

**High Resolution Reflectometry
Techniques
Capabilities and Calibration
Requirements**

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Approved on behalf of Managing Director, NPL

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Summary:

The results of an investigation into the capabilities of various techniques for short-range reflectometry are reported and the requirement for traceable calibration for these techniques is reviewed.

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1. Objectives

Optical time domain reflectometry (OTDR) is a widely used technique for the characterisation of fibre networks and through the NMS, NPL currently provides a calibration service for conventional OTDRs. Conventional OTDRs however do not provide high enough spatial resolution for accurate measurement of subsystem and component reflections. Industry has identified the need for reflectometry with spatial resolution in the millimetre range for optical subsystems and possibly tens of nanometres for silicon waveguide arrays and other optical components. The purpose of this report is to assess short range reflectometry techniques, including a survey of what is commercially available, what additional techniques have been proposed, including the expected performance of all techniques and the resulting calibration requirements.

2. Short range reflectometry techniques

In this section some of the techniques suitable for short-range reflectometry will be introduced, along with their potential performance and cost. This includes some techniques currently commercially available as well as some only currently tested in research facilities.

3. Optical time domain reflectometry

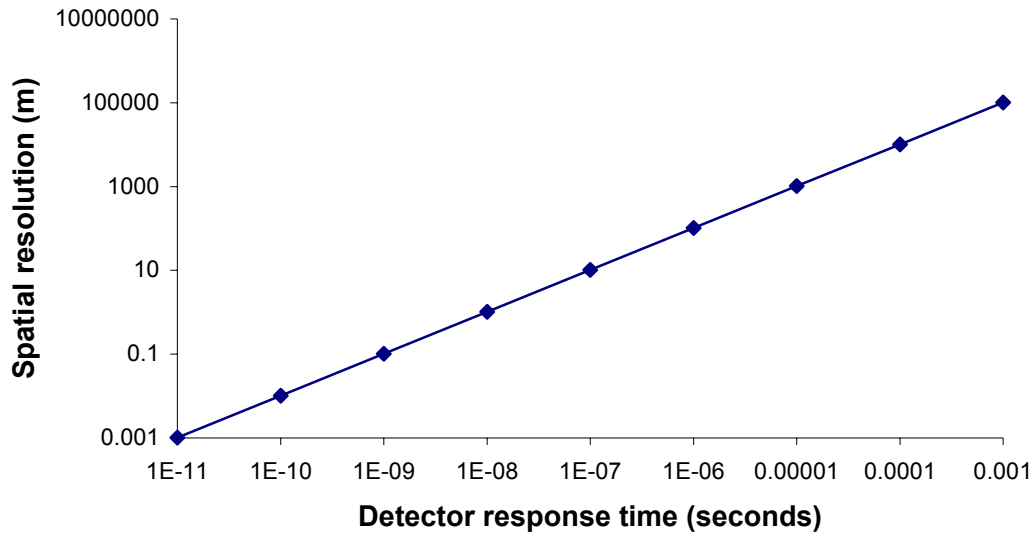
Optical time domain reflectometry (OTDR) is a standard diagnostic technique for measuring fibre optic networks; its performance however, is limited when spatial resolutions of below 1m are required. In short range reflectometry spatial resolution rather than dynamic range due to loss of power is the biggest limiting factor. OTDR is specifically limited by the temporal pulse width of the source laser, detector speed and the dispersion of the network. This relationship is shown in the equation below.

$$\Delta z_r \cong \frac{v_g}{2} \Delta t_s$$

Where Δt_s is the system response time, which is the temporal pulse width if the detector speed is fast enough, v_g is the speed at which the pulse travels along the fibre and Δz_r is the spatial resolution. If the detectors response time is not as fast as the pulse width Δt_s can be modified using the following equation

$$\Delta t_s \cong \sqrt{\tau_p^2 + \tau_r^2}$$

Where τ_p is the optical pulse width and τ_r is the response time of the receiver. Commercially available mode locked lasers can produce very short pulses in the femto second range, but receivers are only commercially available up to 50GHz, although research labs have detectors at 100GHz. For example an OTDR system with a laser producing 10 femto second pulses, and a detector with a 10 pico second response time that is testing a fibre network with a 1.47 group refractive index will yield a spatial resolution of $\sim 1\text{mm}$. Dispersion is also a limiting factor for OTDR systems although its importance in short range reflectometry is limited due to the relatively small lengths of the device under test concerned. Other problems such as isolating a pulse from a mode locked laser and the state-of-the-art laser and detector technology required for high spatial resolution vastly increase the cost of an effective high resolution short range OTDR system. Graph 1. compares photodetector speed with best possible spatial resolution



Graph 1. Best theoretical spatial resolution plotted against photodetector response time

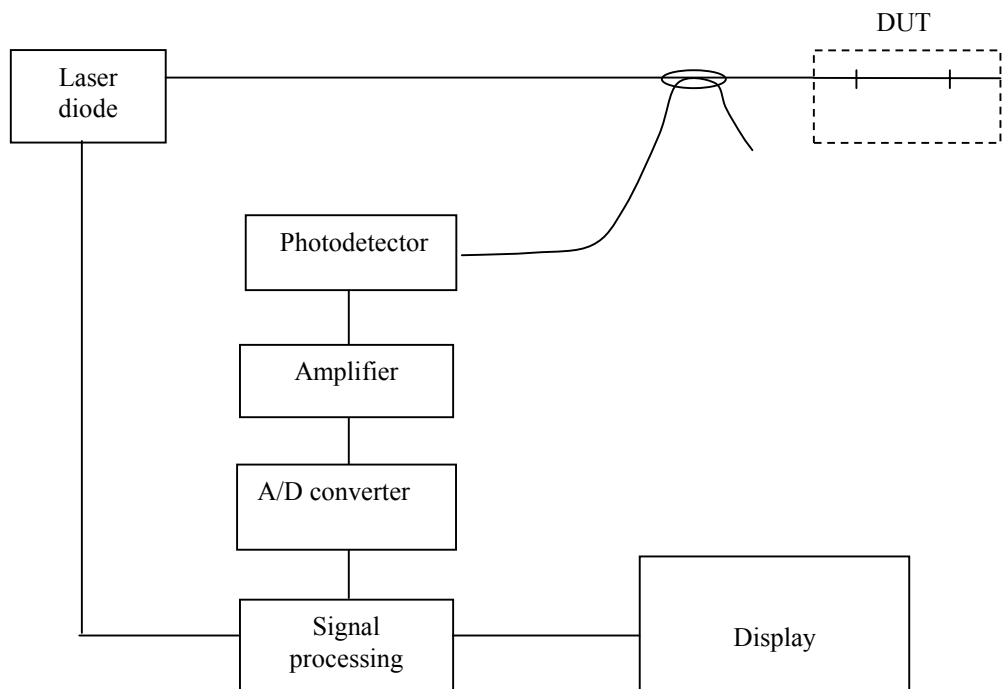


Fig. 1 conventional OTDR system

2.2 Photon counting

The resolution of conventional OTDR techniques can be significantly improved by the use of photon counting techniques employing photo multiplier tubes or avalanche photodiodes. The principle of the technique is that as a pulse is sent to the fibre under test a time counter is triggered, the counter is stopped by a photon hitting the counting receiver; a maximum of one photon is used for each pulse. The timer is used to build up a histogram that in time represents the probability distribution of the time taken for the reflected photons to reach the detector. The system diagram is shown in Fig. 2

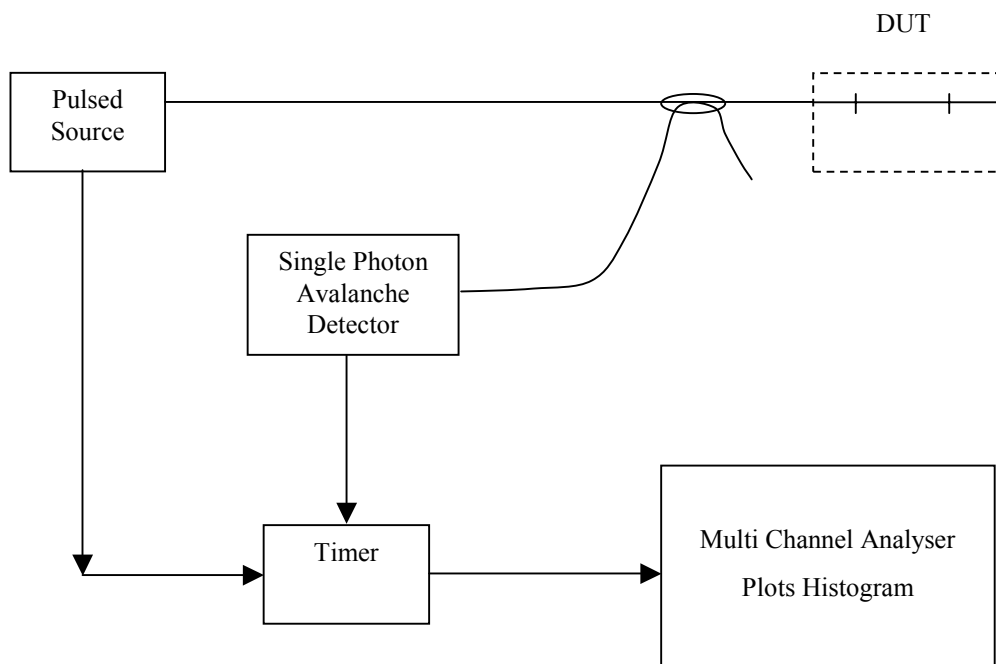


Fig. 2 Photon counting OTDR system

The use of photon counting in place of conventional high-speed photodiode OTDR reduces receiver noise and the usual trade off between spatial resolution and receiver sensitivity relevant to long distance OTDR is redundant. The noise floor is now set by the shot noise from the background dark counts and the quantum efficiency of the photon counting detector.

Luciol instruments produce a commercially available photon counting OTDR, they quote a resolution of 1 cm (which is the expected limit determined by the detector electronics), a range of between 800m and 40km for a single mode fibre and a reflection sensitivity of -110dB. It is also available at a selection of standard wavelengths¹.

4. Optical low coherence reflectometry

Optical low coherence reflectometry (OLCR) is a coherent detection scheme often referred to as white light interferometry. It uses broad spectral sources with short coherence lengths and offers very high resolution reflectometry. As a reference mirror is moved an interference fringe occurs when a reflection in the test arm matches the delay in the moving reference arm and if the DUT has multiple reflectors then multiple fringes can be seen if the reference is scanned far enough. Experimentally, two point resolutions below 2 μ m have been demonstrated² with sensitivities greater than -160dB³. The spectral width of the low coherence source governs the spatial resolution capability of the OLCR system, given by:

$$\Delta z_r \cong \frac{1}{2n_g} \frac{\lambda^2}{\Delta \lambda}$$

Where n_g is the group index of the test medium, λ is the centre wavelength, $\Delta \lambda$ is the full width half maximum (FWHM) of the low coherence source. Typical low coherence sources used are Erbium doped fibre amplifiers (EDFAs), edge emitting laser diodes (EELEDs) and tungsten lamps which have spectral widths of 20nm, 50nm and >600nm, the tungsten lamp can therefore give a resolution of better than 2 μ m. The spectral shape of the linewidth source also effects the resolution, Lorentzian, Gaussian and rectangular shaped require the right hand side of the above equation to be multiplied by 0.44, 0.88 and 1.2 respectively. The optical power is another concern, the lower the optical power available the smaller the reflection sensitivity will be. EDFAs for example can achieve greater than -160dB. EELEDs and tungsten lamps can achieve reflection sensitivities of -120dB and -60dB respectively. The

ideal source would therefore be very broadband but still have enough power to achieve very high reflectivities. As a result with the range of potential sources there therefore exists a trade off between resolution and reflection sensitivity

Commercial equipment is currently available that uses OLCR for optical component characterisation, including the Nettest “WIN-R” and the HP 8504B* precision reflectometer. The Nettest “WIN-R” uses an Erbium doped fibre amplifier as its broadband source, which allows high sensitivity down to -100dB , and a spatial resolution of $50\mu\text{m}$. It allows a scan range of 300mm . The HP model offers selectable wavelength range between 1300nm and 1550nm , a measurement range of -80dB , a resolution of $25\mu\text{m}$ and a similar scan range to the Nettest. A path extension can be added so that the scan range can be moved to various distances within the DUT.

The distance over which such instruments can acquire information has been identified as requiring improvement. Currently it is limited by the practicalities of moving a scanning mirror over a great distance. One technique that has been suggested involves the use of a fibre Fabry-Perot resonator⁴. This generates a series of delayed replicas of the coherence length of the source. The configuration is shown in Fig 3.

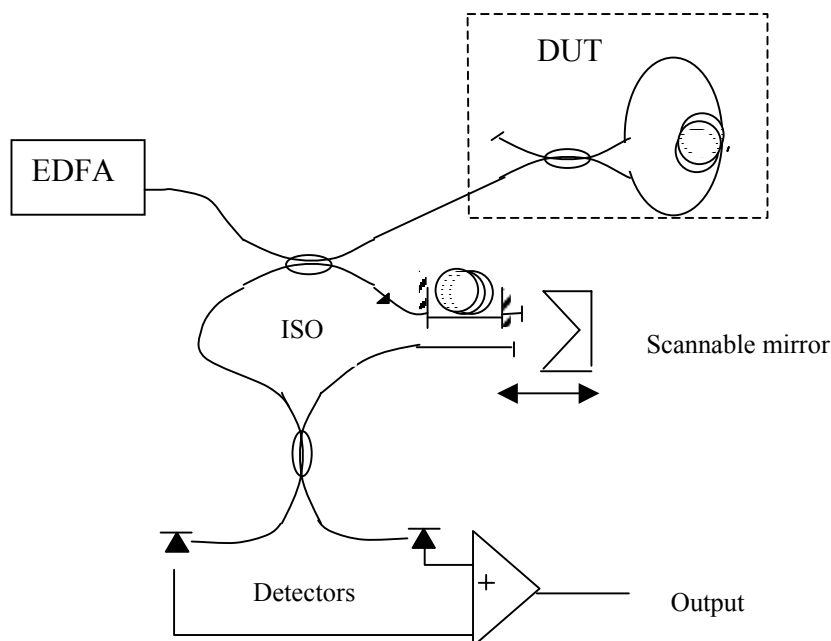


Fig. 3 Extended range OLCR

*Recently withdrawn

There is however a problem associated with the determination of which resonator order coincides with the coherent reflection. This can be overcome by taking a scan with the resonator at a fixed temperature; the reflection peak position is then recorded. Another scan is performed when the fibre cavity is set to a new temperature that changes the resonator's effective length. By using the two reflection positions and the effective length change of the cavity the resonator order of each reflection can be determined by the following equation:

$$N = \text{int} \left[\frac{X_1 - X_2}{n_g[L_2 - L_1]} - \frac{1}{2} \right]$$

Where n_g is the group index of the fibre, X_1 and X_2 are the mirror locations for the reflection peaks for the two different temperatures and int is the integer function.

5. Optical frequency domain reflectometry

Optical frequency domain reflectometry (OFDR) is another viable candidate for a high resolution reflectometry technique and has been reported to provide spatial resolutions below $100\mu\text{m}$ ⁵. The technique is well established but has not seen much commercial implementation. The principal of operation relies upon the frequency sweeping of the laser, and as such a single mode narrow linewidth source with mode hop free operation is a key element. The output from the tuneable laser is sent to a 3dB coupler, which divides light between a reference arm and a DUT. This is shown below in Fig. 4

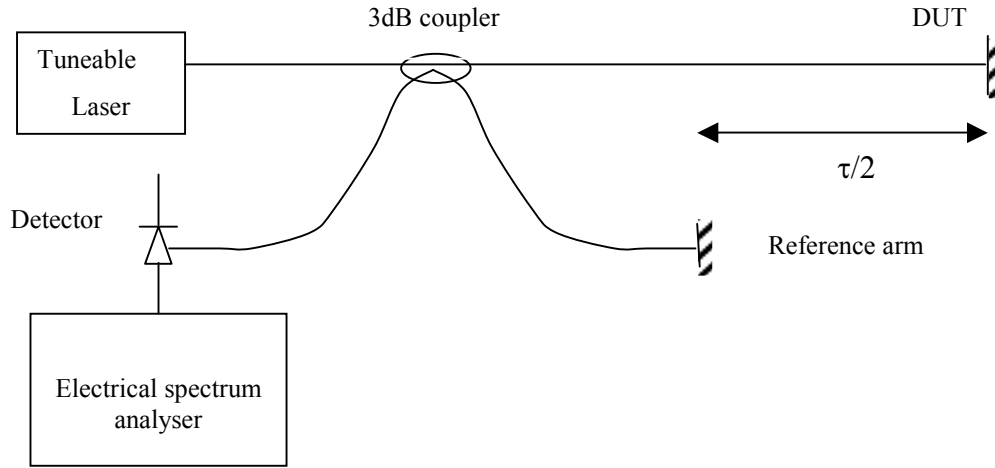


Fig. 4 Optical frequency domain reflectometry

After a Fourier transform has been performed on the detector current, beat frequencies and their corresponding amplitudes encode information on the distance and reflectivity properties of the device under test respectively. As the OFDR system is detecting a beat frequency the ideal optical source has a very narrow linewidth for high spatial resolution. The next limiting factor is the spacing between the FFT frequencies which gives a resolution limit of

$$\Delta z_r = \frac{c}{2n_g \Delta \nu_s}$$

Where $\Delta \nu_s$ is the optical frequency span. Therefore, the greater the frequency sweep the greater the resolution, an optical frequency sweep of 6 GHz will yield a resolution of 1.6cm. There cannot be limitless width to this frequency sweep as both detectors and FFT spectrum analysers have a finite range of around 100 GHz, which would limit the spatial resolution to 1mm. The speed at which the frequency is swept is also a factor as the laser must be able to

sweep in frequency as far as possible between reflections from either end of the device under test for maximum resolution. The laser must also be kept stable, as non-linearities in the frequency scan will cause the beat frequencies corresponding to reflection peaks to change. Although the theoretical resolution is given by the total optical frequency span corresponding to the measurement distance, in practice non-linearity of the frequency shift is the largest limiting factor⁶. Giving a second order term, γ , to the optical frequency sweep, the angular frequency of light can be given as:

$$\omega(t) = \omega_0 + \beta\tau + \gamma\tau^2$$

A non-linear co-efficient of $\gamma = 12.5 \times 10^3 \text{ GHzs}^{-2}$ corresponds to a deviation of ~6%, which will translate into an error in the distance accuracy of the FFT display.

Errors can also occur between multiple reflections, the beat frequencies they generate are mistaken for reflections that do not exist. The measurable range of the OFDR system is limited by phase noise, as the coherence length of the laser limits the length of the device under test that can generate a beat frequency. Typically, laser diodes have an intrinsic linewidth limited to ~300kHz, limiting the measurement range to under 500m. Use of an external cavity reduces linewidth further so that ranges up to a kilometre are possible⁷. A temperature tuned Nd:YAG can measure up to 50km due to its very narrow linewidth.

6. Comparison of techniques

The objective of this report is to identify possible techniques that would satisfy industry requirements for component characterisation in optical systems. Therefore sub cm resolution must be one of the most important considerations. Technologies identified as benefiting from traceable measurement and the availability of a calibration service for short range reflectometry include waveguide arrays, other components incorporated into integrated

optical circuits and Erbium doped fibre amplifiers. Conventional OTDR has excellent range but a resolution of metres and therefore is unlikely to be useful for these applications, although lasers which can produce pulses in the femto second range are commercially available and detectors are improving with bandwidths over 50GHz. Future generation OTDR incorporating high speed components may be considered for component characterisation, but not at present. OLCR has the highest resolution of all techniques at below 2 μ m, however this is achievable using a tungsten lamp which is low power and therefore suffers from low dynamic range. More practical is an OLCR system which incorporates an EDFA or an EELED which will reduce resolution down to 10-40 μ m but will increase potential range with the extended range technique discussed to >150m. OFDR potentially offers very high resolution. However, there are high demands made of the source, as for highest spatial performance a large sweep range is required ideally with little change in optical power across the sweep and the sweep should be as linear as possible. Photon counting OTDR has an advantage over the coherent detection techniques OLCR and OFDR in that the coherence length of the laser or scanning length of the mirror does not limit the measurement range, however spatial resolution is limited to around 1cm. This is because of the response time of the electronics determining the photon arrival times.

In conclusion OLCR, OFDR and photon counting techniques all have potential, although currently OLCR is capable of the highest resolution. A significant factor reducing the application of OLCR has been the low spatial range. Although this can be addressed with recirculating techniques, there is a trade off with sensitivity.

OFDR has great potential but is a relatively unexplored technique with high reflection sensitivity and high spatial resolution. However there are several difficulties including coherence length, linearity and speed of chirp and power variation of the source. As a beat signal is used a detector capable of high speed detection is required.

Photon counting also has high potential although difficulties exist in the control of the source to ensure that it only emits one narrow pulse on receipt of a signal from the timing electronics.

7. Calibration requirements

A calibration service for these techniques would likely encompass the construction of a test network with all parameters of measurement known, including loss, reflectivity, distance and refractive index. Thus an NMS capability would be able to calibrate specifically; reflectivity, distance and spatial resolution. An evaluation of some of the uncertainty contributions would be readily derived from knowledge gained from the current OTDR calibration system. One example would be temperature, which can effect optical source performance and change the refractive index of the test network.

There are two primary parameters of a reflectometry measurement system that require calibration, linearity of the received power and time (equivalent to distance). In addition the operating wavelength of the measurement system must be characterised as fibre and component parameters are wavelength dependant.

In the case of conventional OTDR, for timebase calibration fibres of known optical length are used. In a simple measurement, the reflection from the end of the fibre is used to provide a time (distance) reference. Alternatively the fibre can be incorporated into a recirculating loop with a coupler attached to either end of the fibre as shown in Fig. 5

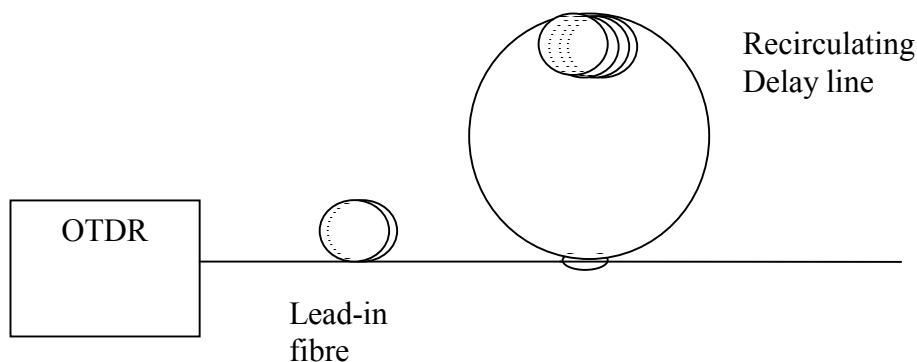


Fig. 5 Length calibration with recirculating delay

If L_a is the lead in fibre and L_b is the loop length then reflection peaks occur at

$$L_{OTDR, i} = L_{a, OTDR} + i \cdot L_{b, OTDR/2} \dots\dots$$

Where $i=0,1,2\dots$

The calibration procedure consists of measuring the position of these spikes (L_{OTDR}) and fitting these by least square to obtain estimates of $L_{b, OTDR/2}$, $L_{a, OTDR}$ and their uncertainties. The transfer standard time of flight (loop fibre) has previously been independently measured and lengths calculated using the group index, 1.46. A scale factor for the instrument can then be calculated:

$$S_L = \left[\frac{L_{b, OTDR}}{L_{b, REF}} \right]$$

The calibration results can be used in two ways: to calculate the uncertainty in the length measured by the OTDR or to correct the uncertainty in the length of a fibre. Location error, ΔL , is made up of offset and scale factor errors.

$$\Delta L = \Delta L_0 + L_{OTDR} \Delta S_L$$

The uncertainties of ΔL_0 and ΔS_L can be calculated using the following equation:

$$\sigma_{\Delta L_0} = \left[\left(\frac{\sigma_{Lb, OTDR}}{L_{b, OTDR}} \right)^2 + \left(\frac{\sigma_{Lb, ref}}{L_{b, ref}} \right)^2 \right]^{\frac{1}{2}}$$

$$\sigma_{\Delta L_0} = \left[\sigma_{L_a, OTDR}^2 + \sigma_{L_b, OTDR}^2 \right]^{\frac{1}{2}}$$

Where $\sigma_{\Delta SL}$ is the scale factor uncertainty and $\sigma_{\Delta SL}$ is the uncertainty of the distance scale offset. $L_{a, OTDR}$ is the OTDR estimate of the lead in length and $L_{b, ref}$ the calibrated loop length. Where $\sigma_{Lb, OTDR}$ represents errors with OTDR sampling, repeatability and marker positioning.

Attention must also be paid to calibration of the attenuation as well as the time domain. The OTDR can be calibrated using a “golden” component with a lead in fibre and an optical attenuator. The calibration is carried out through displayed level of backscatter and the loss standard moved through the full range of received power using the variable attenuator.

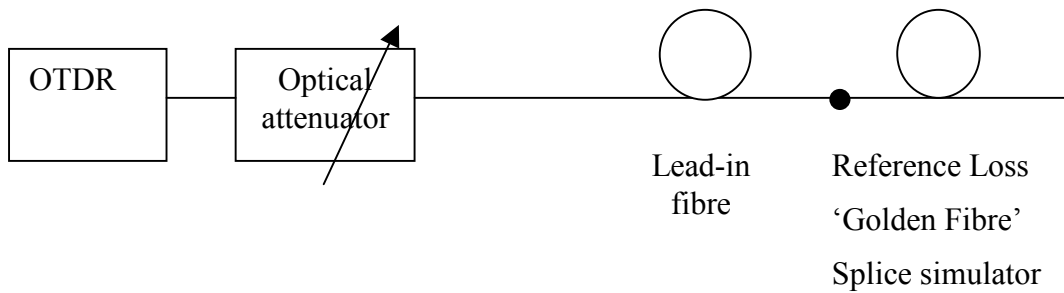


Fig.6 OTDR attenuation calibration

At power level F as measured by the OTDR the loss or attenuation coefficient of the standard is measured. The loss scale factor $S_A(F)$ is then calculated:

$$S_A(F) = \frac{A_{OTDR}}{A_{REF}}$$

The attenuation 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 $S_A(F)$ at a new value of F the process is repeated over the range of received power levels required. Having obtained the loss scale deviation $S_A(F)$ versus F it is possible to correct future measured losses to give the best estimate of true loss. For small losses where $S_A(F)$ is approximately constant over the measured loss then:

$$A_{bestest} = \frac{A_{OTDR}}{S_A(F)}$$

The uncertainty in the loss scale factor depends on the uncertainty in the reference loss and the measurement uncertainty in A_{OTDR} .

Two other factors to be taken into account when calculating uncertainties for an OTDR measurement are the wavelength of the source and polarisation. However, for short range

reflectometry wavelength dependent effects are unlikely to be significant. Polarisation effects can be eliminated using polarisation multiplexing with two optical detectors and subsequent electronic signal combination. A summary of the uncertainty contributions for loss scale and time (distance) scale calibrations can be summarised as:

Table 1. Uncertainty contributions to length scale calibration

symbol	Source of uncertainty
ΔS_L	Distance scale deviation
σ_{LS}	Length scale
σ_{Ref}	Reference loop

Table 2. Uncertainty contributions to loss scale calibration

symbol	Source of uncertainty
σ_{cb}	Reference loss calibration uncertainty
σ_{Rep}	Repeatability of measurements
σ_λ	Wavelength dependence of reference loss w.r.t temperature variation of experiment
U_L	Length
σ_T	Temperature dependence of reference loss w.r.t temperature variation of experiment

8. Conclusion

A test network for short range reflectometry should comprise a set of known reflectivities, either movable or covering a range of spatial separations, allowing measurements to be made at the maximum spatial resolution of the equipment under test. A possible candidate for a distance standard would be a long period fibre Bragg grating or an etalon, with spatial resolution measured by monitoring the reflections from either facet. A ‘golden fibre’ similar to those used for conventional OTDR calibration could provide scale loss calibration.

The measurement range of interest and capabilities of the techniques discussed in this report suggest that calibration artefacts should provide reflectivities down to -160dB and a total test device length of around 10m as this is the typical scale of fibre connected sub-assemblies, such as EDFA modules.

9. Acknowledgement

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Range and resolution of different techniques

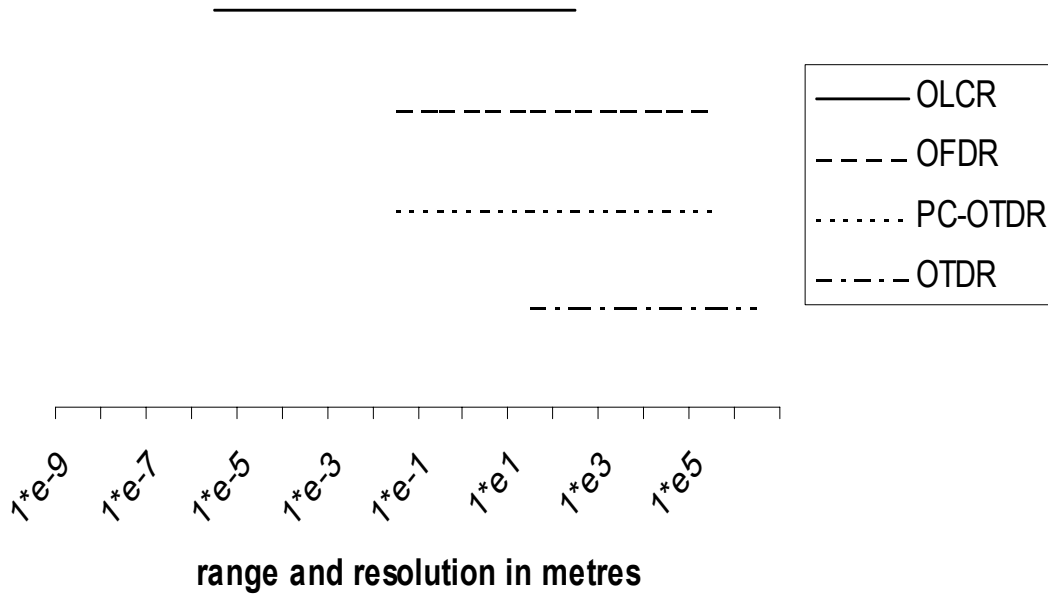


Fig. 5 Resolution and measurement range capabilities of reflectometry techniques

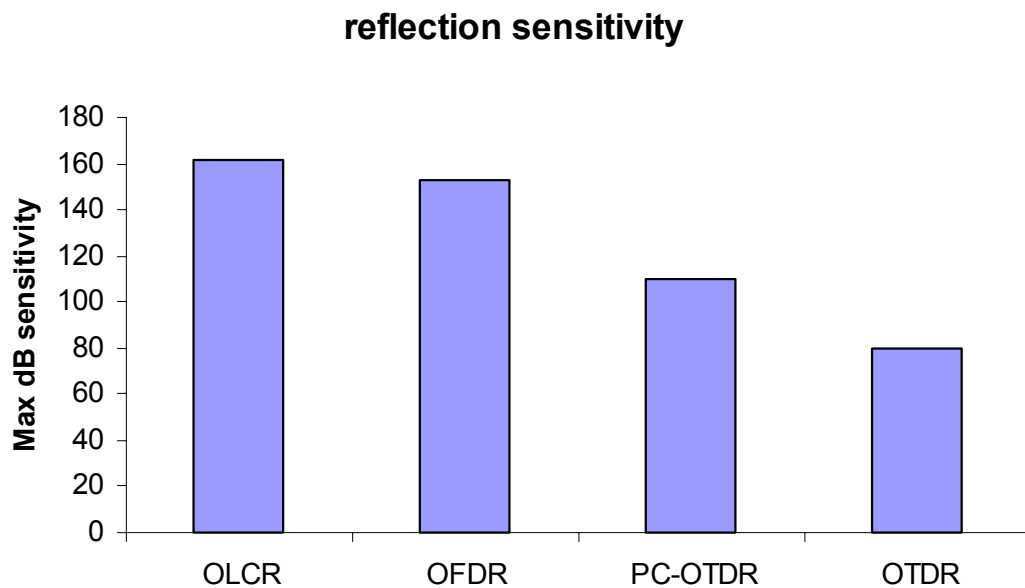


Fig. 7 Best reported reflectivity sensitivities for different reflectometry techniques

Technique	Cost	Advantages	Disadvantages
OTDR	Cost is likely to increase with high specification components required for increased spatial resolution	Already under widespread use	Spatial resolution generally not good enough for short range reflectometry applications
OLCR	Few expensive components required for OLCR system although EDFA laser if required is relatively expensive	Highest resolution so far possible	Limited range governed by translation stage although this can be addressed by the re-circulating loop but it will mean a trade off with sensitivity
Photon counting OTDR	Few expensive components required for the photon counting system	High sensitivity and resolution	Not as instantaneous as other methods in terms of speed of reading
OFDR	Demand on the performance of the laser for increased performance high speed diodes make the system relatively expensive	Possible to attain high range and resolution	Demanding on laser source in terms of frequency sweep, linewidth, linearity and photodiode

Table 3. Summary of all short range reflectometry techniques

1 Luciol instruments website, www.luciol.com

2 X. Clivaz, F. Marquis-Weible and R.P. Salathe, 'Optical low-coherence reflectometry with 1.9 μ m spatial resolution', *Electronics Letts.* 1992, Vol. 28. pp. 1553-1555.

3 K.T. Takada, M. Kitagawa, M. Shimizu and M. Horiguchi. 'High sensitivity low coherence reflectometer using erbium-doped superfluorescent fibre source and erbium doped power amplifier', 1993, *Electronics Letts.* Vol. 29. pp. 365-367.

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6 J.P. Von der Weid, R. Passy, G. Mussi and N. Gisin, 'On the characterisation of optical fiber network components with optical frequency domain reflectometry', *J. of Lightwave technology*, 1997, Vol. 15, pp. 1131-1141.

7 J.P. Von der Weid, R. Passy and N. Gisin, 'Mid-range coherent optical frequency domain reflectometry with a DFB laser diode coupled to a laser diode', *J. of Lightwave technology*, 1995, Vol. 13, pp. 954-960.