving.

3.1 Dynamic range

The dynamic range is one of the most important of the OTDR's parameters and unfortunately one where several definitions exist. The dynamic range is defined as the difference between the backscatter level at the beginning of the trace and the level when a specific signal to noise ratio, SNR, is reached. Unfortunately there are at least three different SNR ratio definitions. $\text{SNR}_{\text{rms}}=1$, $\text{SNR}_{\text{peak}}=1$ and $\text{SNR}_{\text{rms}}=20$ or $N=0.1\text{dB}$ (see Figure 3).

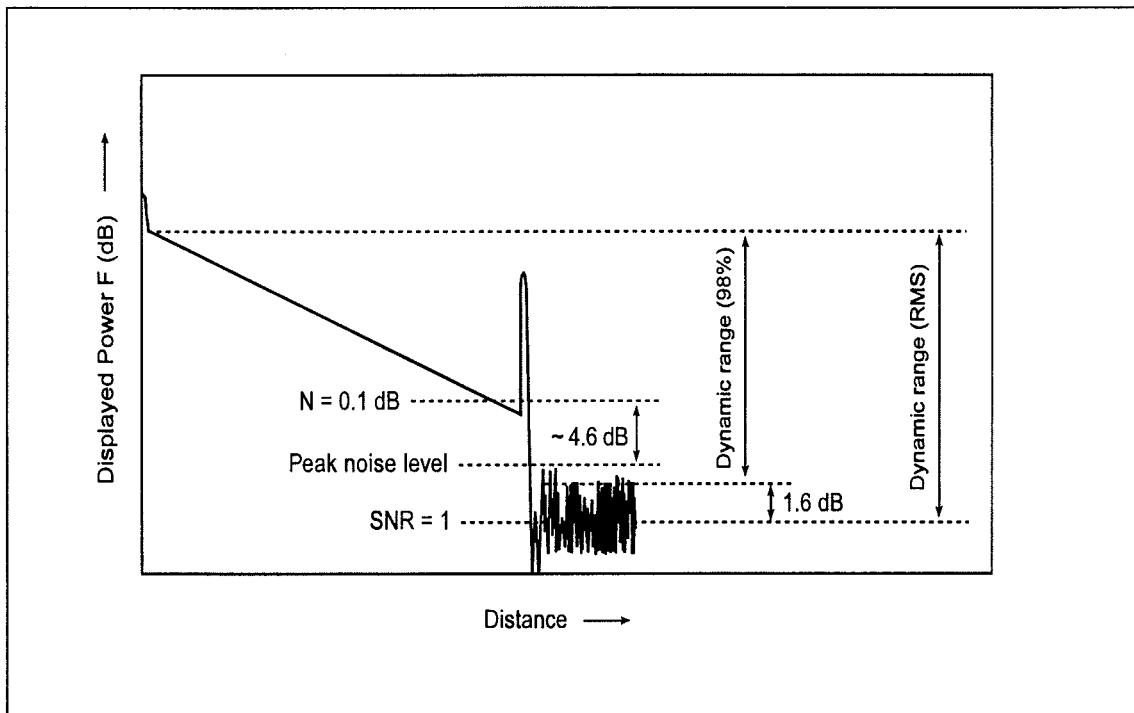


Figure 3. Dynamic range definitions.

The first is where the signal equals the rms level of the noise and as it gives the largest number it is often used by OTDR manufacturers. It has a number of drawbacks; it is difficult to make any meaningful measurements at this level and the level itself may not be readily apparent on the trace as the vertical scale is displayed in a logarithmic rather than linear format. The noise level used in the forthcoming IEC document on OTDR calibration, IEC 617460 [2] is $\text{SNR}_{\text{peak}}=1$. It is the level of the noise below which 98% of the data points fall. It is $\sim 1.6\text{ dB}$ above the rms level. Again it is not obvious where the exact level is on a typical OTDR trace and in practice it is probably easier to measure the level below which all the noise data points fall, this is $\sim 0.4\text{ dB}$ above the 98% level. The third definition uses $N=0.1\text{ dB}$, i.e. the level where the noise on a trace

is 0.1 dB rms or ~ 0.5 dB pk - pk. Under these conditions splice and fibre losses can be measured with fair accuracy. This level is ~ 4.6 dB above the peak level and ~ 6.6 dB above the rms, hence an OTDR with a dynamic range of 30 dB ($\text{SNR}_{\text{rms}}=1$) will probably have a 'useful' measurement range of ~ 23 dB.

The signal to noise ratio obviously depends on the averaging time and hence so does the dynamic range. The most commonly used averaging time for dynamic range specification purposes is three minutes. Sometimes the vague 'maximum averaging time' is used. It is also clear from Eqn. 1 that the backscatter power increases as the pulse width increases. Thus if the launch peak power is kept constant the dynamic range will increase with increasing pulse width. Knowing the definition, averaging time and pulse width used is essential in comparing the dynamic range performance of different OTDRs.

3.2 Dead zone

The OTDR's receiver is designed to detect the very small backscatter signals. The signals from reflective events can be several orders of magnitude greater and can saturate the photodiode and / or amplifier. During the time it takes the diode to recover from saturation backscatter signals will not be accurately recorded. The distance from the leading edge of the reflection to the point where the OTDR again gives accurate information is called the dead zone. It is usually divided into two types, attenuation dead zone and event dead zone.

3.2.1 Attenuation dead zone

The attenuation dead zone is defined (in IEC 61746) as the distance after the start of a reflective event to the point where the backscatter trace returns to within 0.1 dB of the 'true' backscatter level, Figure 4 (sometimes 0.5 dB is used instead of 0.1 dB).

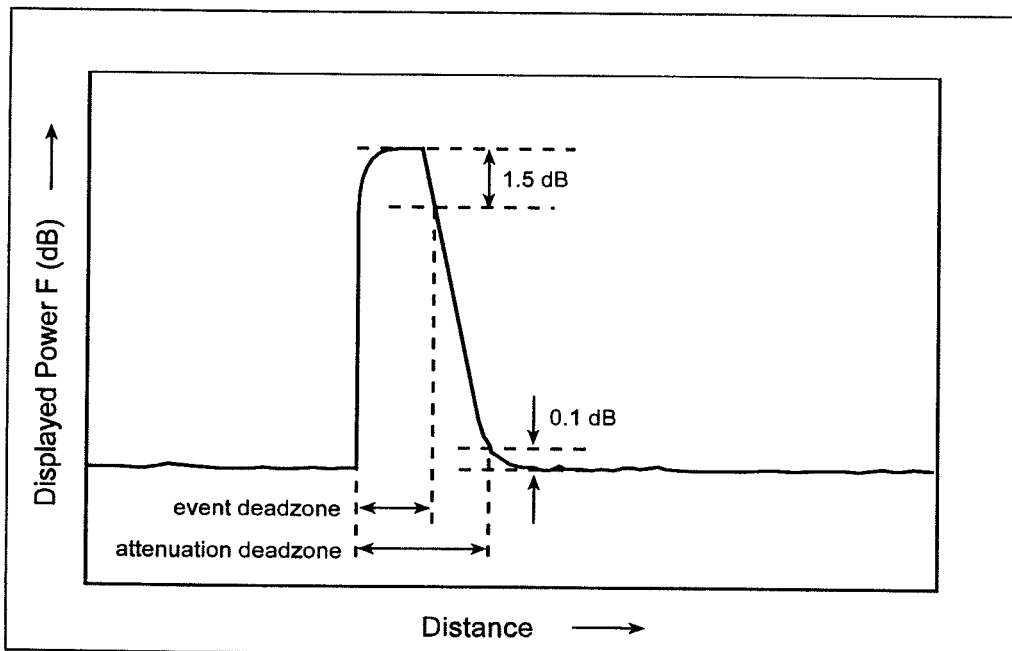


Figure 4. Attenuation and event dead zones.

After this distance attenuation can be measured with reasonable accuracy. Since the first reflection usually occurs at the OTDR's front connector, this dead zone is often called the front end dead zone. Some OTDRs reduce this by using a fast acousto-optic switch to effectively break the optical path from the front connector back to the photodiode for the duration of the laser pulse, this can lead to a reduced front end dead zones. In some OTDRs this 'mask' as it is called can be positioned anywhere on the OTDR trace. The attenuation dead zone depends on a number of factors such as the magnitude of the reflection, the pulse width used (the shortest pulse width does not necessarily give the shortest dead zone) and the receiver bandwidth. This can make it difficult to compare the specifications of different OTDRs.

3.2.2 Event dead zone

The event dead zone is usually related to reflective events on the OTDR trace. It is the minimum distance separation on the OTDR trace over which two closely spaced reflective events can be distinguished. It is defined as the distance between the two points on the leading and trailing edges of a unsaturated reflection peak which are 1.5 dB down from the peak (see Figure 4). This may well be a function of the amplitude of the reflection and the pulse width used and both should really be specified. The shortest pulse width does not necessarily lead to the shortest dead zone as, for a given reflectance, the peak of the reflection above the backscatter trace increases as the pulse width is shortened which may cause the detector to saturate.

The dead zone for lossy events such as splices can be defined in terms of the distance between the points where the OTDR trace falls by 10% to 90% (Figure 5) of the splice loss from its value before the splice. It can be reduced by using smaller pulse widths but it also depends on the bandwidth of the OTDR's receiver.

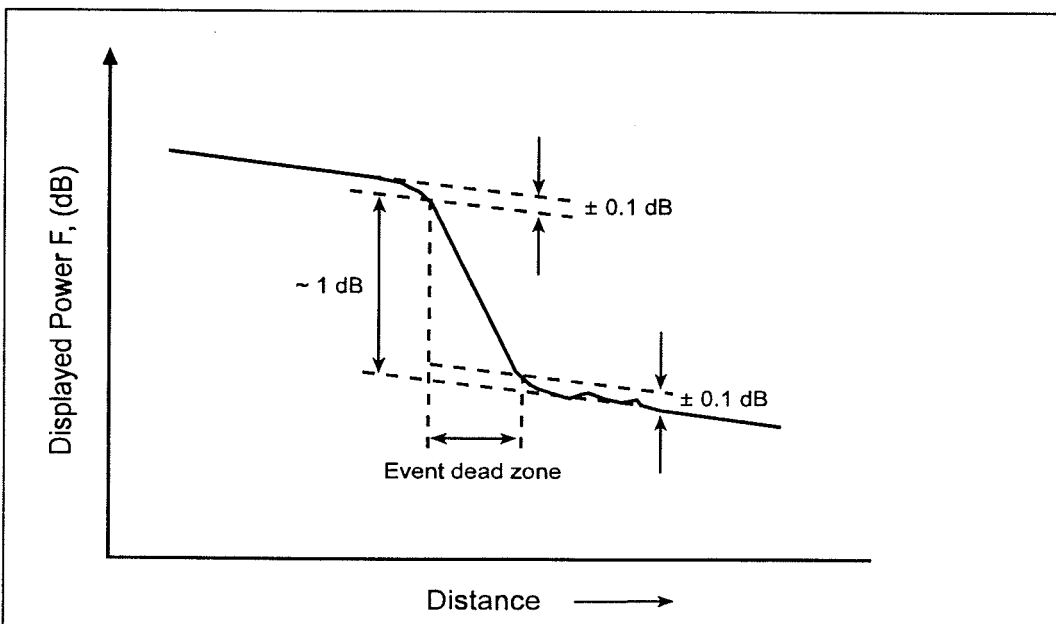


Figure 5. Dead zone definition for a splice.

3.3 Spatial resolution

The spatial resolution for reflective events is closely related to the event dead zone. For two reflective events to be fully resolved the distance between them is typically 2-3 times the event dead zone but is also dependent on the magnitude of the reflections. For lossy events the spatial resolution is the same as or slightly greater than the event dead zone.

3.4 Loss scale linearity (attenuation accuracy)

This is an important OTDR parameter particularly if the OTDR is to be used for fibre uniformity measurements. It is defined by the loss scale deviation, ΔS_A , or the loss scale factor, S_A , both usually expressed in dB/dB,

$$\begin{aligned}\Delta S_A &= (A_{\text{OTDR}} - A_{\text{ref}}) / A_{\text{ref}} \\ &= S_A - 1\end{aligned}\tag{3}$$

where A_{OTDR} is the loss of a fibre, splice or a component as measured by the OTDR and A_{ref} is the true or reference loss. A typical value for A_{ref} would be ~ 1 dB equivalent to ~ 3 km of fibre at 1300 nm and 5 km at 1550 nm. ΔS_A has contributions from any non-linearity in the OTDR's receiver, A to D converter and signal processing. It also includes any 'scale factor errors'. For example ΔS_A for a particular OTDR may not vary with received signal level or distance i.e. the OTDR is 'linear' in that sense but ΔS_A would not be zero if the scale was out by a constant factor. A typical value specified for ΔS_A would be < 0.04 dB/dB for a standard OTDR and < 0.02 dB/dB for a high linearity version. ΔS_A depends primarily on the level of the signal returned to the OTDR, i.e. the height of the signal above the noise floor, but may also depend on distance and previous events prior to the reference loss.

3.5 Distance accuracy

This is usually determined by the sampling resolution (i.e. the distance between successive distance points making up the OTDR trace) and uncertainties in the value of the group index, n_{eff} , of the fibre being measured. (The effective group index is the ratio of the speed of light in vacuum to that in the fibre, $n_{\text{eff}} = c/v$). The uncertainty in n_{eff} can often be the dominant factor as n_{eff} values are not usually quoted to better than 1 in 10^3 and the best measurement accuracy is ~ 1 in 10^4 . Provided the OTDR is set up to optimise distance accuracy, then for fibres longer than ~ 1 km, accuracy is not usually limited by the OTDR itself: distance accuracy is described in more detail in the calibration section.

4 OTDR Calibration

At the time of writing, the IEC document on OTDR calibration (IEC 61746) is essentially in its final form. It deals only with single mode OTDRs and does not contain anything on return loss calibration, although draft Amendment for the latter is nearing completion. Calibration uncertainty calculations are briefly discussed in Section 6, for a full treatment of uncertainty analysis the reader is referred to NPL, UKAS and ISO publications on the subject [3-5].

4.1 Distance calibration

Methods for calibration of the distance scale fall into two basic categories, active and passive. Active methods employ components such as pulsed lasers and time delay generators which provide a stimulus back to the OTDR triggered by the OTDR output pulse. This equipment is quite expensive and usually calibrates the OTDR in an atypical mode of operation. Only passive methods will be considered here and the reader is referred to IEC 61746 for details of the active methods.

The OTDR measures the location, L , of an event from the front panel connector by measuring the round trip transit time, t , for a light pulse to reach the event and return. L is then calculated from

$$L = \frac{tc}{2n_{eff}} \quad (4)$$

where c is the velocity of light ($2.99792458 \times 10^8 \text{ m s}^{-1}$) and n_{eff} the group index of the fibre. When calibrating an OTDR, any error in L results from the error in the OTDR's measurement of the round trip transit time. The uncertainty in n_{eff} , whilst important in making measurements with the OTDR, can in fact be eliminated in its calibration. After all the OTDR does not directly measure length but time and uses Eqn.4 to compute L .

Errors in measuring the round trip transit time arise from errors in the OTDR's internal clock and from errors in locating the event. Errors in the manual or automatic placement of markers and the type of event e.g. reflective, splice loss etc. also affect the accuracy to which features on the OTDR trace can be measured.

The calibration of the OTDR distance scale uses a linear model. This is

$$L_{OTDR} = S_L L_{ref} + \Delta L_0 + f(L_{ref}) \quad (5)$$

where L_{OTDR} is the distance of an event from the front connector as measured by the OTDR, L_{ref} is the true distance, S_L is the scale factor which should ideally be 1 and ΔL_0 is the distance offset which should ideally be zero. $f(L_{ref})$ represents the distance sampling error which is assumed to be a periodic function with an average value of zero and period equal to the distance between the sampling points.

Alternatively, Eqn. 5 can be written

$$\Delta L = L_{\text{OTDR}} - L_{\text{ref}} = \Delta S_L L_{\text{ref}} + \Delta L_o + f(L_{\text{ref}}) \quad (6)$$

where $\Delta S_L = S_L - 1$. The distance error ΔL is illustrated in Figure 6. The uncertainty in a distance reading due to the sampling is taken as the maximum difference between the straight line fit and the measured ΔL values and dividing by $\sqrt{3}$ to give the sampling uncertainty ΔL_{sample} .

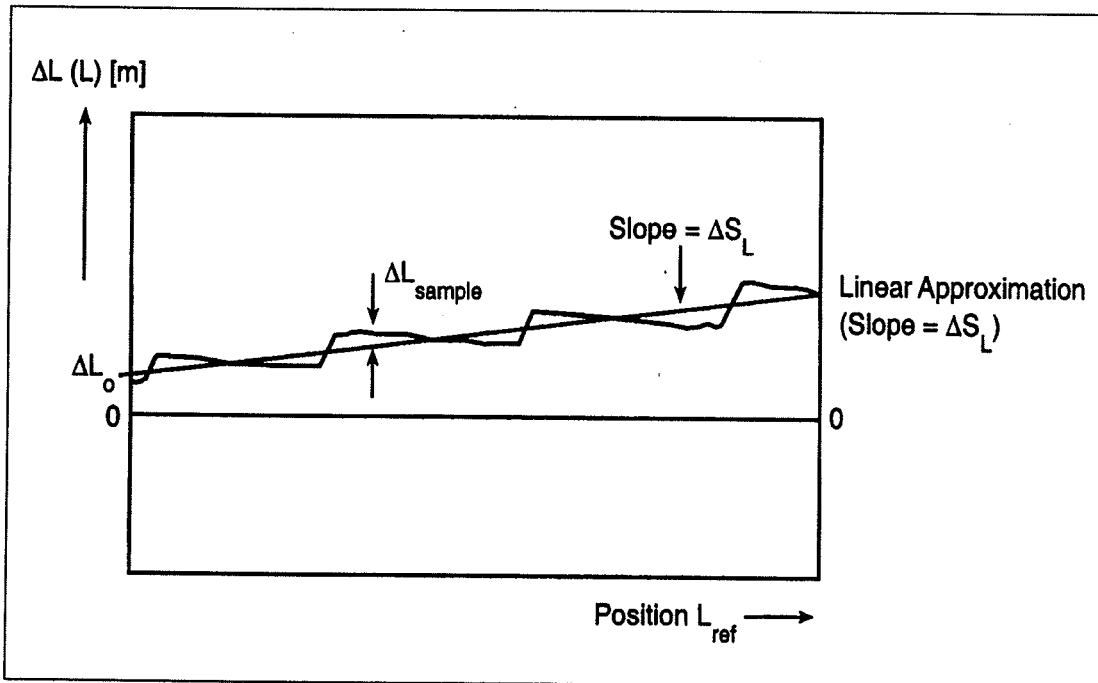


Figure 6. Distance sampling error.

To calibrate the distance scale of an OTDR several fibres of known lengths plus some shorter (< 1 metre) incremental fibres are required. A minimum of two length calibration fibres would usually be used. One should be short, 0.1 to 1 km, as this gives a better estimate of the distance offset at the origin. However, the fibre should be long enough so that the far end is outside the front end dead zone for the pulse width being used. The other fibre should be fairly long, 10 km say.

Incremental fibres whose lengths are sub-multiples of the sample spacing can be used to evaluate the distance sampling error. Often the sample spacing depends on factors such as the pulse width, distance scale and whether any zoom facilities are being used. If the sample spacing is not available from the OTDR's instruction manual or displayed on the OTDR screen, it may be possible to deduce it from the way the cursor moves on the OTDR trace. If not, then a range of random lengths of incremental fibres can be tried ranging from a few centimetres to several metres. It is not usually necessary to measure the time of flight of these fibres; measuring their physical length and assuming a group index of 1.46 will introduce a length uncertainty of < 0.03 m per metre of incremental fibre length.

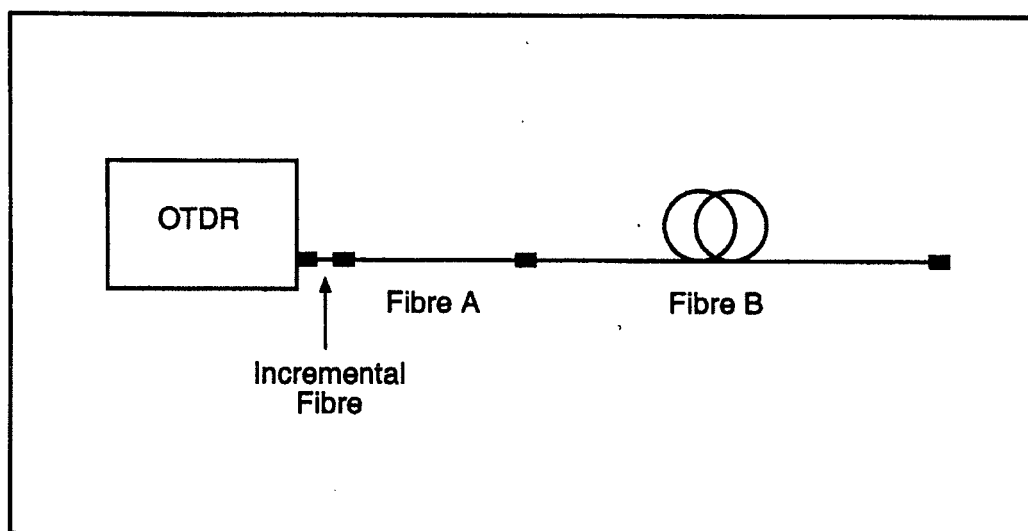


Figure 7. Set up for OTDR distance calibration.

The set up for carrying out the calibration is shown in Figure 7. One end of fibre A is connected either directly to the OTDR or via one or more of the incremental fibres. The other end of the fibre is connected to fibre B, the reflection from the non-terminated connector at the end of which provides a relatively large reflection which is easily seen on the OTDR. The reflection at the connection at the end of fibre A will normally be easily visible unless angled connectors are used.

The procedure is then to measure the distances to the A/B junction and to the end of fibre B. The OTDR cursors may be set using the manufacturer's instructions or by taking the first point on the reflection that rises a specified amount (0.1 dB say) above the backscatter trace. The procedure is repeated with different incremental fibre lengths. The group index setting used by the OTDR during the measurements must be recorded or a default value (1.46) used. The lengths of the reference fibres, $L_{\text{ref},i}$ are calculated by adding the length of the incremental fibre to that of fibre A to get the length to the A/B junction. The length of fibre A is calculated from its one way time of flight, t_{ref} (which will usually be given by the organisation issuing the calibration fibre) using

$$L = \frac{ct_{\text{ref}}}{n_{\text{eff}}} \quad (7)$$

The same value of the group index as was used in the OTDR measurement must be used in this calculation. This leads to pairs of L_{OTDR} and L_{ref} values for each of the incremental fibres. These L_{OTDR} values are then fitted by least squares to

$$L_{\text{OTDR},i} = S_L L_{\text{ref},i} + \Delta L_0 \quad (8)$$

This procedure can produce values for S_L and ΔL_0 and their uncertainties. Most spreadsheets will give the uncertainty in S_L but may not give that for ΔL_0 . An estimate

of the uncertainty in ΔL_o can be obtained by using Eqn. 8 to calculate ΔL_o for each of the incremental fibres and calculating the standard deviation of the values. (A full treatment of uncertainty analysis reader is referred to the Section 6 and UKAS publication on the subject [3]) An estimate of the sampling error ΔL_{sample} may also be available from the fit (may be stated as standard error if Y estimate). If not, the various $f(L_{\text{ref},i})$ values can be calculated using Eqn. 5 and the fitted values of S_L and ΔL_o and taking ΔL_{sample} as the largest value, either positive or negative, divided by $\sqrt{3}$.

Although S_L can be determined from the short fibre measurements, a more accurate value will be obtained for the scale factor from the distances, $D_{\text{OTDR},i}$, from the junction A/B to the end of fibre B determined from each of the measurements with the incremented fibres. The average value D_{av} and its standard deviation (see Section 6) are calculated from the measured $D_{\text{OTDR},i}$. The scale factor is then given by

$$S_L = \frac{D_{\text{av}}}{D_{\text{ref}}} \quad (9)$$

where D_{ref} is the length of fibre B calculated using Eqn. 7. Again the same group index must be used this calculation as in the measurement. The uncertainty in S_L is then calculated from those of D_{av} and D_{ref} .

In our experience the distance scales of typical OTDRs are accurate to better than 1 part in 10^4 (i.e. $\Delta S_L < 10^{-4}$) and any zero offset usually < 1 m. The latter uncertainty can be removed when measuring the length of an unknown fibre with an OTDR by inserting a lead in fibre between the OTDR and the fibre to be measured and measuring from the joint to the end of the fibre as outlined above in the calibration procedure. This removes any offset uncertainty and means that the uncertainties in the length will then be dominated by the sampling resolution and more likely by the uncertainty in the group index of the unknown fibre. There are few if any group index measurements on long fibres which are accurate to 1 in 10^4 . It should also be noted that the temperature coefficient of the length of the fibre is ~ 1 part in $10^5 / ^\circ\text{K}$.

An alternative to using single fibres for OTDR distance calibration is to use a re-circulating delay lane. The device and the OTDR trace it produces are shown in Figures 8 and 9. The device consists of a fibre connected from the OTDR to one of the input ports of a (typically) 50/50 fibre coupler. One of the output ports is connected to a high reflector (which could be a cleaved fibre end) and the other is looped back to the other input port.

On the OTDR trace, the first reflection is produced by the pulse which goes through the coupler to the reflector and back. This is then followed by a pulse which has gone anticlockwise round the loop once, out at the coupler and then reflected back from the reflector (this pulse coincides with a pulse which has gone directly to the mirror, then once clockwise round the loop and back to the OTDR). Successive pulses appear on

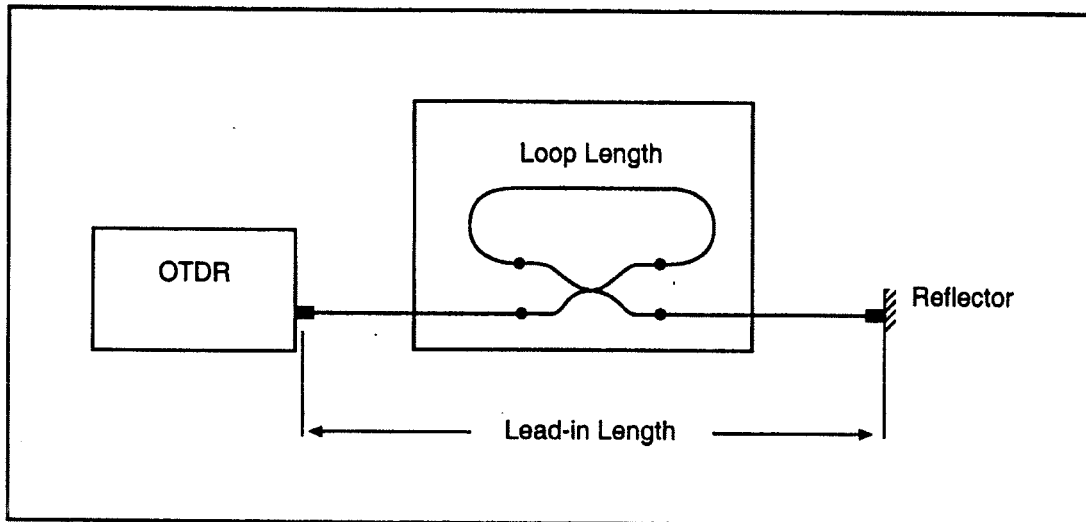


Figure 8. Recirculating loop length calibration set up.

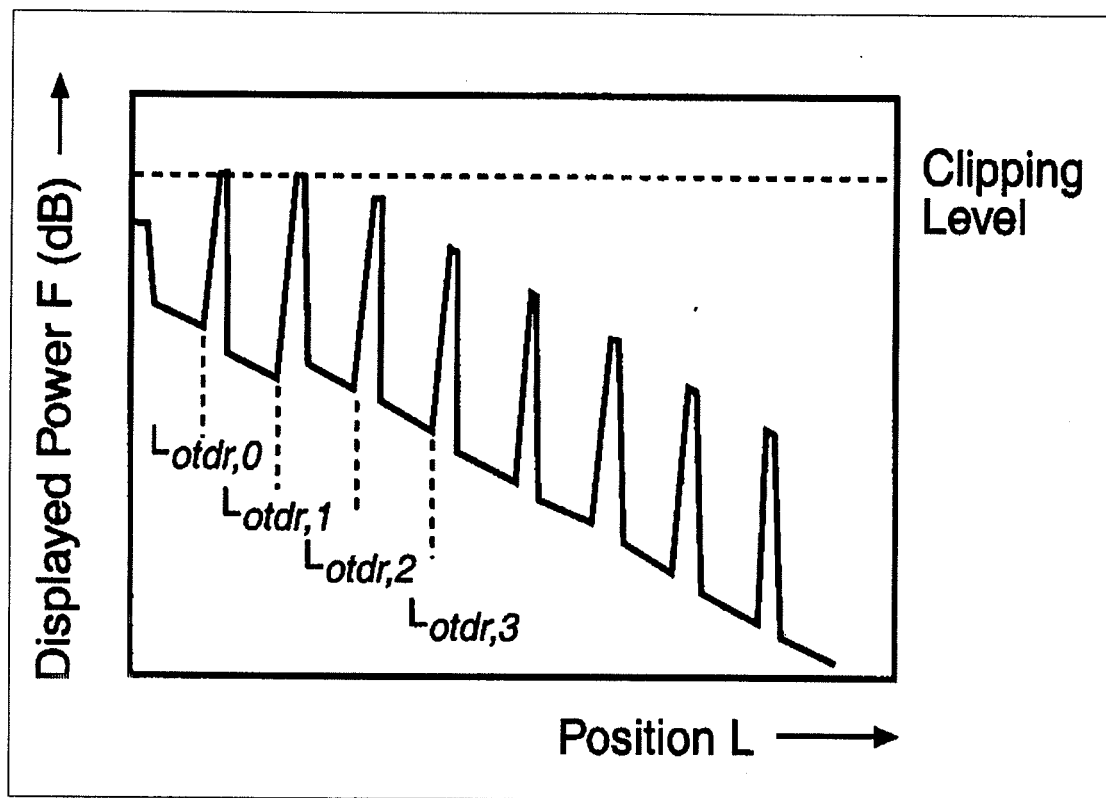


Figure 9. OTDR trace produced by the calibration set up of Figure 8.

the OTDR trace separated by half the length of the loop (they are separated in time by the transit time of the loop and OTDR regards this as a 'two way' time). If L_a is the length of the lead in fibre and L_b the length of the loop fibre then the reflection peaks $L_{OTDR,i}$ occur at

$$L_{OTDR,i} = L_{a,otdr} + i \cdot L_{b,otdr} / 2 \quad i = 0, 1, 2 \quad (10a)$$

or alternatively

$$L_{OTDR,i} = S_L L_{ref,i} + \Delta L_o \quad i = 0, 1, 2 \quad (10b)$$

where $L_{ref,i} = L_a + i L_b/2$

The calibration procedure thus consists of measuring the $L_{OTDR,i}$ values and fitting (using Eqn. 10a) by least squares as before to obtain estimate of $L_b/2$, L_a and their uncertainties. An example of a typical spreadsheet for doing this is shown in Table 1. As a number of reflections, typically 7 or 8, are recorded any sampling error effects tend to be averaged out although incremental fibres can be used if desired.

1310 nm Data		Reference Lengths		Lead-in	Loop
All data is expressed in m				1007.2	4511.2
		Uncertainty		0.15	0.2
Reflection		OTDR		OTDR-Fitted	Delta Lo
	i	Values		Values	
1	0	1015.06		-0.28	7.82
2	1	3269.17		-1.87	6.23
3	2	5527.39		0.65	8.75
4	3	7783.56		1.13	9.22
5	4	10039.72		1.59	9.69
6	5	12293.83		0.00	8.10
7	6	14550		0.47	8.57
8	7	16806.16		0.93	9.03
9	8	19058.21		-2.71	5.39
10	9	21314.38		-2.24	5.86
11	10	23574.65		2.33	10.43
				Mean	8.10
				SDOM	0.49
Regression Output:					
Constant		1015.34227		Lead-in	
Std Err of Y Est		1.72245101			
R Squared		0.99999995			
No. of Observations		11			
Degrees of Freedom		9			
				Loop	
X Coefficient(s)		2255.70		4511.40	
Std Err of Coef.		0.16		0.33	

Table 1. Typical spread sheet output for OTDR length calibration.

The i and OTDR values form the input to the fitting routine which then outputs a number of parameters. The constant is the lead-in length L_a , the standard error of the Y estimate is the sampling error, the X coefficient is half the loop length and standard error of coefficient its uncertainty. (If the data were fitted using Eqn. 10b, then the constant would be ΔL_o and the X coefficient S_L). The scale factor and the offset are then calculated from

$$\begin{aligned}
 S_L &= L_{b,OTDR} / L_{b,ref} \\
 &= 4511.4/4511.2 \\
 &= 1.000044
 \end{aligned}
 \tag{11}$$

and

$$\Delta S_L = 4.4 \times 10^{-5}$$

The uncertainty in the scale factor (Table 2) is obtained by combining the fit and reference uncertainties in quadrature, (see section 6.4 and references [3] & [4]).

Symbol	Source of Uncertainty	value $\pm m$	Probability Distribution	Divisor	c_i	$u_i(L_i)$ m/m	$\hat{\sigma}_i$ or $\hat{\sigma}_{eff}$
u_{ref}	reference loop length	0.2	Normal	1	1/4511.2	0.000044	∞
u_{otdr}	OTDR length	0.33	normal.	1	1/4511.4	0.000073	9
$U_{\Delta SL}$	Combined uncertainty		Normal			0.000086	16
$U_{\Delta SL}^{95\%}$	Expanded Uncertainty		Normal ($k = 2.17$)			0.00019	16

Table 2. Uncertainty budget for the distance scale deviation of the OTDR.

Hence the distance scale deviation is $0.44 \pm 1.9 \times 10^{-4}$ at the 95% confidence level. For all practical purposes it is zero.

Once the fitted loop and lead in values have been computed then the difference between the measured and fitted values can be calculated (see Table 1). Dividing the largest difference by $\sqrt{3}$ gives an estimate of the sampling uncertainty of 1.58 in acceptable agreement with the value from the fit of 1.72.

The offset value is calculated from

$$\begin{aligned}
 \Delta L_o &= L_{a, OTDR} - L_a \\
 &= 1015.34 - 1007.2 \\
 &= 8.14
 \end{aligned}
 \tag{12}$$

An estimate of its uncertainty can be obtained by using Eqn. 8 to calculate ΔL_o for each OTDR measurement (see Table 1) and calculating the mean and standard deviation of the mean (SDOM) of these values. This yields values of 8.10 and 0.49 respectively. In this particular example the offset is exceptionally large (more usual values are < 1 metre) and would be the dominant source of error in length measurement even for long fibres (ignoring those due to uncertainty in group index). As described previously, the use of a lead-in fibre removes this source of uncertainty.

The lengths of the lead in and loop fibres used in the calibration will depend on the distance range and pulse width values over which it is required to calibrate the OTDR. A lead-in fibre length of ~ 1 km is usually adequate. A loop length of 4 km would produce peaks with 2 km separation out to a usable distance of ~ 20 km for a $1 \mu s$ pulse on a typical OTDR, a 12 km fibre would produce reflections out to ~ 50 km.

To use either of the passive fibre methods requires calibrated fibres. These can be obtained from NPL and other accredited laboratories. The fibres are calibrated using active methods which measure the one way time of flight. This is then translated into a

length value using an assumed value of the group index, usually 1.46. Note also that the time of flight depends on the wavelength used but, as the same group index is used to calculate the length, the lengths as recorded by the OTDR will be $\sim 0.4 \text{ m km}^{-1}$ longer at 1550 nm than at 1310 nm for standard single-mode fibre.

The calibration results can be used in two ways, to calculate the uncertainty in the length of a fibre measured by the OTDR or to correct the measured value for any scale or offset errors. The error in location of a particular feature, ΔL , is, in addition to sampling errors, made up of offset and scale factor errors. It is given by

$$\Delta L = \Delta L_o + L_{\text{OTDR}} \Delta S_L \quad (13)$$

A corrected value for the true length can be obtained by subtracting ΔL from the measured OTDR value.

The above calibration procedure is applicable to single-mode fibres but can be adapted to multimode. The problem with multimode fibre is that the time of flight depends on the way the light is launched into the fibre and is therefore not uniquely defined. One way round this is to put mode filters consisting of a few turns of fibre round a mandrel $\sim 20 \text{ mm}$ in diameter at the beginning of the reference fibres when they are calibrated for time of flight and when they are used for OTDR calibration. This helps to ensure that the time of flight will be the same in both cases, errors are then likely to be less than 0.5 m. km^{-1}

4.2 Loss and attenuation calibration

The aim of loss and attenuation calibration is to determine the magnitude of any difference between the loss or attenuation measured by the OTDR, A_{OTDR} and the true loss, A_{ref} . Again both active and passive methods can be used (IEC 61746). The active methods require quite a lot of extra equipment and calibrate the OTDR under conditions which are usually not typical of its use. The most common passive method is one based on a calibrated fibre and only this is described here. For details of the other methods the reader is referred to the IEC document.

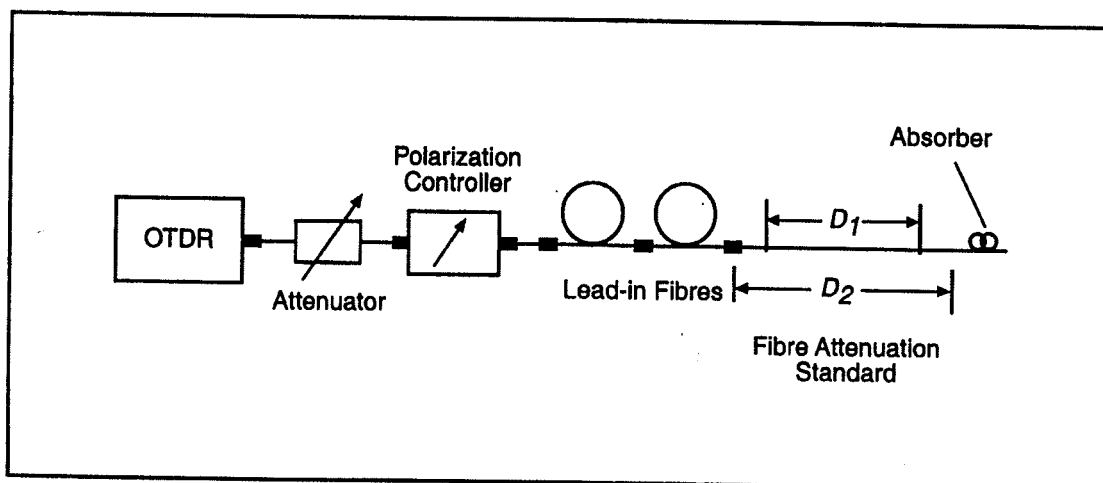


Figure 10. Loss calibration set up.

The set up for loss calibration with a standard fibre is shown in Figure 10 and the OTDR trace it produces in Figure 11.

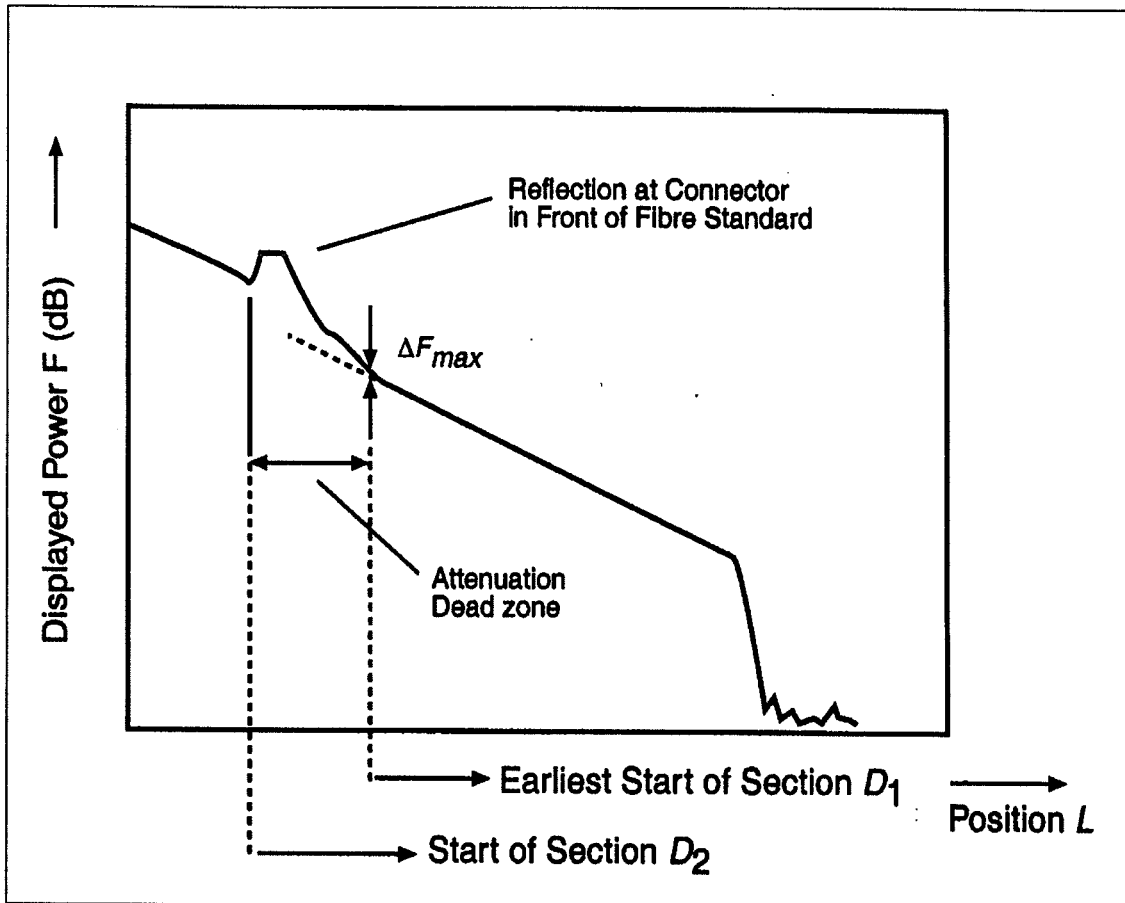


Figure 11. OTDR trace produced by loss calibration set up.

The calibration is carried out in terms of the displayed level of backscatter power F [dB] on the OTDR screen and it is essential that there is some way of knowing this. Some OTDRs display this on the vertical axis, others specify the level at the bottom of the OTDR screen and the displayed level can then be calculated by measuring the trace vertical position relative to this level. If no reference level is available, then the trace position is measured relative to the clipping level.

The system shown in Figure 10 is assembled with the appropriate lead-in fibre to position the fibre standard far enough away from the OTDR to overcome any front end dead zone effects. The attenuator is set to zero attenuation. (It may actually be removed from the set up for the first calibration point so as to obtain a higher return signal level and then inserted for subsequent measurements).

The standard fibre should be > 4 km in length (D_2) to provide a section D_1 which is ~ 3 to 5 km long after allowing for any dead zone effects. This will give a loss for the section D_1 of ~ 1.3 dB at 1310 nm and ~ 0.8 dB at 1550 nm. The loss of this fibre must be known if it is used to calibrate the loss scale absolutely but need only be known approximately if only scale non-linearities are to be investigated.

First of all the distance and level at the beginning of the section D_1 defined with the OTDR's cursors are noted. The loss of the section D_1 is then measured using the OTDR. It is recommended that this is done using least squares averaging rather than two point loss to obtain a better signal to noise ratio. The loss of the section D_1 can then be calculated from the attenuation coefficient as displayed by the OTDR and the distance D_1 between the cursors i.e. $\alpha \text{ (dB.km}^{-1}\text{)} * D_1 \text{ (km)} = A_{\text{OTDR}}$. The loss scale deviation is then calculated as $\Delta S_A = A_{\text{OTDR}}/A_{\text{ref}} - 1$. The attenuator is then adjusted so that the trace is lowered by about 0.5 times the reference loss and the measurement repeated to obtain another value of ΔS_A at the new backscatter level at the beginning of D_1 . The process repeated over the range of received power levels required. The results for a particular OTDR are shown in Figure 12.

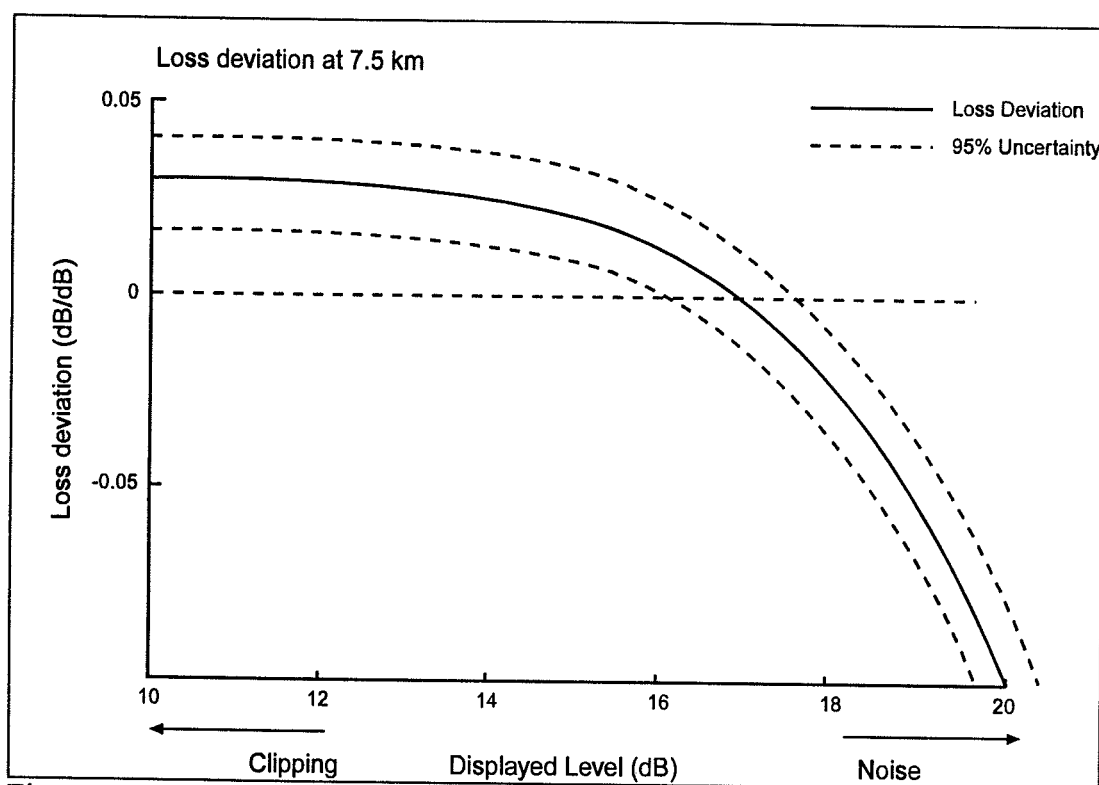


Figure 12. Loss calibration curve for an OTDR.

This shows that this OTDR has a loss deviation of 0.03 dB/dB which is essentially constant over a 6 dB range corresponding to ~20 km of fibre. Note that the above calibration was carried out with the reference fibre 7.5 km from the OTDR and is strictly only valid for this distance. Lead-in fibres can be used to position the reference fibre at different distances from the OTDR to check for any distance dependence of ΔS_A .

It is also important to note that ideally the OTDR measurements should be carried out from both ends of the fibre and the average value of A_{OTDR} used in calculating ΔS_A (see Section 2.1). However, not only does this double the number of measurements but also requires matching the signal levels at the start of D_1 on the second set of measurements. The reference fibre should ideally 'bi-directional' i.e. the attenuation as measured by an OTDR is the same for both directions, for in this case measurement from one end only is required. If this is not the case then A_{ref} should be specified (by the

supplier) for measurements carried out in a particular direction or an additional uncertainty included in the uncertainty of A_{ref} .

The uncertainty in loss scale factor depends on the uncertainty in the reference loss and the measurement uncertainty in A_{OTDR} . Usually the uncertainty will be dominated by that of the reference loss. It should be noted that if only OTDR linearity is to be determined then A_{ref} could be taken as the loss measured by the OTDR at the highest received level.

Two other factors need to be taken into account in the overall uncertainty evaluation. These are the wavelength of the OTDR and polarization effects. The wavelengths of OTDRs are usually fairly loosely specified e.g. 1310 ± 20 nm. The value of A_{ref} could change by 0.1 dB/dB over this wavelength range for a single-mode fibre. Either the wavelength of the OTDR is measured and A_{ref} of the reference fibre at that wavelength used, or the additional uncertainty taken into account in calculating the overall uncertainty in ΔS_A .

An example of an uncertainty budget for the loss scale factor is shown in Table 3. It includes contributions from the uncertainty in: - the cutback attenuation measurement of the reference fibre and the latter's temperature coefficient of attenuation, the OTDR wavelength (± 2 nm in this case), the OTDR distance scale and the OTDR reproducibility. It can be seen that the cut-back and wavelength are the major contributions and that it is improvements in these uncertainties which will do most to improve the accuracy of the calibration.

Symbol	Source of uncertainty	value $\pm$ dB/dB	Probability distribution	Divisor	c_i	$u_i(A_x)$ $\pm$	v_i or v_{eff}
u_{ref}	Reference fibre	0.002	Normal	1	1	0.002	5
u_{rep}	OTDR Reproducibility	0.0005	Normal	1	1	0.0005	2
u_λ	Wavelength	0.0022	Normal	1	1	0.0022	5
u_L	OTDR Length Scale	0.0001	Normal	1	1	0.0001	37
u_T	Temperature	2°C	Rectangular	$\sqrt{3}$	0.0003	0.0004	∞
U_{sf}	Combined uncertainty	-	Normal	-	-	0.0030	11.7
$U_{\text{SA}}^{95\%}$	Expanded uncertainty	-	Normal ($k=2.24$)	-	-	0.0068	11.7

Table 3. Uncertainty budget for the loss scale calibration factor.

All OTDRs will exhibit a polarization dependence to the backscatter light to a greater or lesser degree. Light launched into the fibre from the laser is usually polarized. As it passes down the fibre its polarization state changes and the backscatter light has the same polarization at the scattering point as the probe pulse. Its state in turn changes as it propagates back to the OTDR. Thus the OTDR not only sees a decreasing backscatter level but also one the polarization state of which is changing. If the OTDR has any polarization dependence in its detector system, then this will manifest itself as ripples on

the OTDR trace. One way of overcoming this is to vary the polarization of the light during the measurement so that the ripples average to zero. Another is to depolarise the laser pulse launched into the fibre.

Having obtained the loss-scale deviation versus F and possibly distance, it is possible to correct future measured losses to give a better estimate of the true loss.

For loss regions where $S_A(F)$ is approximately constant then

$$A_{best.est}(F) = \frac{A_{otdr}}{S_A(F)} \quad (14)$$

When $S_A(F)$ varies, then the OTDR trace needs to be split up into small sections where $S_A(F)$ is constant and the corrections applied to each section in turn. Alternatively, the average value of $S_A(F)$ over the range of received power used in the measurement can be used in Eqn. 14.

4.3 Return loss calibration

The reflectance in dB, $R(\text{dB})$, at a particular point in a fibre system is defined in terms of the incident and reflected powers as.

$$R(\text{dB}) = 10 \log_{10} \frac{(P_{\text{refl}})}{(P_{\text{inc}})} \quad (15)$$

where P_{inc} and P_{refl} are the incident and reflected powers. The return loss $RL(\text{dB})$ is defined as $-R(\text{dB})$. As the OTDR has no means of measuring the power at a point in a system just prior to a reflection, it uses the backscatter level, which of course depends on the incident power, as a 'reference' level for the incident power. At the distance L (see Figure 13) the reflected power is

$$P_{\text{refl}} = R P_{\text{inc}} \quad (16)$$

where R is the linear reflectance. The backscatter power is from Eqn. 1

$$P_{\text{bs}} = K \Delta T P_{\text{inc}} \quad (17)$$

Here ΔT is the OTDR pulse width and K the fibre backscatter parameter. The incident power can thus be measured in terms of the backscatter power along with knowledge of K and ΔT .

The OTDR measures the height of the reflection peak, ΔF , above the backscatter level. It can be shown that

$$RL(\text{dB}) = - \{ 10 \log_{10} K + 10 \log_{10} \Delta T + 10 \log_{10} (10^{\Delta F/5} - 1) \} \quad (18)$$

For high value of ΔF e.g. > 6 dB the above equation reduces to

$$RL(dB) = -\{ 10 \log_{10} K + 10 \log_{10} \Delta T + 2\Delta F_{dB} \} \quad (19)$$

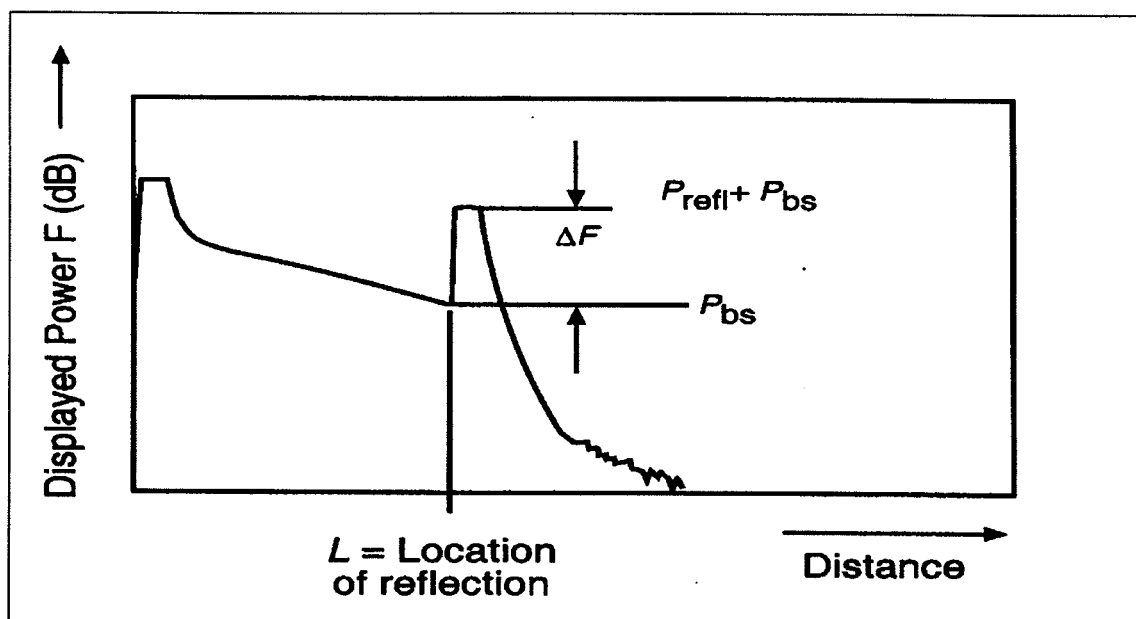


Figure 13. OTDR trace from a reflective event.

The OTDR calculates the return loss by measuring ΔF and then using Eqn. 18. To do this it needs a value for K ; this will exist as a default value within the OTDR's software and can also be input by the operator. This is often done in the form of the backscatter coefficient, $C(\Delta T) = K \cdot \Delta T$, which is usually expressed in dB as

$$C_{dB}(\Delta T) = 10 \log_{10} K + 10 \log_{10} \Delta T \quad (20)$$

Eqn.19 then becomes,

$$RL(dB) = -\{C_{dB}(\Delta T) - 2\Delta F(dB)\} \quad (21)$$

$C_{dB}(\Delta T)$ is quoted for a particular pulse width, for example $1 \mu s$. Typical values for single-mode fibre would be

$$C_{dB}(1310 \text{ nm}, 1 \mu s) = -48 \text{ dB}$$

$$C_{dB}(1550 \text{ nm}, 1 \mu s) = -51 \text{ dB}$$

Multimode fibres have values which are 5 to 10 dB higher at 1310 nm and up to 20 dB higher at 850 nm. A system for calibrating an OTDR for return loss and the trace it produces are shown in Figure 14.

The OTDR is connected to the input fibre, F0, the other end of which is connected to a 90/10 coupler. Because the coupler has a split ratio of $\sim 90:10$, nearly all the backscatter power returned to the OTDR comes from fibre F2. Thus adjusting the attenuator to

change the amplitude of the reflection at the end of fibre F1 has very little (<0.03 dB) effect on the backscatter trace and the backscatter before and after the reflection is essentially the same. If required, a non-reflective attenuation can be added in fibre F2 at L_1 to simulate a reflection combined with a loss as would be given by a connectorized joint. The easiest way of doing this would be to put bends in F2 at L_1 .

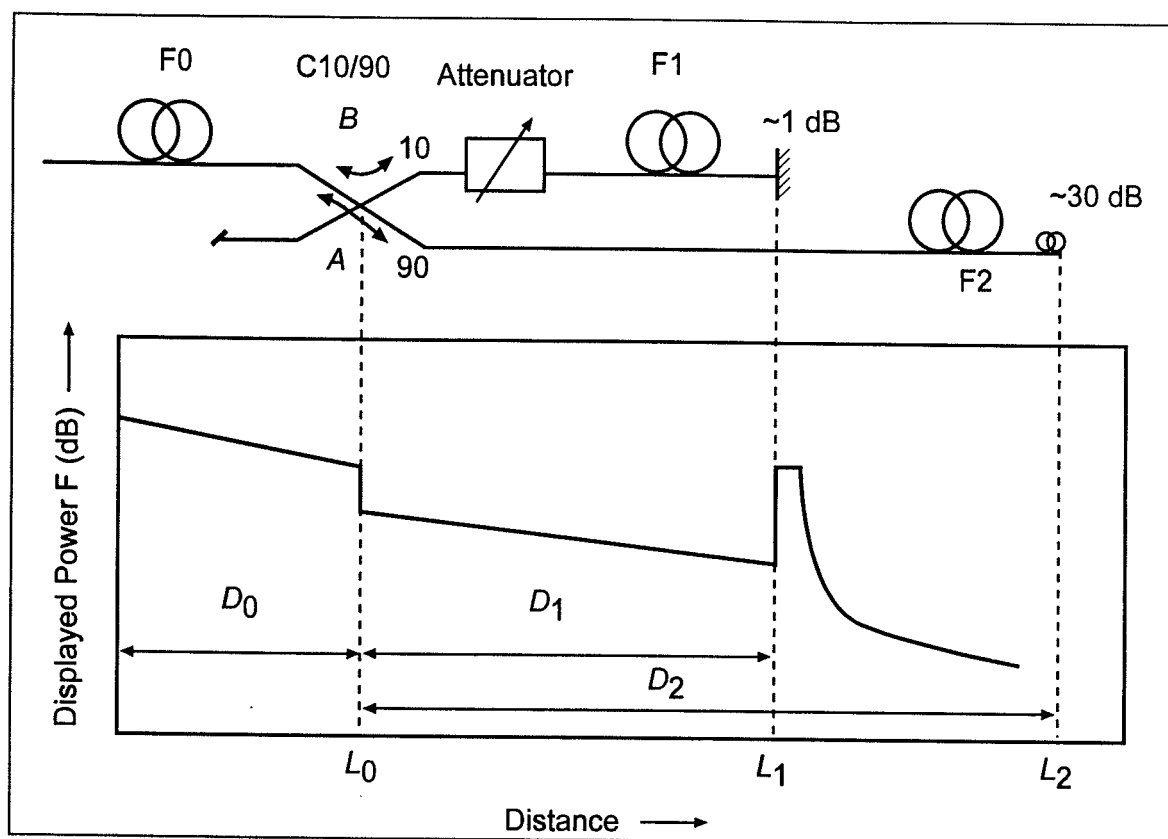


Figure 14. Return loss calibration.

It can be shown that the value of return loss produced by such a device is

$$RL \text{ (dB)} = A + 2AT_{\text{dB}} \quad (22)$$

where A is a constant depending mainly on the fibre backscatter factor and the coupler ratio. AT_{dB} is the attenuator setting in dB (AT_{dB} is taken as being positive). A calibrated attenuator is thus required. The determination of the constant A is quite involved and is described in detail in a forthcoming new sections on reflectance calibration in IEC 61746. For a 90/10 coupler A will be ~ 25 dB, 20 dB from the two way loss of this coupler and 5 dB from the two way insertion loss of the attenuator and any connectors/splices.

Some idea of whether the OTDR is giving the correct return loss can be gauged by increasing the attenuator by 0.5 dB increments and seeing if the peak height changes by 1 dB each time (it may not be exactly 1 dB due to the wavelength dependence of the attenuator but should be the same for each 0.5 dB attenuation increment). If this is the case, then the OTDR is probably recording the height of the peak in a linear fashion and giving the correct value of return loss. NPL can also supply fibres with a known

reflection and return losses at the ends which can be used to check the return loss accuracy.

4.4 Wavelength

For length measurements the exact wavelength of the OTDR need not usually be known. Most OTDRs have the wavelength specified to within ± 20 nm. This will cause a negligible uncertainty at 1310 nm and $< 0.06 \text{ m.km}^{-1}$ at 1550 nm on standard fibre. The uncertainty in the fibres group index is likely to cause a larger uncertainty.

However, a ± 20 nm wavelength range could cause significant errors in attenuation measurements especially at 1310 nm where for a typical fibre the attenuation coefficient might vary by 0.03 dB.km^{-1} over the range 1290 to 1330 nm. At 1550 nm the variation is likely to be $< 0.01 \text{ dB.km}^{-1}$.

5 Getting the most out of the OTDR

The OTDR is a very versatile instrument but it is still necessary to select an OTDR which is suitable for the job in hand. For example if short lengths are to be investigated, high resolution is likely to be more important than a high dynamic range.

5.1 Launch level

For the OTDR to perform optimally the maximum amount of light should be launched into the fibre. This means that the front panel connector should be clean and not have excessive wear. The launch level on the screen of the OTDR when used with a particular type of fibre and given pulse width and wavelength should be available from the OTDR manufacturer's handbook for the instrument. Some OTDRs also give a good/bad indication of the launch level. If the launch level is more than 1 dB down from the expected level then first clean the OTDR and launch lead connectors. Some OTDRs have a demountable front connector which makes cleaning easier. If no improvement results then the launch lead may need replacing. If changing this makes no improvement then the OTDR's front connector may have become damaged, for example by being scratched with a dirty connector. It will then need to be returned to the manufacturer for service.

It is usual to insert a lead-in or launch fibre between the OTDR and the fibre being measured. This should be long enough so that by the end of the fibre any dead zone effects due to reflection at the front panel connector are negligible. The length of this fibre depends on the pulse width but ~ 1 km will be suitable except for very long pulse widths. The additional loss of this fibre and connector, typically ~ 0.5 dB, will not significantly increase the measurement time or reduce the dynamic range.

The connection between the end of the launch fibre and the fibre being measured should also be as good as possible with low loss and reflection, a fusion splice being the best if not the most convenient option. Connectors should have a loss of <1 dB and a return loss >30 dB. A large reflection here can give rise to an effect known as ghosting where a reflection occurs on the OTDR trace where none actually exists. What happens is that the reflected pulse travels back to the OTDR where it is reflected at the front connector back-down the fibre and is again reflected at the poor connection. A reflection thus appears at twice the distance from the OTDR of the poor connection. The solution is obviously to clean the connectors and if this fails, replace them. In addition to the above, the use of a lead-in fibre also allows the operator to control the launch level by for example putting bends in the fibre.

5.2 Distance

The major uncertainties in using OTDRs for distance measurements are uncertainty in the group index, sample point spacing and the wavelength used by the OTDR. Depending on the type of fibre, the group index of single mode fibre is usually in the range 1.465 to 1.471. Even when the type of fibre is known, e.g. normal or dispersion

modified, it is unlikely to be known to better than 1 in 10^4 . The distance scale factor for a modern properly calibrated OTDR is likely to be better than this.

Marker placement will also affect distance accuracy. What is important here is to use the same criteria (or as close to it as possible) in the measurement as was used in the calibration e.g. 0.1 dB up from the backscatter trace for a reflective event. Use of the shortest practical pulse width and zooming in to get the highest possible resolution will also improve accuracy. If required the measured length can be corrected if the distance scale factor is known by dividing the measured distance by the scale factor to get the true distance. From results of intercomparisons, accuracies of ± 0.7 m are achievable on ~ 13 km long fibres using OTDRs which have been calibrated using reference fibres. This is comparable to the accuracy of the reference fibres themselves.

5.3 Attenuation measurements

To obtain accurate attenuation values the launch precautions outlined above should be observed taking care that the measured fibre is outside any dead zones. Usually the longest pulse width commensurate with any spatial resolution requirements is used as this gives a better signal to noise ratio and/or a shorter measurement time. Any reflection at the far end of the fibre should, if possible, be removed as this can cause measurement errors on some OTDRs. It also corresponds to the condition under which the OTDR was calibrated. This is most easily done by wrapping a few turns of the fibre round a small diameter mandrel such as a pen or pencil.

The effects of polarization were discussed in the section on calibration. Ideally a 'polarization scrambler' which goes through all polarization states during the measurement should be inserted between the OTDR and the fibre under test. Manual and automatic versions of this exist ranging in price from a few hundred pounds for the manual versions to several thousands for automatic versions. The insertion loss of such a device should be ~ 2 dB and polarization dependent loss (PDL) as low as possible, figures of < 0.2 dB for PDL are achievable.

Whether polarization effects will be important depends on the OTDR itself, the fibre being measured, the pulse width being used and the length of fibre being measured. The shorter the pulse width used then the greater the amplitude of any 'ripples' on the OTDR trace. Also, if the attenuation coefficient measurement is carried out over a short distance, less than 1 km say, then there is less averaging out of the ripples than for longer distances. For typical fibres and OTDRs, if a 3 km length is used for calibration and measurement, the effect will be < 0.01 dB. km⁻¹.

When all the corrections for wavelength, polarization etc. are carried out, attenuation coefficient measurements with an accuracy of ~ 0.003 dB. km⁻¹ are possible. This is comparable to the accuracy of the cut back technique on shorter (≤ 3 km) fibres. Note that for accurate attenuation measurements the fibre must be measured from both ends and the average of the measurements taken to get the true attenuation. This is because the backscatter on a single direction depends also on any changes in mode field diameter and refractive index which may occur. Indeed the OTDR trace can be analysed to

extract this information. These effects cancel out when the bi-directional average is taken.

The attenuation coefficient of fibres varies with wavelength in a fairly predictable fashion but less is known of the wavelength dependence of fibre attenuation coefficient uniformity. For example, on a long fibre a 1 km section at one end may have a higher attenuation coefficient than one at the other at 1550 nm but is the same true at 1310 nm? On the basis of the small amount of data we have collected it seems that this is only partially correct but seems to be a good approximation over more limited wavelength ranges such as 1550 ± 20 nm.

5.4 Splice loss

The splice loss is usually made using the five point method, Figure 15. Typically, markers (1,2,3,4) are placed either side of the splice. A straight line fit to the trace is performed on both pairs of markers and extrapolated to the position of the splice, marker 5, and the difference between the two traces calculated at that point. Splice losses of <0.1 dB can be measured in this way. The accuracy of the measurement can be estimated from the loss calibration factor for the signal level F at the beginning of the splice. If necessary the measured value can be corrected in the same way as attenuation measurements.

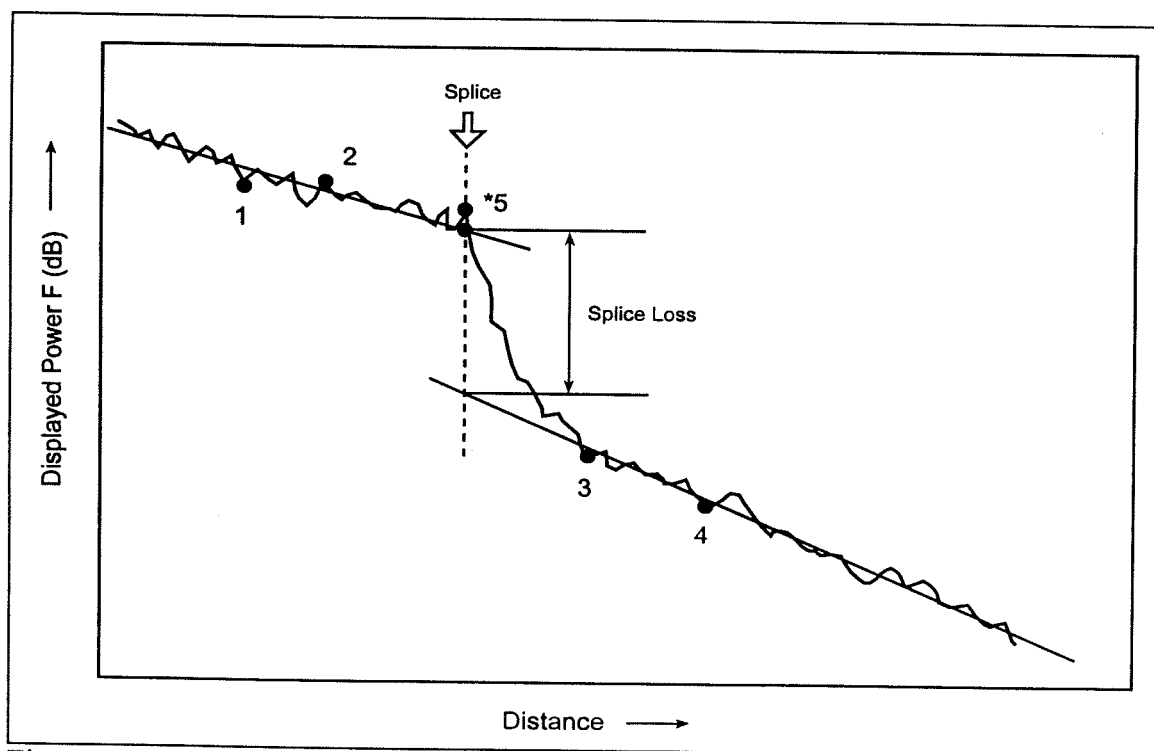


Figure 15. Splice loss measurement.

As is the case of attenuation measurements, reliable values of splice loss are only obtained by taking the average of the values measured in both directions. This is especially the case if the splice is between fibres of different types with different

backscatter parameters. It is possible in some cases for splices to show gain rather than loss; however, the bi-directional average gives the true splice loss. The difference in the splice loss measurement in both directions can be used to calculate mode field diameter differences between the fibres at the splice, although this is only really applicable if the fibres are of the same type and from the same manufacturer.

5.5 Return loss

As noted in the section on calibration, absolute calibration of an OTDR whilst straightforward involves quite a lot of effort. Some idea of the accuracy can be obtained using the linearity checking procedure outlined in 4.3. Alternatively some kind of reflectance standard fibre can be used. This should be specified for return loss accuracy and any wavelength, temperature and polarization dependence should also be given. The value of the backscatter coefficient should also be stated. The uncertainty in this parameter is likely to be <1 dB especially if the type of fibre being measured is known e.g. matched clad or depressed clad single-mode fibre. Good OTDRs can however have return loss accuracies of <0.3 dB.

For a given OTDR setting it will not be possible to measure all reflectance values. The minimum measurable pulse amplitude above the backscatter trace is zero. However, it is better to choose a minimum value of say 3 dB if possible. This is because for small values of ΔF , small errors in this quantity lead to large errors in the return loss, as the last term in Eqn. 18 tends to infinity as ΔF goes to zero. One way of doing this is to use a shorter pulse width for the measurement as from Eqn.19 this leads to a larger value of ΔF for a given return loss value. However, if the pulse width is made too short then ΔF can become so large that the detector saturates. This is especially the case for low return losses such as a 14.6 dB value obtained from a glass/air interface. There a longer pulse width reduces the peak height above the backscatter but unfortunately the longer the pulse width also can overload the detector on the backscatter itself. One solution is to place an attenuator between the OTDR and the reflection being measured and use this to reduce the return signal from the reflection. This may however result in the backscatter trace falling into the noise if the peak height exceeds the dynamic range of the OTDR.

5.6 Wavelength

The wavelength of the OTDR should be measured under the same conditions (pulse width, distance etc.) used for fibre measurements. The easiest way of measuring the wavelength is to use an optical spectrum analyser, OSA. However, care needs to be taken in doing this as the OTDRs pulse rate and the OSA scan rate can interact to give spurious results. Generally as slow a scan rate as is practically possible is likely to give the more accurate result. Alternatively a monochromator or scanning filter may be used. Some OTDRs can be switched to give a continuous output which makes wavelength measurement easier. However, this wavelength can be several nm different from the pulsed wavelength.

6 Calibration and uncertainty of measurement

6.1 Calibration

6.1.1 Specification versus calibration

Performance criteria for an instrument can be described in terms of a specification. This will give limits within which the behaviour of the instrument can be expected to fall. For instance if an instrument is specified to have an uncertainty of $\pm 0.1\%$ of reading, then the user can reasonably hope that if the instrument is used correctly, the value it indicates will be correct, give or take 0.1% of the result. However, this performance cannot be relied upon unless verified by calibration of the instrument. A specification is not the same as a calibration, and is no substitute for one. Rather it indicates how an instrument is expected to perform between calibrations.

6.1.2 What is calibration?

Calibration is the process of comparing a measuring instrument against an authoritative reference for the same type of measurement, to identify any error in the readings. The outcome of a calibration is normally a certificate listing any corrections that need to be applied to the values indicated by the instrument, together with an estimate of the uncertainty in the calibration, and other relevant information. For example a calibration of a given instrument when measuring, say, 1 ohm, might show that it reads too high by 1%. If so, a correction of -1% would be shown on the certificate.

Calibration is often taken to mean 'adjustment of the instrument to read correctly'. This is not true. Calibration and adjustment of an instrument are quite separate concepts, and the two should not be confused. Thus when arranging for the calibration of any instrument, it is important to establish clearly whether or not the instrument is to be adjusted as well as calibrated. If so, it should be specified whether calibration information is required only after adjustment, or whether results are also required for the initial or 'as found' condition.

6.1.3 Calibration by the user or elsewhere

With suitable expertise, calibrations can be carried out successfully by the user without sending instruments to an outside laboratory. However, setting up an in-house calibration facility may require considerable investment in equipment and training. It is often better to have the work done by an expert laboratory, and perhaps one which holds a recognised measurement accreditation.

6.1.4 Calibration with or without recognised measurement accreditation

Some laboratories hold recognised accreditation (such as UKAS, in the UK) for calibration or testing; others do not. An absence of accreditation does not necessarily mean a lack of quality management, or a poor standard of measurement. However, in the absence of recognised accreditation, it falls to the user to make a personal judgement

of the quality of the measurements provided. The user can audit laboratories directly, or simply trust!

6.1.5 Calibration intervals

A calibration is only strictly correct for the instant and place it was carried out. To be useful the calibration has to be trustworthy in other places at later times. This trust can be gained from past calibration performance of the item, or similar ones, as well as its likely stability from its working principles, design and construction. The amount of trust determines the time that can be allowed to elapse before recalibration (calibration interval). Choosing suitable intervals for recalibration of instruments therefore depends on many factors including

- 1) type of instrument
- 2) manufacturer's advice
- 3) required accuracy in use
- 4) severity of conditions of use
- 5) history of past stability or drift
- 6) frequency of checks against other instruments (preferably stable ones)
- 7) maintenance in between calibrations
- 8) cost of calibrations
- 9) importance of avoiding incorrect results

Until a record of performance has been built up, initial choice of intervals may be based on the first four in the list.

Checks of a measuring instrument against another (stable) instrument or transfer standard are often useful at intervals in between calibrations to confirm whether or not some condition is fulfilled (for example to confirm that the performance of an instrument has not deteriorated).

6.1.6 Traceability

Traceability to authoritative standards is the best way to ensure accuracy of measurements, and leads to consistency of measurements among users at different times and locations. A traceable measurement is one which can be related to appropriate measurement standards, generally national or international, through an unbroken chain of comparisons. In the UK this normally means that the calibrations have been undertaken by NPL or by a UKAS accredited laboratory or by an accredited laboratory in another country with which there is a reciprocal recognition agreement.

Measurement standards are defined at a primary level, by a single authoritative measuring instrument (usually one serving the whole country as a 'national standard'). The primary standard is used to calibrate other instruments or fibres, and these in turn can be used as references or 'transfer standards' to calibrate further instruments, and so on.

6.2 Uncertainty of measurement

There is always some uncertainty associated with any measurement result. This uncertainty indicates the range of values about the actual result of a measurement that could also reasonably be attributed to the measurand. For calibration purposes measurement uncertainty is normally quoted as a range that is expected to encompass approximately 95% of the values that could reasonably be attributed to the measurand. Therefore if the uncertainty of a measurement has been correctly assessed, there is a 1 in 20 chance that the value of the measurand actually lies outside this range.

The terms ‘uncertainty’ and ‘error’ are sometimes incorrectly used interchangeably, leading to some confusion. The error of a measurement is simply the deviation of the result from the value which would be obtained using a theoretically perfect measuring system in conformance with stated defining conditions.

In the following sections sources of uncertainty are explained and discussed qualitatively. More rigorous definitions and discussions can be found in the ISO *Guide to the expression of uncertainty in measurement* [5] which gives a particularly clear discussion of the basic concepts, and the UKAS document M3003 [3].

6.2.1 General Principles

No measurement or test is perfect and the imperfections give rise to error in the result of a measurement. Consequently, the result of a measurement is only an approximation to the value of the measurand as specified by defining conditions which may themselves be incomplete or subject to uncertainty. A result is only complete when accompanied by a statement of the uncertainty arising from that approximation.

Uncertainty of measurement comprises, in general, many components. Some components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterised by experimental standard deviations. These are called ‘type A’ or random uncertainties. The size of this component may be reduced by increasing the number of observations and applying statistical analysis. The other components are evaluated from assumed probability distributions based on experience or separate experimental investigations and cannot be reduced by making more observations. These are called ‘type B’ or systematic uncertainties.

The total uncertainty of a measurement is a combination of a number of uncertainties arising from different causes. Even a single instrument reading may be influenced by several factors. Careful consideration of each measurement involved in the calibration or test is required to identify and list all the factors that contribute to the overall uncertainty. This is a very important step and requires a good understanding of the measuring equipment, the principles and practice of the calibration or test and the influence of environment.

6.2.2 Sources of uncertainty

As there are many possible sources of uncertainty and as these will depend on the technical discipline involved, it is not possible to give detailed guidance here, but the following general points will apply to many areas of calibration and testing. The more

important ones from the point of view of OTDR calibration are given in the OTDR calibration section.

- 1) Incomplete definition of the quantity being measured - the requirement may not be clearly described, e.g. the temperature of a test may be given as 'room temperature'.
- 2) Imperfect realisation of the test procedure; even when the test conditions are clearly defined it may not be possible to produce the theoretical conditions in practice due to unavoidable imperfections in the materials or systems used.
- 3) Sampling - the sample may not be fully representative. In some disciplines, such as microbiological testing, it can be very difficult to obtain a representative sample.
- 4) Inadequate knowledge of the effects of environmental conditions on the measurement process, or imperfect measurement of environmental conditions.
- 5) Personal bias in reading analogue instruments.
- 6) Instrument resolution or discrimination threshold, or errors in graduation of a scale.
- 7) Values assigned to measurement standards (both reference and working) and reference materials.
- 8) Changes in the characteristics or performance of a measuring instrument since the last calibration.
- 9) Values of constants and other parameters used in data evaluation.
- 10) Approximations and assumptions incorporated in the measurement method and procedure.
- 11) Variations in repeated observations made under similar but not identical conditions - such random effects may be caused by, for example: electrical noise in measuring instruments; short-term fluctuations in the local environment, e.g. temperature, humidity and air pressure; variability in the performance of the person carrying out the test.

In any measurement, there may also be sources of uncertainty that have been overlooked. For this reason, measurement organisations are encouraged to participate in inter-laboratory comparisons to increase confidence that the accuracy of their results is consistent with their uncertainty evaluations.

6.2.3 Statistical approach to uncertainty

'Type A' evaluations are made from a series of repeated observations, using statistical methods. For example, if n measurements of a quantity x are taken, then the mean $\bar{x}$ and estimate of the population standard deviation s are given by:

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n} \quad \text{and} \quad s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}}$$

The uncertainty associated with the mean is given by

$$s(\bar{x}) = \frac{s}{\sqrt{n}}$$

since the mean consists of n values.

Systematic or Type B uncertainties are more difficult to evaluate than random ones. This is because repeated measurements with the same measurement system will involve exactly the same systematic errors, whilst changing the measurement system may remove some errors but introduce others. Once an error has been identified it can either be eliminated (or at least reduced) by careful system design, or quantified and allowed for by calculation. In the latter case there will be an uncertainty in the size of the correction to be applied; this is one source of systematic uncertainty. In even the most carefully performed measurement, there will be some systematic errors which have either not been considered or else are too indeterminate for a satisfactory correction to be applied. These too are sources of systematic uncertainty.

The assessment of the magnitude of systematic uncertainties must be based mainly on past experience and on a knowledge of the difference between results using different techniques. This makes intercomparisons between different laboratories an important tool to identify unexpected causes of systematic errors and can lead to improved measurement practice.

By their very nature, systematic uncertainties are difficult to treat statistically. It is not possible to calculate confidence limits directly, but instead they must be estimated. There is no definite rule as to how this should be done, although various methods have been proposed.

Normally systematic errors are assessed as lying between two values. For example, stray light in a monochromator may be assessed as being no more than 5% of the measured signal, i.e. lies in the range of 0% to 5%. The best correction for this systematic error would therefore be 2.5% but would be uncertain to $\pm 2.5\%$. In this case the probability distribution of the uncertainty is best described by a top hat or uniform function. Most systematic uncertainties are of this type and are best estimated in this way.

6.2.4 Combining Type A and Type B uncertainties

The most exact way to specify uncertainties is to keep the random and systematic contributions separate. However, in most practical applications a single figure is required for the total uncertainty. To achieve this statisticians have calculated that the equivalent standard deviation of a top hat probability distribution is given by the equation:

$$u_B = \frac{\Delta x}{\sqrt{3}}$$

where Δx is the half width of the top hat distribution, 2.5% in the above example.

Having estimated an equivalent standard deviation for each systematic uncertainty, they can be combined with the random uncertainties in quadrature to calculate the total

uncertainty of the measurement. However, there is always the danger that a cause of systematic error has been overlooked and this can only be discovered by intercomparisons with other measurement techniques or the results of other independent workers.

An expanded uncertainty, U_c , is usually required to meet the needs of most applications, especially where safety is concerned. It is intended to provide a greater interval about the result of a measurement than the standard uncertainty with, consequently, a higher probability that it encompasses the actual value of the measurand. It is obtained by multiplying the combined standard uncertainty u_c by a coverage factor, k . The choice of factor is based on the level of confidence required. Taking $k = 2$ corresponds to approximately 95% of measured values being expected to lie in the stated range. Taking k to be 2.6 and 3 yields confidence levels of 99% and 99.7% respectively.

The result of the measurement is reported in the form $y \pm U$. This statement is not complete without quoting the coverage factor k used to obtain the expanded uncertainty U . An indication of the confidence level obtained should also be included. The following statement is suggested to provide completeness of the information associated with a stated measurement uncertainty:

‘The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%’.

The values for k and for the confidence level can, of course, be modified if different ones are required.

7 Calibration artefacts

Throughout this guide reference has been made to various OTDR calibration artefacts, usually fibres. These are available from a number of standards laboratories. Those available from NPL are given below. Further details of these and other services can be found at www.npl.co.uk/npl/sections/photonics/index.html

7.1 Length

Length calibration fibres with lengths from 100 m to over 100 km are available. The 95% uncertainty for these fibres is $(0.1 + 1.7 \times 10^{-5} L)$ m where L is the length of the fibre in metres. These are normally supplied with FC/PC connectors as standard although other types can be fitted if required. In addition NPL can calibrate fibre supplied by the customer. Longer or shorter fibres are available to special order. The calibration certificate will give both time of flight and length based on a group index of 1.46. Lengths are given for both 1310 and 1550 nm.

Also available is the recirculating loop calibration device described in the length calibration section 4.1. Length of the lead-in and loop fibres are tailored to the customer's individual requirements. Length accuracies are the same as those given above.

Multi-mode calibration fibres (50/125 μm and 62.5/125 μm) are also available though the uncertainty for these will be higher than those quoted above as the time of flight depends on the way the light is launched into the fibre.

7.2 Attenuation

An attenuation calibration fibre typically 4 to 10 km long and packaged to ensure attenuation stability during transport and changes in temperature to better than ± 0.03 dB is available. Total loss calibration accuracy is typically better than ± 0.03 dB. Calibration is normally carried out over the range 1200 to 1600 nm at 5 nm intervals. This fibre can be fitted with connectors and calibrated for length and attenuation coefficient uniformity if required. Both single and multimode versions are available. Fibres supplied by the customer can also be calibrated.

Fibres can also be calibrated for attenuation coefficient uniformity. Usually the attenuation coefficient for each 1 km section is quoted starting ~ 0.5 km from one end of the fibre. Attenuation coefficient accuracies are typically $\pm 0.006 \text{ dB.km}^{-1}$. Measurements are carried out at both 1310 nm and 1550 nm.

7.3 Return Loss

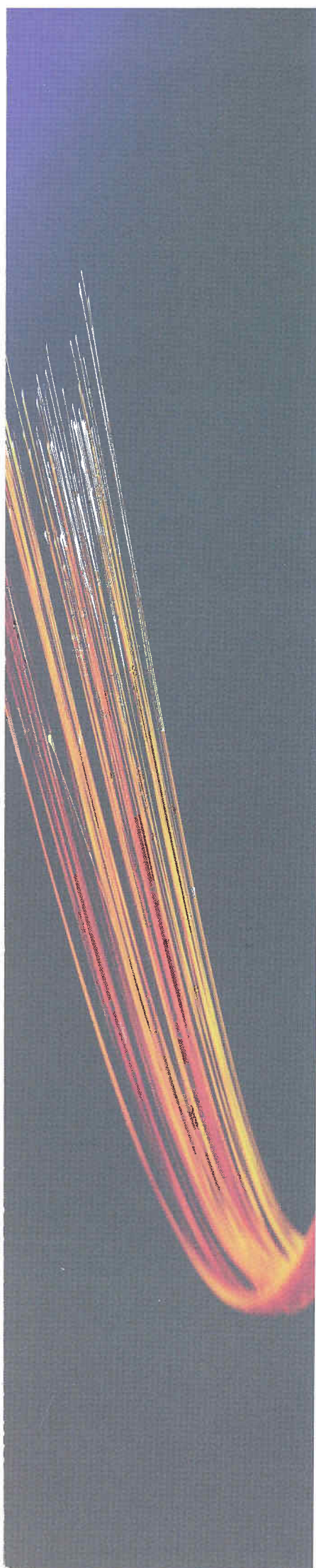
Return loss calibration artefacts can be supplied with values from 30 to 60 dB. These consist of a reflection of known value at the end of a fibre typically 1 km long. Uncertainty is ± 0.6 dB at 30 dB rising to ± 3 dB at 60 dB return loss. Values are quoted both 1310 and 1550 nm, only single-mode versions are available.

8 References

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