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Calibration of Optical Time Domain Reflectometers using Time Delay Generator

Abstract

Calibration of Optical Time Domain Reflectometers using time delay generator

A calibration method called "external source method" for measuring Optical Time Domain Reflectometers (OTDR) is evaluated. The work is based on one of the proposed methods in IEC/TC86/WG4/SWG2 "Calibration of optical time-domain reflectometer".

The method simulates an optical fibre in terms of length and attenuation. This is done with a set of instruments which are described and evaluated in this report. The optical pulse from the test object is delayed and attenuated with the instruments. This corresponds to a certain length with a certain attenuation of a fibre.

The OTDR is then calibrated with the set of instruments which simulate known length and attenuation. The report describes the instrument set-up and evaluates it. The proposed calibration procedure is also described. Uncertainty calculation of the instrument set-up and of a complete calibration are evaluated. A short description of the computer control system is also given where the programme language is written in visual basic.

The capability of the instrument set-up is described with the following uncertainties with the coverage factor $k=2$:

Length simulation (L in km):

For 850 nm $U_{osL} = \pm 0,11 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]}$

For 1300/1550 nm $U_{osL} = \pm 0,10 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]}$

Loss simulation (2-4 dB step):

For 850 nm $U_{osA} = \pm 0,049 \text{ [dB]}$

For 1300/1550 nm $U_{osA} = \pm 0,017 \text{ [dB]}$

Key words: OTDR, delay generator, external source, calibration, location offset, distance scale deviation, loss deviation.

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Preface

During recent years fibres in the telecommunication network have been commonly used. An Optical Time Domain Reflectometer is an all-purpose instrument used in construction, installation and documentation of telecommunication networks. As networks will become more and more complex, it is very important to be able to measure the properties as accurately as possible.

This project was carried out in collaboration with Swedish Telecom, SWEDAC (Swedish board for Technical Accreditation) and SP. Swedish Telecom have financed part of the development time. Swedac have partly financed the instrument investments.

We thank Gösta Werner, Leif Liedquist and Lars-Åke Norsten, who encouraged us during the work with the project.

Summary

The purpose of this work was to establish a calibration method to calibrate an Optical Time Domain Reflectometer. An OTDR basically measures the length and attenuation of an optical fibre. A calibration of an OTDR can be done with a fibre or a fibre-like device with known properties. To do this, its transmitted, received and displayed parameters must be analysed.

A method, the external source method is evaluated. The method is one of the methods which are proposed in IEC/TC86/WG4/SWG2, "Calibration of optical time-domain reflectometer". A set of instruments simulates an optical fibre with known properties concerning length and attenuation. The instruments which simulate an optical fibre are connected together and the capability of the set-up to calibrate OTDR is evaluated.

A calibration of an OTDR can briefly be described as follows. The instrument being tested is attached to the instrument set-up. The pulse from the instrument is detected, delayed and regenerated and is sent back to the OTDR. The calibration result of the OTDR shows the location offset, scale deviation and loss deviation of the instrument. The report shows that it is possible to calibrate an OTDR according to the described procedure.

The quality of a calibration system can be characterised by values of its uncertainty. The capability of the instrument set-up, which is implemented and presented in this report, can be described by the following uncertainties with the coverage factor $k=2$:

Length simulation (L in km):

$$\begin{aligned} \text{For 850 nm} & \quad U_{osL} = \pm 0,11 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]} \\ \text{For 1300/1550 nm} & \quad U_{osL} = \pm 0,10 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]} \end{aligned}$$

Loss simulation (2-4 dB step):

$$\begin{aligned} 850 \text{ nm} & \quad U_{osA} = \pm 0,049 \text{ [dB]} \\ 1300/1550 \text{ nm} & \quad U_{osA} = \pm 0,017 \text{ [dB]} \end{aligned}$$

The total uncertainty of an OTDR is evaluated. It is done in an example where figures from a typical OTDR are used but the random uncertainty from the calibration is neglected.

Assume the following parameters:

Read-out resolution of the length scale: 0,1 m

Sampling resolution: 0,1 m

Limited resolution of the attenuation scale: 0,01 dB

Limited resolution from one of the attenuators: 0,01 dB

This can be summed up by the following table:

Wavelength nm	$U_{\Delta L_o}$ $\pm m$	$U_{\Delta sL}$ $\pm m/km$	$U_{\Delta sA}$ $\pm dB$
850	0,30	0,0060	0,067
1300	0,30	0,0060	0,049
1550	0,30	0,0060	0,049

It is shown that it is possible to calibrate an OTDR with the standard proposed in IEC/TC86/WG4/SWG2 according to the external source method.

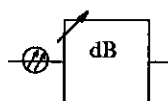
0 Terminology

The following abbreviations are used in the report:

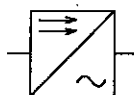
IEC / TC86	International Electrotechnical Commission / Technical Committee 86
WG4	Working Group 4
OTDR	Optical Time Domain Reflectometer
n	Group index, if nothing else is specified, the numerical value is 1,46
c	Velocity of light in vacuum. The numerical value 299792458 m/s is used
O/E	Short form for Optical to Electrical converter
E/O	Short form for Electrical to Optical converter
FC/PC	Fibre optic connector with spherical end face
APC	Fibre optic connector with an end face angle of about 8°

The following symbols are used in the report:

Variable optical attenuator



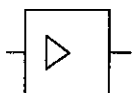
Optical to electrical converter



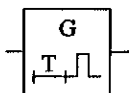
Electrical to optical converter



Electrical amplifier



Delay generator



Optical coupler



Optical connector



Optical fibre



Electrical cable



1 Introduction

Fibre optics has more and more become an established technique. It is used in different areas, for example in medicine, sensor- and telecommunication techniques. Several properties have to be measured in order to characterise a fibre optic network. The most important properties are the ability to measure the length and the attenuation of a fibre. These can be evaluated with an Optical Time Domain Reflectometer, OTDR.

An OTDR sends out an optical pulse with a certain length and amplitude. The pulse propagates in the fibre, reflects at the end and returns to the OTDR, where it is detected. In order to measure the length and attenuation of a fibre, the transition period and the amplitude of the pulse to go to and fro in the fibre is measured. With the result of these data, the corresponding length and attenuation are calculated.

However, calibration laboratories have, up to now, suffered from lack of methods to calibrate these instruments. Bigger laboratories and manufacturers of OTDRs, though, have used in-house standards to overcome the problem. These standards have often consisted of a certain fibre which has been more and more documented as the years have passed. These fibres can, however, only be treated as relative standards and not as absolute ones.

Standard methods which describe how to calibrate an OTDR are now being prepared in IEC/TC86/WG4/SWG2. We have at SP evaluated one of the methods "External source method" in the proposal. We have, using the method described in the proposed standard, showed that it is possible to calibrate an OTDR. The capability of the instrument set-up can be described with the following uncertainties, with the length L in km:

Length simulation (L in km):

For 850 nm	$U_{osL} = \pm 0,11 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]}$
For 1300/1550 nm	$U_{osL} = \pm 0,10 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]}$

Loss simulation (2-4 dB step):

For 850 nm	$U_{osA} = \pm 0,049 \text{ [dB]}$
For 1300/1550 nm	$U_{osA} = \pm 0,017 \text{ [dB]}$

2 Presentation of an OTDR

2.1 Description

The Optical Time Domain Reflectometer (OTDR) is an instrument for single-ended characterisation of optical fibre. The OTDR operates by launching pulses of light into a fibre and then detecting the backscattered light level as a function of time. The signal level is then displayed in dB and with the time base translated to fibre distance.

The backscattered light is caused by Fresnel reflections and Rayleigh scattering. Fresnel reflections are caused by discontinuities and mismatches in the index of refraction, for example in connectors and splices. This can be used for fault location and length measurements. The Rayleigh scattering is caused by small inhomogeneities in the index of refraction, and because of this such parameters as splice loss and fibre attenuation can be measured.

2.2 General specifications of an OTDR

In order to find the desired performance for a calibration set-up, research on the specifications of commercial OTDRs has been done. An OTDR design is always a compromise between dynamic range and high spatial resolution. Therefore OTDRs are often classified as long-haul or short-haul OTDRs, depending on which parameter of dynamic range and spatial resolution is optimised. A short explanation and some typical values of the most important parameters follow below.

2.2.1 Wavelength range

The most commonly used wavelengths are 850 and 1300 nm for multimode fibres, and 1300 and 1550 nm for single-mode fibres. In order to make the instrument flexible, the OTDR is often based on a mainframe which normally contains a screen, data process unit and power supply. Different plug-in units for each wavelength can be attached to the mainframe. The plug-in units contain the optical components, and some plug-in units are even able to operate at two different wavelengths.

2.2.2 Dynamic range

The dynamic range, measured in dB, is the range of signal levels the receiver can use. It is defined as the difference between the initial backscatter level and the noise floor. This data establishes how "deep" into the fibre the instrument is able to see. Therefore, with respect to the fibre attenuation, the dynamic range is the main limiting factor of the distance range for the OTDR.

In order to achieve a high dynamic range, the receiver in the OTDR uses a small bandwidth when detecting the pulses. This reduces the noise level, but a small bandwidth also reduces high frequency response and therefore reduces the spatial resolution. An OTDR in which high dynamic range is preferred is most suitable for long distance measurement and it is often called a long-haul OTDR. On the other hand, if high spatial resolution is optimised, the instrument can resolve events that are close together and then it is often called a short-haul OTDR.

The dynamic range for a long-haul OTDR is about 30 dB to 40 dB and for a short-haul OTDR about 10 dB to 20 dB

2.2.3 Averaging time

All OTDRs use averaging techniques to reduce the noise. Longer averaging time increases the dynamic range. The averaging time can normally be selected from a few seconds up to several hours. Therefore a certain dynamic range value should be specified with the required averaging time.

2.2.4 Optical output power

Most instruments are fitted with semiconductor lasers because the light source in an OTDR should be small and reliable. The optical output peak power is limited. In some OTDRs it is possible for the user to attenuate the output power directly from the front panel. The typical maximum output power varies from 0.3 mW to 1 mW.

2.2.5 Pulse length

Mostly OTDRs have a wide range of pulse lengths. The possibility for an OTDR to resolve events that are close together depends in part on how short pulses the instrument uses. This entails that the pulse should be as short as possible. On the other hand, the strength of the received back-scatter signal is proportional to the energy of the pulse from the OTDR. The energy is a product of pulse length and peak power. With limited peak power, the longer pulses are needed to perform long distance measurements. Depending on the plug-in unit, OTDRs use pulse widths from approximately 2 ns to 20 μ s.

2.2.6 Spatial resolution

The possibility of the OTDR to resolve close events is specified by its spatial resolution. Depending on the definition, there is a distinction between spatial resolution for Fresnel reflections and spatial resolution for back-scattered light. The spatial resolution is directly related to the pulse width but also depends on the bandwidth of the receiver.

The spatial resolution for back-scattered light defines the distance after a reflective event, at which point correct attenuation measurements can be made. See figure 2.1. Attenuation dead-zone is sometimes used instead of spatial resolution for back-scattered light. Typical values are 30 m to 1300 m, depending on the selected measurement range.

The spatial resolution for Fresnel reflections defines the minimum distance between two reflections that can be resolved as separate reflections. See figure 2.1. Event dead-zone and response resolution are sometimes used instead of spatial resolution for Fresnel reflections. Typical values are 3 m to 1200 m, depending on the selected measurement range.

Then the spatial resolution is specified from the front connector of the OTDR. This is often called near-end dead-zone.

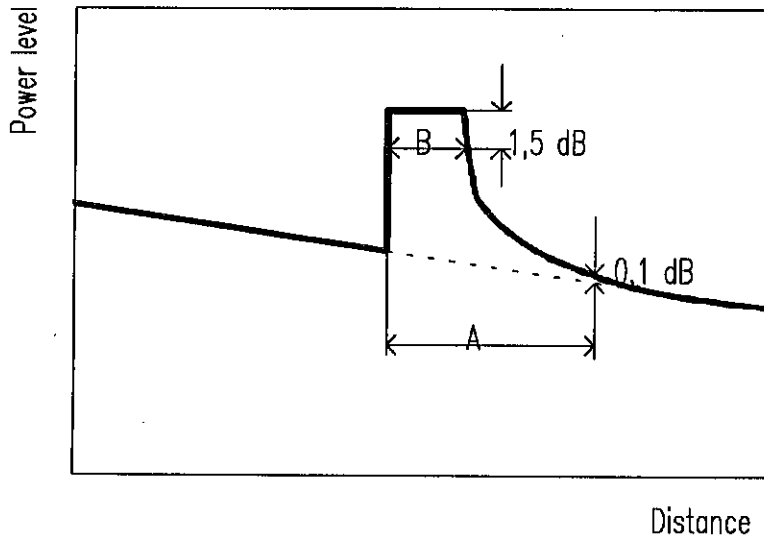


Figure 2.1: Example of a definition of spatial resolution, where A is the spatial resolution for back-scattered light and B is the spatial resolution for Fresnel reflections.

2.2.7 Sampling resolution

The sampling resolution is the distance between each measurement point. Accurate length measurements require high sampling resolution. However, a high sampling resolution must correspond to a sufficiently high spatial resolution if the measurement result is to be correct. The sampling resolution was found to be between 0,05 m and 50 m, partly depending on the selected measurement range.

2.2.8 Read-out resolution

The read-out resolution is the distance between each displayed data point. Also here, accurate length measurements require high read-out resolution. The read-out resolution must not only correspond to a sufficiently high spatial resolution but also to a sufficiently high sampling resolution. Higher read-out resolution than sampling resolution can give an incorrect resultant measurement. The read-out resolution was found to be between 0,05 m and 500 m, partly depending on the selected measurement range.

3 Principle of the measurement method

As stated in the introduction, this work is one of the proposed methods prepared by the standardisation Committee TC86/WG4/SWG2. The principle of the method is based on a simulation of an optical fibre with electrical and optical instruments. The length is simulated by a certain delay of the pulse. The corresponding attenuation is simulated with optical attenuators.

3.1 Calibration of the instrument set-up

When the method is carried out, two of the instruments must be calibrated. The time interval counter in the figure below is constantly connected to the system and measures the delay time set by the digital delay generator. The established trigger levels set on the input of the generator and the counter are measured by the oscilloscope. To generate different power levels, the two optical attenuators are used. The first attenuator is toggled between two fixed values and is calibrated using an optical power meter. The second attenuator is used to adjust the output power from the e/o converter to fit a simulated response from a fibre. The power level is set relative to the simulated length and the attenuator does not need to be calibrated.

3.2 Requirements and specifications for the instruments

The instruments are electrically and optically connected according to figure 3.1 below. The output pulse from the OTDR is detected with a fast O/E converter. The digital delay generator is then triggered by the electrical pulse from the O/E converter via an amplifier. Depending on the desired length, L_{ref} , the output pulse from the digital delay generator is delayed with the corresponding total delay time, T_{td} , according to the following equation:

$$L_{ref} = \frac{c \cdot T_{td}}{2 \cdot n}$$

The E/O converter regenerates the optical pulse back to the OTDR via two optical attenuators. With these attenuators the corresponding attenuation is simulated.

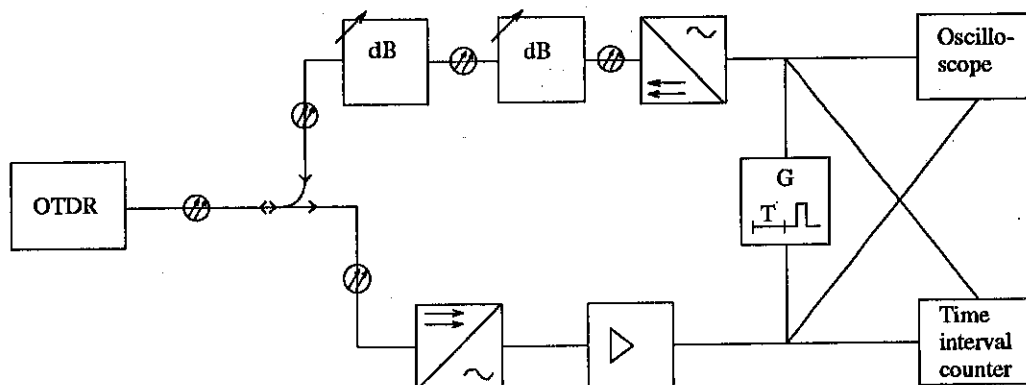


Figure 3.1. Principle of instrument set-up.

The general requirement for the performance of the calibration equipment was:

Length $\pm 0,5 \text{ m} \pm L \cdot 10^{-5} \text{ m}$
 Loss $\pm 0,01 \text{ dB/dB}$

To perform this, a certain demand was predetermined for each component in the instrument set-up.

3.2.1 O/E converter and amplifier

In order to minimise the length error, the translation times must be fast. According to the formula above, a length of 0,05 m corresponds to approximately 0,5 ns, which is a desirable rise time. The relationship between rise time and bandwidth is:

$$B \approx \frac{0,35}{t_{\text{rise-time}}}$$

Demanding a rise time of 0,5 ns gives a bandwidth of 700 MHz. The maximum back reflection is limited to -40 dB. The O/E converter which was chosen for the instrument set-up had a bandwidth of 20 GHz or a rise time of 17,5 ps. The responsivity of the detector is approximately 0,5 A/W at 1300 nm and 1550 nm. The output pulse from the OTDR is typically around 1 mW or 20 mV into 50 Ω . However, since this signal is too low to detect, an amplifier was installed with an amplification of 125, which gives a maximal amplitude of 2,5 V. The bandwidth of 300 MHz generates a limited rise-time of 1,2 ns.

3.2.2 E/O converter

The optical source of an OTDR consists in most cases of a laser. The demand on rise time of 0,1 ns gives a bandwidth of 3,5 GHz with a stability of $\pm 0,005 \text{ dB}$ and a possibility to generate a dynamic range of about 35 dB. The dynamic range from the OTDR had to be covered by the optical power from the E/O converter. In general, most standard long-distance OTDRs have an optical dynamic range of 30 dB. This can be compared with the sensitivity of the inherent detector of an OTDR with a sensitivity of 0,1 nW. This gives the required optical power level of the E/O converter of 0,1 nW $1000000 = 0,1 \text{ mW}$.

The choice of an E/O-converter for 1300 nm and 1550 nm was a commercial laser source with external digital modulation and a bandwidth of 850 MHz which corresponded to a rise time of 0,42 ns. Its stability was specified to $\pm 0,003 \text{ dB}$. However, a decision was made to implement an E/O-converter at 850 nm. This was solved for the moment with an analogue modulated E/O-converter with a lower cut-off frequency of 300 Hz and with a bandwidth better than 300 MHz.

There is however in most cases differences in wavelength between the OTDR and the E/O converter. This has been carefully measured and evaluated in the error budget.

3.2.3 Coupler

The requirements for the coupler was: a 2x1 bi-directional coupler with lower back-reflection than -40 dB. The coupler should have higher isolation than 50 dB between two of the channels. A multimode coupler with FC-connector was chosen for 850 nm, with a back-reflection less than -22 dB and an isolation between two of the channels greater than 35 dB. For 1300 nm and 1550 nm a single mode coupler with FC/PC connectors was chosen with a back-reflection less than -65 dB and having an isolation greater than 53 dB.

3.2.4 Digital Delay Generator

The required time delay range was from about 5 ns to 1 ms. The instrument should be able to create pulse duration in the interval from 2 ns up to 10 μ s with a rise time better than 0,1 ns. The pulse jitter must be less than 1/10 of 0,5 m, which corresponds to approximately 250 ps. The instrument which was chosen for the system had the following specifications. Delay and width settings: 0,005 ns to 999 s, with a rise time of 1,2 ns and a jitter lower than 100 ps.

3.2.5 Attenuator 1 and 2

One of the attenuators has to be able to attenuate through the measurement range of the OTDR. The maximum dynamic range of an OTDR is set to approximately 45 dB. This will be covered by an attenuator of 90 dB attenuation range. The purpose of the second attenuator is to toggle between two levels. The difference between the two levels must be well defined, in this case 4 dB.

For 1300 nm and 1550 nm, the first attenuator was realised with an 100 dB attenuator with -60 dB back-reflection with an accuracy of $\pm 0,15$ dB or $\pm 0,15$ dB/dB which ever was greater. The second with, an attenuation range of 60 dB, had a specified linearity of $\pm 0,05$ dB.

For 850 nm both of the attenuators were specified to: attenuation range of 60 dB and linearity of $\pm 0,05$ dB.

3.2.6 Time interval Counter

The time interval counter should be equipped with a dual input with a resolution of 0,01 ns and an accuracy of 250 ps. The input trigger levels must be able to set individually, in order to generate trigger pulses in the range of $\pm 5,00$ V with a resolution of 0,01 V and a stability of 0,001 ppm with a rise time of 1,2 ns.

3.2.7 Oscilloscope

The digital oscilloscope should be capable of measuring rise times in the order of 0,1 ns, which corresponds to 3,5 GHz. The instrument must at least be a two-channel oscilloscope with possibilities to automatically measure rise-time and amplitude. A band width of 3,5 GHz is quite a demanding requirement. A four channel 1 GHz sampling oscilloscope with a bandwidth of 500 MHz was chosen to measure the pulse shapes from the instruments.

3.2.8 OTDR

To be able to develop and control both the instrument settings and the calibration routines, an OTDR was needed. Obviously, the instrument must be an all-purpose instrument to be suitable for different kinds of measurements. The choice for the job was an MW9040B from Anritsu, equipped with the two plug-in units MW0947B (1310/1550 nm single-mode fibre) and MW0967B (850 nm multimode fibre).

The MW9040B have the following important characteristics:

- Sampling and displaying resolution down to 0,1 m (MW0947B) and 0,05 m (MW0967B)
- Dynamic range up to 44 dB (MW0947B) and 29 dB (MW0967B)
- Pulse widths from 20 ns to 10 μ s (MW0947B) and 5 ns to 2 μ s (MW0967B)
- Variable optical output power

3.2.9 Optical and electrical connection

The electrical connection consists of a 50 Ω coax cable with a BNC-connector. Some of the instruments are equipped with SMA-connectors. These are converted to BNC. The optical fibre for 1300 and 1550 nm is a 10/125 μ m single-mode fibre with a FC/PC-connector. A graded index fibre with FC/PC-connector for 850 nm was chosen.

4 Evaluation of the equipment

The instruments were electrically and optically connected according to figure 4.1 below. The set-up was finalised at the time the instruments was specified, but some parameters had to be evaluated after the instruments were connected. Therefore, in 4.1 the problem of connecting one instrument output to several inputs is discussed and in 4.2 the principles for the trigger levels are decided.

The calibration of the length scale of an OTDR depends on the delay time the equipment is able to realise. Therefore the delay time and timing jitter in all instruments and connections must be known. The delay times are measured and calculated in 4.4.

The power scale calibration of an OTDR depends on the stability of the power level back to the OTDR. The returning optical signal is generated by an E/O converter. The spectral qualities of the signal back to the OTDR must therefore be considered. Power level stability and spectral measurements are discussed further on in 4.5, 4.6 and 4.7.

The calibration procedure involves three wavelengths. For 1300 nm and 1550 nm, different E/O converters are used and for 850 nm the optical part is changed from single-mode to multi-mode fibre. As a result of this, most of the measurements must be done for each group of wavelength.

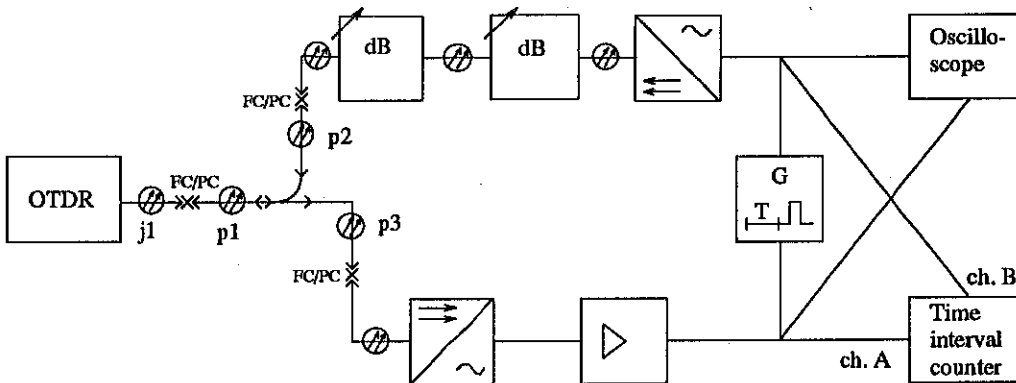


Figure 4.1. The instrument set up where j stands for jumper fibre and p for pigtail.

4.1 Matched termination

It is of great importance to have matched termination in all parts of the circuit, in the electrical part as well as the optical part. An unmatched termination can cause errors such as slow rise times or superimposed pulses.

The main problem is to connect up to three instruments to one output. This can be done in several ways. One way is to use a power-splitter according to figure 4.2. All instruments will then see a "true" 50 Ω impedance. The pulse shape recorded with the oscilloscope shows small over-shoots and reflections. The slew rate measured at the possible trigger level region is 0,25 V/ns.

Another method is to connect all instruments with standard TEE coaxial connectors as in figure 4.3. Because of the mismatch, the pulse shape with overshoots are recorded. Despite the pulse shape, this procedure gave a higher slew-rate, 0,36 V/ns. High slew-rate will reduce time error caused by noise and trigger level error. This technique was therefore used both for the amplifier output and for the generator output.

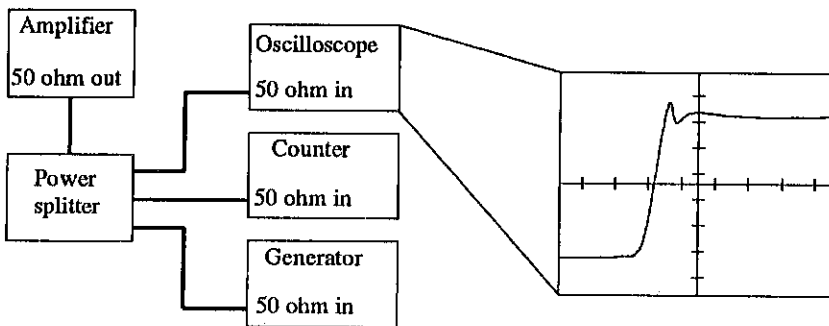


Figure 4.2. Schematic pulse shape with power splitter.

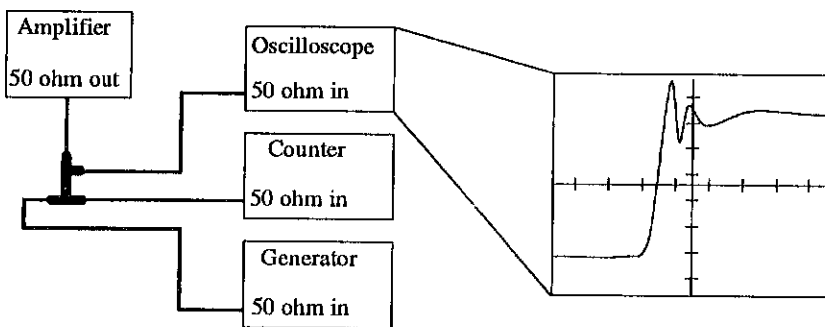


Figure 4.3. Schematic pulse shape with standard TEE connectors.

4.2 Trigger levels

Exact trigger levels are required on the input and output port of the digital delay generator. The correct position of the pulse at which time measurement should be performed is the beginning of the rising edge, according to the OTDR working principles. This is in practice impossible, because of the noise which will cause a large timing jitter. Therefore the trigger point was placed differently, in the middle of the rising edge.

The signal from the O/E converter at the amplifier output was analysed by means of the oscilloscope. The maximum amplitude on the positive edge was measured and the 50% level was defined. This level was used as trigger level both at the input of time interval counter and at the external trigger input of the delay generator.

The output pulse from the delay generator activates the E/O converter with a trigger pulse. The pulse was symmetrically adjusted to fit the trigger requirement on "EXT RF" input port of the E/O converter. The trigger level in the E/O converter is 0 V and can not be adjusted.

The following settings were used in the generator: Amplitude = 2,0 V, Offset = -0,9 V and Impedance load = 50 Ω external.

4.3 Pulse measurement principles

For the pulse measurements in 4.4.1 and 4.4.2, the following parameters were used:

- $U_{\max} - U_{\min}$ The voltage between the maximum and minimum position at the positive edge of the pulse, see figure 4.4 below.
- Rise-time The time for the pulse to rise from 10 % to 90 % of $U_{\max} - U_{\min}$.
- Trigger level The level at the midpoint of $U_{\max} - U_{\min}$, according to 4.2.
- Slew-rate The voltage/time ratio at the trigger level.

To obtain a smooth curve for measuring the pulse parameters, the trace at the oscilloscope was averaged 100 times before the read-out.

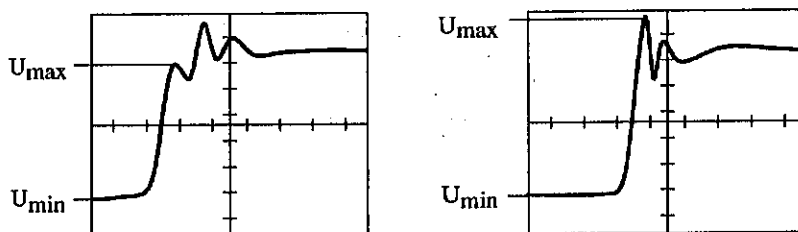


Fig 4.4. Example on pulse shapes.

4.4 Measurement of delay times in the circuit

The length simulation was based on a certain total delay time, T_{td} , of the OTDR pulse, according to chapter 3.1. Therefore it is important to know every time-delay that can occur in the instrument set-up, when the pulse propagates from the OTDR, through the instruments and back to the OTDR. See figure 4.1. The delay generator is programmed to a desired time-delay but every instrument, fibre and cable represents a certain time delay that must be measured. In order to do this, the total delay time T_{td} is divided into the following parts:

$$T_{td} = T_{vd} + T_{loop} + 2 \cdot T_{jf} + T_{p2-p1} + T_{diff}$$

where:

- T_{vd} The variable delay time which is programmed in the delay generator. This time also includes the fixed internal delay time in the generator, from the detection of the trigger pulse to the start of the delay sequence.
- T_{loop} The delay time in the instrument loop. This time includes all instruments and fibres except the generator, the jumper fibre from the OTDR to the coupler and one way through the coupler.
- T_{jf} The one-way delay time in the jumper fibre.
- T_{p2-p1} The delay time from pigtail p2 to p1 in the coupler.
- T_{diff} A time difference that can appear if there is a difference in pulse shape between the OTDR output pulse and the E/O converter output pulse. The method for reaching this time is given in chapter 4.4.3.

The variable delay time is measured when each OTDR calibration point is made. The time difference due to difference in pulse shape must be measured for each OTDR before a calibration is initiated. The other delay times, T_{loop} , T_{jf} and T_{p2-p1} , is not OTDR dependent, but of course they must be measured at certain intervals. Since the measuring procedure is rather simple, it is recommended that also these times before each calibration has to be measured.

In chapter 4.4.1 to 4.4.3 the delay times above are measured and a summary follows in chapter 4.4.4.

4.4.1 Measured delay times in jumper fibre and coupler

The instrument was connected according to figure 4.5. First, the time T_0 for the pulse to propagate from the generator via the E/O-converter, 2 pieces of jumper fibre and O/E-converter to the amplifier was measured. Second, the fibre alternative the coupler was inserted between the two jumper fibres. The delay times T_{jf} and T_{p2-p1} were then calculated as the difference between the two measurements. See table 4.1. The delay times can then be calculated as:

For 850 nm $T_{jf} = 15,30$ ns and $T_{p2-p1} = 15,78$ ns
 For 1300 nm $T_{jf} = 15,35$ ns and $T_{p2-p1} = 37,68$ ns
 For 1550 nm $T_{jf} = 15,38$ ns and $T_{p2-p1} = 37,88$ ns

The time delay is measured from channel A to channel B at the counter, and the counter values are based on 1000 measurements. The measured jitter is the standard deviation. The delay generator is set in the internal trigger mode with the frequency 2 kHz. Other instrument settings are in accordance with chapter 4.2.

Measurement:	Pulse parameters for the stop pulse (B):					Counter values:	
	Wave length (nm)	$U_{max} - U_{min}$ (mV)	Rise-time (ns)	Trigger level (mV)	Slew rate (V/ns)	Time A→B (ns)	Jitter (ns)
1. T_0	850	400 - 125	3,5	270	0,09	90,53	0,04
2. $T_0 + T_{jf}$	850	400 - 125	3,5	260	0,09	105,83	0,04
3. $T_0 + T_{p2-p1}$	850	190 - 50	2,7	120	0,05	106,31	0,05
4. T_0	1300	836 - 302	2,0	570	0,24	59,15	0,04
5. $T_0 + T_{jf}$	1300	790 - 240	2,0	520	0,24	74,50	0,04
6. $T_0 + T_{p2-p1}$	1300	590 - 114	1,8	350	0,25	96,84	0,05
7. T_0	1550	870 - 340	2,2	600	0,28	59,15	0,04
8. $T_0 + T_{jf}$	1550	820 - 270	2,0	540	0,30	74,53	0,04
9. $T_0 + T_{p2-p1}$	1550	575 - 100	1,8	340	0,25	97,03	0,05

Table 4.1. Delay times in fibre and coupler at different wavelengths.

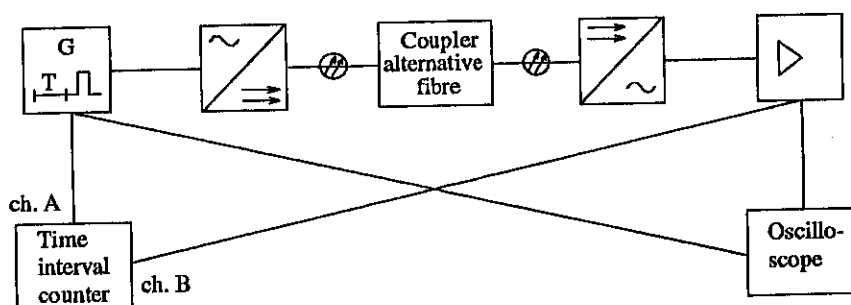


Figure 4.5. Instrument set-up for measuring delay times in jumper fibre and coupler.

4.4.2 Measured delay time in the loop

First the output pulse from the generator is connected to both channels of the counter so the internal error in the counter can be compensated for. The instrument is then connected according to figure 4.6. The time T_{loop} is then measured for a pulse to propagate from the generator output, through the loop and back to the generator trigger input. See table 4.2.

It is important that the coaxial cable from the amplifier output to the generator trigger input relative to the counter stop trigger input are of equal length. It is also important that the coaxial cable from the generator output to the E/O input relative to the counter start trigger input are of equal length. Remember that 1 metre of a coaxial cable is equal to approximately 5 ns. The time delay T_{loop} is measured from channel A to channel B at the counter, and the counter values are based on 1000 measurements. The measured jitter is the standard deviation. The delay generator is set to the internal trigger mode with the frequency 2 kHz. Attenuator 1 is set to "MIN/LOSS" and attenuator 2 is set to 0 dB. Other instrument settings are in accordance with chapter 4.2.

Pulse	Pulse characteristics for counter trigger pulse:					Counter values:	
	Wave length (nm)	$U_{max} - U_{min}$ (mV)	Rise-time (ns)	Trigger level (mV)	Slew rate (V/ns)	Time A to B (ns)	Jitter (ns)
1. Start pulse (A)	850	580 - -580	2,0	0	0,40	142,15	0,10
2. Stop pulse (B)	850	470 - 130	3,0	290	0,11		
3. Start pulse (A)	1300	540 - -312	1,6	0 (*)	0,36	121,65	0,15
4. Stop pulse (B)	1300	205 - 23	1,8	110	0,09		
5. Start pulse (A)	1550	540 - -312	1,6	0 (*)	0,36	121,71	0,12
6. Stop pulse (B)	1550	225 - 18	1,9	120	0,11		

(*): Fixed value in the E/O converter

Table 4.2. Delay time in the instrument loop at different wavelengths.

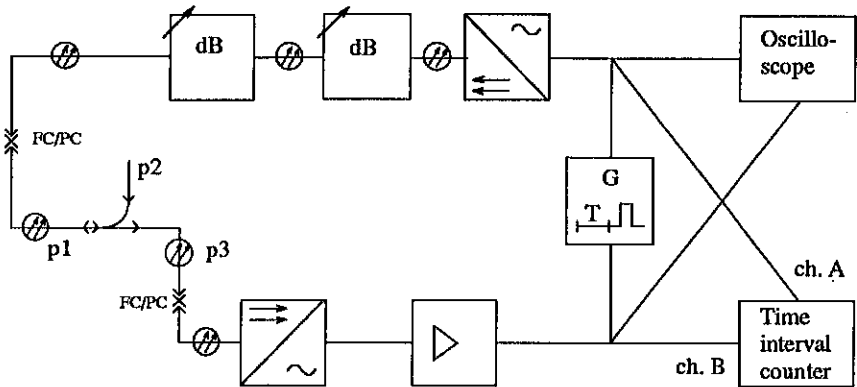


Figure 4.6. Instrument set-up for measuring the delay time in the loop.

4.4.3 Discrepancy in pulse shape between E/O converter and OTDR

As a result of the chosen trigger levels according to chapter 4.2, a time error can occur which must be quantified. To find out the total simulated delay time, the summation according to 4.4 is done. All times except T_{vd} are measured before the calibration procedure. The time T_{vd} is measured during the calibration procedure. An effect of this is that for the time T_{vd} , the start pulse is the OTDR pulse detected by the o/e converter and the stop pulse is the generator output pulse. For the time T_{loop} the start pulse is the generator output pulse and the stop pulse is the e/o converter output pulse detected by the o/e converter.

This means that the stop point of the time T_{vd} must be located at exactly the same time position as the start point of the time T_{loop} . This is true because both pulses come from the same source and the pulse parameters have not been changed. Therefore, the trigger level is the same, and the time position must then also be the same.

This also means that the stop point for the time T_{loop} and the start point for the time T_{vd} must be located at exactly the same time position. As mentioned above, the respective start and stop pulses differ, so a time difference will probably occur. It is possible that the trigger point of the pulse from the E/O-converter arrives before the trigger point of the OTDR pulse which will create a positive T_{diff} . See figure 4.7 for a typical pulse situation after the O/E-converter.

This time difference T_{diff} depends on the shapes of the two pulses. The time T_{diff} can be either positive or negative. It must be measured for each OTDR before calibration, to ensure that the total delay time is correct. The measurements below are done with an oscilloscope, and for the MW9040, the measured times are:

At 850 nm	$T_{diff} = 0,3 \text{ ns}$
At 1300 nm	$T_{diff} = 2,0 \text{ ns}$
At 1550 nm	$T_{diff} = 1,8 \text{ ns}$

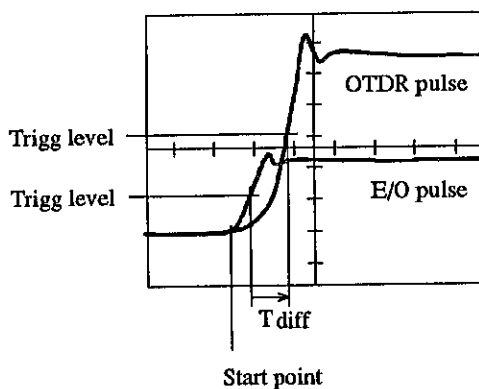


Figure 4.7. Example of a positive time difference due to different pulse shapes.

4.4.4 Summary of the delay times

Using the results in 4.4.1 to 4.4.3, the total delay time according to the formula in 4.4 can be calculated. This gives the following times for the different wavelengths:

$$\text{At 850 nm} \quad T_{td} = T_{vd} + 142,15 + 15,78 + 2 \cdot 15,30 + 0,3 \text{ [ns]} = T_{vd} + 188,8 \text{ [ns]}$$

$$\text{At 1300 nm} \quad T_{td} = T_{vd} + 121,65 + 37,68 + 2 \cdot 15,35 + 2,0 \text{ [ns]} = T_{vd} + 192,0 \text{ [ns]}$$

$$\text{At 1550 nm} \quad T_{td} = T_{vd} + 121,71 + 37,88 + 2 \cdot 15,38 + 1,8 \text{ [ns]} = T_{vd} + 192,2 \text{ [ns]}$$

These times correspond to the following distances ($n=1,46$) for the different wavelengths:

$$\text{At 850 nm} \quad \text{Total simulated distance} = \text{Variable distance} + 38,77 \text{ [m]}$$

$$\text{At 1300 nm} \quad \text{Total simulated distance} = \text{Variable distance} + 39,02 \text{ [m]}$$

$$\text{At 1550 nm} \quad \text{Total simulated distance} = \text{Variable distance} + 39,09 \text{ [m]}$$

As a result of the equation above there is a shortest possible distance of about 40 m that can be simulated. For uncertainty calculations, see chapter 5.

4.5 Measurement of power level stability

When using the OTDR to measure a fibre, the instrument measures the back-reflected power level from the fibre during a certain averaging time. This gives requirement of the short term stability of the power level of the instruments and optical components in the instrument set-up.

The stability of the optical source which belongs to the instrument set-up are therefore measured. This is carried out with the equipment according to figure 4.6. The instruments have a warm-up period of 24 hours in order to stabilize in terms of the optical power.

The optical power from the sources is attenuated by means of two attenuators. One of them is toggled between two settings in order to simulate the conditions in the instrument set-up. The attenuated power is led via fibres and a coupler and recorded with a power meter HP 8152A and the detector head HP 81521B. The measuring time is 15 minutes and the instrument set-up can be described by the following figure.

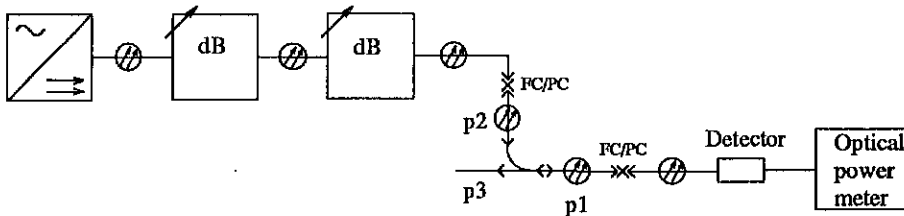


Figure 4.6. Instrument set-up for measuring the power level stability.

The power level is recorded by a computer, and the maximum deviation D_{max} during the measuring time is calculated. For each of the three wavelengths the following values are obtained:

$$\text{At 850 nm} \quad D_{max} = \pm 0,007 \text{ dB}$$

$$\text{At 1300 nm} \quad D_{max} = \pm 0,005 \text{ dB}$$

$$\text{At 1550 nm} \quad D_{max} = \pm 0,007 \text{ dB}$$

4.6 Wavelength measurements of optical sources

As a result of the measurement procedure, the E/O and E/O converters of the OTDR are not equal in wavelength to the converters of the instrument set up. This can cause errors and will add an extra uncertainty. The optical sources of OTDR and the E/O converter are measured according to the following figure.

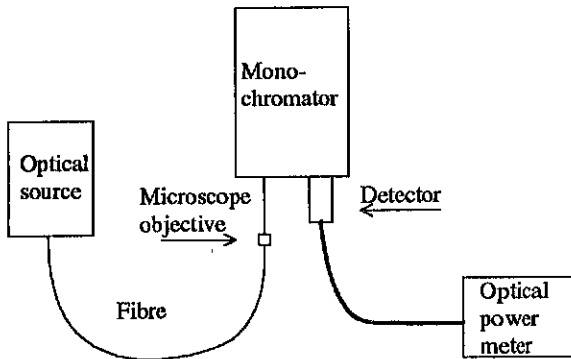


Figure 4.6. Instrument set-up for wavelength measurement.

The optical power from the source is lead into a monochromator Jobin Yvon HR1000 via a single-mode fibre and focused on a 0,1 nm wide entrance slit with a 4/0,10 micro lens. The monochromator scans the actual wavelength region, which corresponds to the optical source. The output power from the monochromator is measured by a HP 81521B/501005. The wavelength is calculated from the data according to the main central point of the area of the wavelength diagram. The results in table 4.3 show that the wavelengths of the sources are within the specified wavelength. The wavelengths of the OTDR were slightly shifted due to the current setting. Note that the power level of the OTDR is variable and set to the maximum level.

Instrument	Wavelength (nm)	Instrument Setting	Wave- length region (nm)	Step (nm)	Band- width (nm)	Calculated wavelength (nm)
MW9040B	850±15 nm	100 km, 2 µs	850-870	0,1	0,1	861,9
		10 km, 500 ns	850-870	0,1	0,1	859,4
	1310±15 nm	250 km, 10 µs	1300-1330	0,2	0,1	1317,1
		10 km, 500 ns	1300-1325	0,1	0,1	1315,3
	1550±15 nm	250 km, 10 µs	1525-1575	0,2	0,1	1549,8
		10 km, 500 ns	1525-1575	0,2	0,1	1546,5
E 500205	850	cw	845-850	0,05	0,1	847,9
E 500205	850	100 km, 2 µs	845-850	0,05	0,1	848,1
E 500205	850	10 km, 500ns	845-850	0,05	0,1	848,1
HP8155A	1300	cw	1300-1325	0,1	0,1	1310,5
HP8155A	1300	250 km, 10µs	1300-1325	0,1	0,1	1309,0
HP8155A	1300	10 km, 500 ns	1300-1325	0,1	0,1	1309,0
HP8155A	1550	cw	1530-1555	0,1	0,1	1543,3
HP8155A	1550	250 km, 10µs	1530-1555	0,1	0,1	1540,2
HP8155A	1550	10 km, 500 ns	1530-1555	0,1	0,1	1540,2

Table 4.3 Summary of measured wavelengths of OTDR and O/E converter.

4.7 Spectral responsivity measurement of the OTDR

A result of the measurements in 4.6 is that the E/O converter pulse back to the OTDR differs in wavelength from the original OTDR pulse. This may cause an error at loss calibration if the linearity of the OTDR receiver is wavelength-dependent. The linearity has therefore been measured at different wavelengths. The following measurements were however only valid for the OTDR belonging to the instrument set-up. Both the centre wavelength and the linearity wavelength dependence could differ from OTDR to OTDR. The linearity wavelength dependence will probably vary much less. With the knowledge from previous measurements on different OTDRs, possible error can be compensated for. At this moment, it is only possible to give a rough estimation of possible error.

The linearity has been measured in two different ways, which gave the linearity at two relatively close wavelengths. In the first measurement, a fibre was used to delay the OTDR pulse and the reflected pulse was then attenuated before it returned to the OTDR. This means that the returning pulse had the same wavelength as the OTDR. See figure 4.8. In the second measurement, the OTDR pulse was converted to an electrical signal and then delayed. The e/o converter then returned the pulse to the OTDR via an attenuator and the returning pulse had the same the wavelength as the E/O converter. See figure 4.9. In both cases was the attenuator switched between two exact settings to create a repeatable power step. After the two power levels P_H and P_L were noted, the linearity was calculated as:

$$\text{Linearity} = \frac{P_H - P_L - \text{Attenuator value}}{\text{Attenuator value}} \quad (\text{dB} / \text{dB})$$

The attenuator value was measured at each wavelength with an HP 81521B power meter. The OTDR was set to 180 seconds averaging, 10 dB input attenuation, 10 μs pulse-width, 250 km distance range and 2,05 m sampling resolution. The linearity was measured at different power levels from the OTDR clipping level by adjusting the second attenuator in the set-up. Each measurement was carried out three times. For the linearity at 1300 nm see table 4.4 and for 1550 nm see table 4.5.

The only difference that can be seen in the tables is at 1550 nm about 4 dB below the OTDR clipping level.

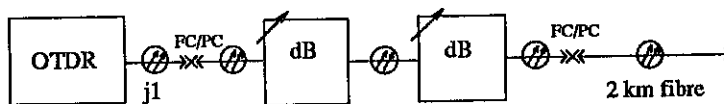


Figure 4.8. Linearity measurement with OTDR and fibre.

Pulse source and wavelength (from chapter 4.6)	OTDR level P_L (dB)	OTDR level P_H (dB)	OTDR value $P_H - P_L$ (dB)	Attenuation value (dB)	Linearity (dB/dB)
OTDR according to figure 4.8 $\lambda = 1317 \text{ nm}$	0,986	2,985	1,999	2,013	-0,007
	0,977	2,981	2,004		-0,004
	0,979	2,980	2,001		-0,006
	3,962	5,970	2,008	2,013	-0,002
	3,968	5,973	2,005		-0,004
	3,955	5,962	2,007		-0,003
	6,947	8,942	1,995	2,013	-0,009
	6,963	8,944	1,981		-0,016
	6,979	8,977	1,998		-0,007
e/o converter HP8155A accord. to figure 4.9 $\lambda = 1309 \text{ nm}$	1,057	3,048	1,991	2,000	-0,004
	1,019	3,018	1,999		0,000
	1,011	3,013	2,002		0,001
	4,065	6,063	1,998	2,000	-0,001
	4,001	5,995	1,994		-0,003
	3,986	5,984	1,998		-0,001
	7,088	9,055	1,967	2,000	-0,016
	7,095	9,023	1,928		-0,036
	6,720	8,699	1,979		-0,010

Table 4.5. Linearity of the OTDR receiver at 1300 nm.

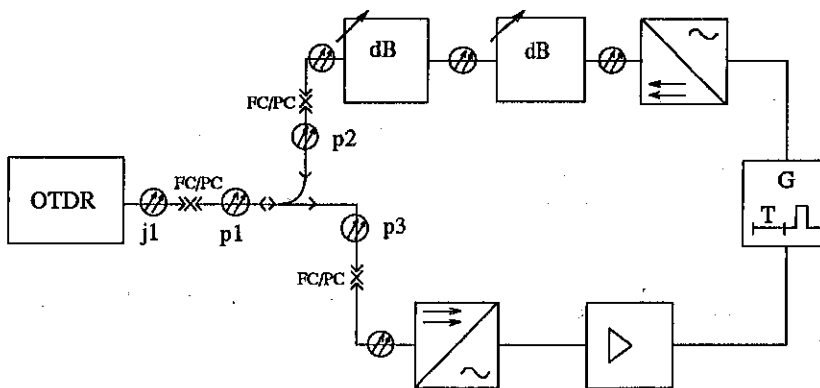


Figure 4.9. Linearity measurement with E/O converter.

Pulse source and wavelength (from chapter 4.6)	OTDR level P_L (dB)	OTDR level P_H (dB)	OTDR value $P_H - P_L$ (dB)	Attenuation value (dB)	Linearity (dB/dB)
OTDR according to figure 4.8 $\lambda = 1550$ nm	1,032	3,035	2,003	2,001	0,001
	1,041	3,038	1,997		-0,002
	1,048	3,047	1,999		-0,001
	4,055	6,047	1,992	2,001	-0,004
	4,060	6,052	1,992		-0,004
	4,067	6,062	1,995		-0,003
	6,971	8,930	1,959	2,001	-0,021
	6,974	8,941	1,967		-0,017
	6,991	8,976	1,985		-0,008
e/o converter HP8155A accord. to figure 4.9 $\lambda = 1540$ nm	1,019	3,033	2,014	2,013	0,000
	1,019	3,035	2,016		0,001
	0,970	2,986	2,012		-0,001
	3,993	5,955	1,962	2,013	-0,025
	3,994	5,950	1,956		-0,028
	4,052	6,008	1,956		-0,028
	6,984	8,961	1,977	2,013	-0,018
	6,989	8,946	1,957		-0,028
	7,033	9,007	1,974		-0,19

Table 4.6. Linearity of the OTDR receiver at 1550 nm.

5 Uncertainty calculations in the measurement system

In this chapter the overall uncertainty in the measurement system is calculated. This does not include the uncertainties of the OTDR. The overall uncertainty of an OTDR calibration is presented in chapter 6.

To evaluate the total uncertainty, the guidelines from WECC document 19-1990 is used. The evaluation of the total uncertainty is carried out by measuring the standard deviation or an estimation of it. The measured component is of type A with a standard deviation s . The estimated uncertainty u is of type B. According to the document, a rectangular distribution is assumed, where the maximum uncertainty is divided by the square root of three to obtain the estimated uncertainty.

5.1 Uncertainty in the length measurement

The different errors which affect the simulated length are listed below. The simulated length corresponds to a certain delay time and for convenience the errors are given as time errors. If nothing else is stated the given figures are valid for all three wavelengths. In 5.1.7 the overall uncertainty for the simulated length is calculated.

5.1.1 Uncertainty of counter

All time measurements are carried out with the time interval counter. The instrument uncertainty is therefore evaluated and the result can be used in the following uncertainty calculations. According to the instrument manual [1], the error in time measurement mode is given by:

$$\text{Time error} = \pm \text{resolution} \pm (\text{time-base error} \times \text{time interval}) \pm \text{trigger level error} \pm \text{offset}$$

The resolution error includes such errors as the short term stability of the oscillator and the jitter of the start and stop trigger pulse. The resolution error is reduced by the square-root of the number of measurements. The short term stability is specified to be $1 \cdot 10^{-9}$ and for all time intervals in this application the resolution error will be within 5 ps. This part can be neglected if the standard deviation of the actual measurement is incorporated in the error budget as a type A error.

The time-base error is dominated by the long term stability of the oscillator. The time-base is calibrated to $1 \cdot 10^{-8}$. With an ageing of $5 \cdot 10^{-10}/\text{day}$ and a temperature response of $5 \cdot 10^{-9}$, the time-base will be within $2 \cdot 10^{-7}$ if the calibration is performed once a year.

The trigger level error of the start and stop pulse is calculated with the formula below.

$$\text{Trigger level error} = \frac{15 \text{ [mV]} + 0,5 \% \text{ of setting}}{\text{Slew rate}}$$

Finally the offset error is specified to a maximum of 1000 ps for absolute measurements and to a maximum of 100 ps for relative measurements. The time measurements are therefore carried out as relative measurements as often as possible.

5.1.2 Uncertainty in measurement of delay time of a jumper fibre

The standard deviation of the measurement, S_{jt} , is $\pm 0,04$ ns according to 4.4.1 and is a type A error.

For the counter uncertainty the following conditions must be considered: It is a relative measurement and the time interval is about 15 ns. For 850 nm the stop pulse trigger level is about 0,25 V and the stop pulse slew rate is 0,09 V/ns. For 1300/1550 nm the stop pulse trigger level is about 0,50 V and the stop pulse slew rate is 0,24 V/ns. This gives a time error for the counter (according to 5.1.1) to measure the delay time of a jumper fibre:

$$\begin{aligned} \text{Time error} &= \pm(2 \cdot 10^{-7} \cdot 15 \text{ [ns]}) \pm(0,015 \text{ [V]} + 0,5 \% \cdot 0,25 \text{ [V]})/0,09 \text{ [V/ns]} \\ (850 \text{ nm}) &\quad \pm 0,1 \text{ [ns]} \approx \pm 0,29 \text{ [ns]} \\ \text{Time error} &= \pm(2 \cdot 10^{-7} \cdot 5 \text{ [ns]}) \pm(0,015 \text{ [V]} + 0,5 \% \cdot 0,50 \text{ [V]})/0,24 \text{ [V/ns]} \\ (1300/1550 \text{ nm}) &\quad \pm 0,1 \text{ [ns]} \approx \pm 0,18 \text{ [ns]} \end{aligned}$$

5.1.3 Uncertainty in measurement of delay time in coupler

It is in principal, the same instrument set-up to measure the time delay in the splitter as in a jumper fibre. The standard deviation of the measurement, S_{p2-p1} , is $\pm 0,04$ ns according to 4.4.1 and is a type A error.

The following conditions must be considered for the counter uncertainty: It is a relative measurement and the time interval is less than 40 ns. For 850 nm the stop pulse trigger level is about 0,12 V and the stop pulse slew rate is 0,05 V/ns. For 1300/1550 nm the stop pulse trigger level is about 0,40 V and the stop pulse slew rate is 0,25 V/ns. This gives a time error for the counter (according to 5.1.1) to measure the delay time in the coupler:

$$\begin{aligned} \text{Time error} &= \pm(2 \cdot 10^{-7} \cdot 40 \text{ [ns]}) \pm(0,015 \text{ [V]} + 0,5 \% \cdot 0,12 \text{ [V]})/0,05 \text{ [V/ns]} \\ (850 \text{ nm}) &\quad \pm 0,1 \text{ [ns]} \approx \pm 0,41 \text{ [ns]} \\ \text{Time error} &= \pm(2 \cdot 10^{-7} \cdot 40 \text{ [ns]}) \pm(0,015 \text{ [V]} + 0,5 \% \cdot 0,40 \text{ [V]})/0,25 \text{ [V/ns]} \\ (1300/1550 \text{ nm}) &\quad \pm 0,1 \text{ [ns]} \approx \pm 0,17 \text{ [ns]} \end{aligned}$$

5.1.4 Uncertainty in measurement of delay time in the loop

The standard deviation of the measurement, S_{loop} , is $\pm 0,15$ ns according to 4.4.2 and is a type A error.

For the counter uncertainty the following conditions are of importance: It is a relative measurement and the time interval is about 140 ns. For 850 nm the start pulse trigger level is 0 V, the start pulse slew rate is 0,40 V/ns, the stop pulse trigger level is 0,29 V and the stop pulse slew rate is 0,11 V/ns. For 1300/1550 nm the start pulse trigger level is 0 V, the start pulse slew rate is 0,36 V/ns, the stop pulse trigger level is 110 mV and the stop pulse slew rate is 0,09 V/ns. This gives the following time error of the counter (according to 5.1.1) to measure the delay time in the loop:

$$\begin{aligned} \text{Time error} &= \pm(2 \cdot 10^{-7} \cdot 140 \text{ [ns]}) \pm(0,015 \text{ [V]}/0,40 \text{ [V/ns]}) \\ (850 \text{ nm}) &\quad \pm(0,015 \text{ [V]} + 5 \% \cdot 0,29 \text{ [V]})/0,11 \text{ [V/ns]} \pm 0,1 \text{ [ns]} \approx \pm 0,29 \text{ [ns]} \\ \text{Time error} &= \pm(2 \cdot 10^{-7} \cdot 120 \text{ [ns]}) \pm(0,015 \text{ [V]}/0,36 \text{ [V/ns]}) \\ (1300/1550 \text{ nm}) &\quad \pm(0,015 \text{ [V]} + 5 \% \cdot 0,11 \text{ [V]})/0,09 \text{ [V/ns]} \pm 0,1 \text{ [ns]} \approx \pm 0,32 \text{ [ns]} \end{aligned}$$

5.1.5 Uncertainty in measurement of the variable delay time

The jitter for the OTDR used, an Anritsu MW9040B, is approximately 70 ps. The number is rounded off to 100 ps where the number is a type A error.

The uncertainty of the variable delay time depends on the simulated length. The time delay is approximately 5 ns per meter. The length-dependent error of the counter will then be:

$$\begin{aligned}\text{Length dependent error} &= \text{Time-base error} \cdot \text{Delay-time/meter} = \pm 2 \cdot 10^{-7} \times 5 \text{ [ns/m]} \\ &= \pm 0,001 \text{ [ps/m]} = \pm 1 \text{ [ps/km]}\end{aligned}$$

Measurement results from MW9040B OTDR gave the following typical start pulse parameters at the counter input : For 850 nm, amplitude 0,95 V, trigger level 0,45 V and slew rate 0,60 V/ns. For 1300/1550 nm, amplitude 1,0 V, trigger level 0,50 V and, slew rate 0,50 V/ns.

The stop pulse parameters are: For 850 nm, trigger level 0 V and slew rate 0,40 V/ns. For 1300/1550 nm, trigger level 0 V and slew rate 0,36 V/ns.

There were only small differences between the different wavelengths, thus only one error needs to be evaluated. This gives the following time error of the counter (according to 5.1.1) if the simulated length is L:

$$\begin{aligned}\text{Time error} &= \pm 0,001 \text{ [ps/m]} \cdot L \pm (0,015 \text{ [V]} + 5 \% \cdot 0,50 \text{ [V]}) / 0,50 \text{ [V/ns]} \\ &\quad \pm 0,015 \text{ [V]} / 0,36 \text{ [V/ns]} \pm 100 \text{ [ps]} \\ &\approx \pm 180 \text{ [ps]} \pm L \cdot 0,001 \text{ [ps/m]}\end{aligned}$$

The result above is rounded off to: $\pm 250 \text{ [ps]} \pm L \cdot 0,001 \text{ [ps/m]}$ and is used for all three wavelengths.

5.1.6 Discrepancy in pulse shape between E/O converter and OTDR

The error when measuring the time difference between the trigger points of the OTDR output pulse and the E/O converter output pulse depends mainly on the difficulty to decide where the pulse starts, see 4.4.3. The error is estimated to a maximum value of $\pm 500 \text{ ps}$.

5.1.7 Summary of the length measurement uncertainty

The different errors evaluated in 5.1.2 to 5.1.6 are added in table 5.1. The result shows that there is only a small difference between 850 nm and 1300/1550 nm. Therefore, the uncertainties given below are valid for all three wavelengths. The result from table 5.1 gives the overall uncertainty of the total simulated delay time, which corresponds to a single one-way fibre. The OTDR measures the fibre double-way and therefore the OTDR measures only half of the simulated length. This will also reduce the uncertainty by a factor of 2. This gives the following overall uncertainty by the coverage factor $k=2$ in simulated delay time U_{osL} corresponding to "double-way" fibre length (the length L in km):

For 850 nm	$U_{osL} = \pm 1,1 \text{ [ns]} + L \cdot 0,0012 \text{ [ns/km]}$
For 1300/1550 nm	$U_{osL} = \pm 1,0 \text{ [ns]} + L \cdot 0,0012 \text{ [ns/km]}$

This corresponds to the following uncertainty in length using $n = 1,46$ (L in km):

For 850 nm	$U_{osL} = \pm 0,11 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]}$
For 1300/1550 nm	$U_{osL} = \pm 0,10 \text{ [m]} + L \cdot 0,00012 \text{ [m/km]}$

The uncertainty is partly based on a specific OTDR. Some approximations have been made in order to make the result independent of the OTDR used, but if the output pulse of the OTDR under calibration differs from the MW9040B, this could affect the calculated uncertainty.

Table 5.1. Uncertainty calculations of measurements for length measurement of an OTDR according to the WECC document 19-1990. If nothing else is stated the given figures are valid for all three wavelengths.

Uncertainties of the total simulated delay time:			
Standard uncertainty component		standard uncer- tainty	vari- ance
Measured component of type A		s	s ²
Jitter in jumper fibre delay time, s _{if} [ns]		0,04	0,0160
Jitter in coupler delay time, s _{p2-p1} [ns]		0,04	0,0160
Jitter in loop delay time, s _{loop} [ns]		0,15	0,0225
Jitter in variable delay time, s _{vd} [ns]		0,10	0,0100
Estimated components of type B	max error	u _j	u _j ²
Length independent error			
Jumper fibre delay time, T _{jf} (850 nm)	±0,29 [ns]	0,167	0,0280
Jumper fibre delay time, T _{jf} (1300/1550 nm)	±0,18 [ns]	0,104	0,0108
Coupler delay time, T _{p2-p1} (850 nm)	±0,41 [ns]	0,237	0,0560
Coupler delay time, T _{p2-p1} (1300/1550 nm)	±0,17 [ns]	0,098	0,0096
Loop delay time, T _{loop} (850 nm)	±0,29 [ns]	0,167	0,0280
Loop delay time, T _{loop} (1300/1550 nm)	±0,32 [ns]	0,185	0,0341
Discrepancy in pulse shape between e/o converter and OTDR	±0,50 [ns]	0,289	0,0833
Variable delay time, T _{vd}	±0,25 [ns]	0,144	0,0208
Length dependent error			
	max error	u _c	u _c ²
Uncertainty of counter (L = actual length in km)	±0,001 [ns/km]·L	0,00058·L	3,3·10 ⁻⁷ ·L ²
Combined uncertainty			
		$U_{sL} = \sqrt{\sum_{i=1}^n s_i^2 + \sum_{i=1}^n u_i^2} + \sqrt{\sum_{i=1}^n u_c^2}$	
	For 850 nm	U _{sL} ≈ 0,53 [ns] + L·0,0006 [ns/km]	
	For 1300/1550 nm	U _{sL} ≈ 0,47 [ns] + L·0,0006 [ns/km]	
Overall uncertainty with k=2:			
		U _{osL} = ±k · U _{sL} = ±2 · U _{sL}	
	For 850 nm	U _{osL} = ±1,1 [ns] + L·0,0012 [ns/km]	
	For 1300/1550 nm	U _{osL} = ±1,0 [ns] + L·0,0012 [ns/km]	

5.2 Uncertainty in loss measurement

The different errors which affect the loss measurement are listed below. The uncertainty is based on a simulated attenuation step of about 2-4 dB. This step is obtained by toggling the HP attenuator between two fixed values. The overall uncertainty is calculated in 5.2.6.

5.2.1 Calibration uncertainty of attenuator

The difference between the high and the low level attenuation is measured with an optical power meter. Measurements have been confirmed that the linearity of the power meter is better than $\pm 0,1\%$. This gives a corresponding uncertainty of $\pm 0,005$ dB.

5.2.2 Repeatability of attenuator

The repeatability of the attenuator is evaluated by switching the attenuation between two defined settings. The measurement is repeated five times and the standard deviation is used in the uncertainty calculation. The measured value of the standard deviation at 850 is $\pm 0,0031$ dB and $\pm 0,005$ dB for 1300 and 1550 nm.

5.2.3 Spectral shifts between OTDR and E/O converter

The difference between the centre wavelength of the OTDR and the E/O converter can result in an error, if the linearity of the OTDR is wavelength-dependent. Measurements have been done in 4.7 in order to evaluate this. The measurement results show no significant differences. The uncertainty is therefore estimated to $\pm 0,01$ dB.

5.2.4 Power level stability of the system

It is important that the power level of the E/O converter, attenuators and optical components are stable during the two different settings of the attenuator. The short-term stability over 15 minutes which is measured in 4.5, gives a maximum error of $\pm 0,035$ dB for 850 nm and $\pm 0,007$ dB for 1300 and 1550 nm.

5.2.6 Summary of loss measurement uncertainty

The different errors evaluated in 5.2.1 to 5.2.5 are added in table 5.2. The result is the overall uncertainty with the coverage factor of $k=2$ of the simulated attenuation step.

850 nm	$U_{osA} = \pm 0,049$ [dB]
1300/1550 nm	$U_{osA} = \pm 0,017$ [dB]

This uncertainty does not include the resolution error of the OTDR. See 6.3.3 for further discussions.

Table 5.2 Uncertainty calculations of measurements for attenuation measurement of an OTDR according to WECC document 19-1990. If nothing else is stated, the given figures are valid for all three wavelengths.

Uncertainties of the total simulated attenuation:			
Standard uncertainty component		standard uncer- tainty	vari- ance
Measured component of type A		s	s ²
Repeatability of attenuator 850 nm		0,031	534·10 ⁻⁶
Repeatability of attenuator 1300 and 1550 nm		0,005	120·10 ⁻⁷
Power level stability 850 nm	±0,035 dB	0,020	163·10 ⁻⁷
Power level stability 1300 and 1550 nm	±0,007 dB	0,004	163·10 ⁻⁷
Estimated components of type B		u _j	u _j ²
Calibration uncertainty of attenuator	±0,005 dB	0,0029	84·10 ⁻⁷
Spectral shifts between OTDR- and E/O converter	±0,01 dB	0,0058	333·10 ⁻⁷
Combined uncertainty	$U_{sA} = \sqrt{\sum_{i=1}^n s_i^2 + \sum_{i=1}^n u_i^2}$		
Overall uncertainty with k=2 : $U_{osA} = \pm k \cdot U_{sA}$			
850 nm	$U_{osA} = \pm 2 \cdot 0,024 = \pm 0,049$ [dB]		
1300/1550 nm	$U_{osA} = \pm 2 \cdot 0,0081 = \pm 0,017$ [dB]		

6 Measurement method for calibrating OTDR

The equipment accurately calibrates the length and loss scale. The set-up requires a calibrated time interval counter and one of the attenuators. The measurement system can easily be automated which gives high efficiency at low cost.

In order to calibrate an OTDR a set of definitions, location offset, distance scale deviation and loss deviation have to be defined. These quantities are shown in the following figures and are presented below:

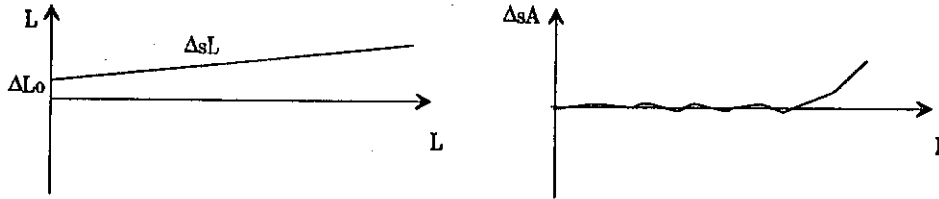


Figure 6.1 Description of location offset ΔL_0 , distance scale deviation Δs_L and loss deviation Δs_A .

6.1 Measurement conditions

The following parameters of the OTDR must be defined before performing a calibration: Distance range, nominal pulse width, nominal wavelength, input attenuation averaging time, use of masking, selection of refractive index, n . In this document n is equal to 1,46.

6.2 Distance measurement

The distance scale is calibrated by delaying the optical pulse from the OTDR of a known length. The pulse from the instrument is detected by the O/E converter and put a trigger pulse on the digital delay generator. The output pulse from the generator trig the E/O converter where its optical pulse is regenerate and is returned via the attenuators and the coupler, see figure 3.1.

The purpose of the distance measurement is to determine the location error ΔL between the measured and the true value of the OTDR. This error can be expressed as:

$$\Delta L = \Delta L_0 \pm U_{\Delta L_0} + L \cdot (\Delta s_L \pm U_{\Delta s_L})$$

where:

ΔL	=	Location error
ΔL_0	=	Location offset, the error in length at $L=0$ meter
$U_{\Delta L_0}$	=	Length independent uncertainty of the true length
Δs_L	=	Distance scale deviation
$U_{\Delta s_L}$	=	Length dependent uncertainty of the true length

6.2.1 Measurement procedure

With the known delay time T , the corresponding length is determined. Measured and true lengths are compared, and the uncertainty is calculated. Measurement points are measured through the actual measurement range. Then the location error is plotted against the true length, and the slope and the intersection with the y-axes are decided where linear regression and least-square fitness is used. The slope and the intersection with the y-axes correspond to "distance scale deviation" and "location offset" respectively.

The calculated reference length is (where T_d is determined in 4.4):

$$L_{\text{ref}} = \frac{c \cdot T_{\text{dt}}}{2 \cdot n}$$

If applicable, the measurement points are chosen in clusters. The reason for this is to avoid a certain impact from the read-out and sampling resolution. This procedure is according to the procedure in [2]. The set of times (index i) in each cluster has the form:

$$T_i, T_i + t_{\text{saml}} / n, T_i + 2t_{\text{saml}} / n, \dots, T_i + (n-1)t_{\text{saml}} / n$$

The value of n is at least 4 and is the same in every cluster. The number of clusters can be as small as 2. The centre of every cluster is uniformly spaced from the dead zone to the maximum of the distance range over which the instrument is to be calibrated. An alternative method is to randomly spread out the measurement points over the measurement range. To each measurement point a random time interval is added.

6.2.2 Measurement result

The reference length is calculated according to the formula above in 6.2.1. The location offset in every measurement point is calculated according to:

$$\Delta L_i = L_{\text{otdr},i} - L_{\text{ref},i}$$

The location offset ΔL_0 and distance scale deviation Δs_L are chosen to minimise the following equation according to the least square criteria:

$$\Sigma (\Delta L_i - \Delta s_L L_{\text{ref},i} - \Delta L_0)^2$$

6.2.3 Measurement uncertainty

The measurement uncertainty is both from the measurement set-up and from the OTDR itself. The same philosophy is used as in chapter five, where the method is based on a root-sum-square from the estimated and measured standard deviation $u(x_i)$.

6.2.3.1 Length independent uncertainty

The uncertainty which contributes to the length-independent uncertainty consists of:

- u_{Lotdr} = the random uncertainty from the measurement samples of the test object
- u_r = read-out resolution of the OTDR
- u_s = sampling resolution of the OTDR
- u_{eq} = length independent uncertainty which comes from $T_{\text{td}}-T_{\text{vd}}$, see 4.4.

This gives the following equation:

$$u_{\Delta L_o} = \sqrt{(u_{\text{Lotdr}})^2 + (u_r)^2 + (u_s)^2 + (u_{\text{ea}})^2}$$

The overall uncertainty with the coverage factor = 2 is calculated according to:

$$U_{\Delta L_o} = 2 \cdot u_{\Delta L_o}$$

The result above can be summarised in the following table. To exemplify values of $U_{\Delta L_o}$, u_r and u_s are set to 0,1 m and the random uncertainty u_{Lotdr} is set to zero.

Wavelength nm	u_{Lotdr} m	u_r m	u_s m	u_{ea} m	$U_{\Delta L_o}$ $\pm m$
850		0,1	0,1	0,05	0,30
1300		0,1	0,1	0,04	0,30
1550		0,1	0,1	0,04	0,30

6.2.3.2 Length dependent uncertainty

The length-dependent uncertainty can be derived from the displayed OTDR location, the length-dependent uncertainty from the instrument set-up, and also the measurement of the variable time delay:

- u_{Lotdr} = random uncertainty from the measurement samples of the test object
- u_{vd} = uncertainty in measurement of variable time delay
- u_c = length-dependent uncertainty of counter

This gives the following equation:

$$u_{\Delta s_L} = \sqrt{(u_{\text{Lotdr}})^2 + (u_{\text{vd}})^2 + (u_c)^2}$$

The overall uncertainty with the coverage factor = 2 is calculated according to:

$$U_{\Delta sL} = 2 \cdot u_{\Delta sL}$$

The result for $u_{\Delta sL}$ can be summarised in the following table and as before, $u_{L_{otdr}} = 0$:

Wavelength nm	$u_{L_{otdr}}$ m/km	u_{vd} m/km	u_c m/km	$U_{\Delta sL}$ \pm m/km
850		0,003	0,0001	0,0060
1300		0,003	0,0001	0,0060
1550		0,003	0,0001	0,0060

6.3 Loss measurements

The objective of the loss measurement is to calibrate the loss deviation $\Delta S_A(F)$ and its uncertainty for the OTDR being tested. This is evaluated along a fictitious backscatter trace, A, which corresponds to a response from a fibre according to figure 6.2.

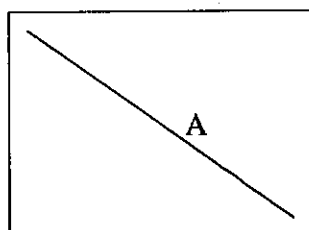


Figure 6.2. A schematic backscatter trace of an OTDR.

$\Delta S_A(F)$ is a function of the displayed power F and includes deviation from the slope and the non-linearity of the OTDR power scale.

6.3.1 Measurement procedure

The measurement was carried out in the following way. The dynamic range and the length of measurement were defined. The number of measurement points over the length scale were also defined. The equipment used was the same as mentioned under 6.3.

One of the OTDR cursors was placed at the beginning of the trace. The first measurement point was taken by setting attenuator 1 so that the received pulse on the OTDR appeared within 0,2 dB of the clipping level. The high level was read and attenuator 2 was shifted A_{ref} and read low level of the OTDR was read. $A_{OTDR}(F)$ was calculated as the high minus the low power level. The following points were reached according to figure 6.2. That means that both the delay generator and attenuator 2 were set so that the following high level points appeared along the fictitious backscatter trace A. The result was a number on the loss deviation ΔS_A in [dB/dB] at different length settings.

6.3.2 Measurement result

The loss scale is calibrated with the two attenuators combined with different settings of the digital delay generator. At each point the loss deviation is calculated as:

$$\Delta S_A(F) = \frac{A_{\text{OTDR}}(F) - A_{\text{ref}}}{A_{\text{ref}}} \quad [\text{dB/dB}]$$

where:

A_{ref} \approx reference loss

$A_{\text{OTDR}}(F)$ = change in displayed power level

6.3.3 Loss uncertainty

The loss uncertainty is accumulated according to the root-sum-square of measured and estimated uncertainties. The uncertainty contributions are from:

- u_{Aotdr} = random uncertainty from the measurement samples of the test object
- u_r = uncertainty in dB caused by limited read-out resolution of OTDR.
- $u_{\lambda\lambda}$ = uncertainty in dB caused by the wavelength difference between the OTDR
and E/O converter centre wavelength.
- u_{Ar} = uncertainty in dB caused by the attenuators limited resolution.
- U_{sA} = uncertainty in dB based of the uncertainty calculation in 5.2.

This gives the following equation:

$$u_{\Delta S_A} = \sqrt{(u_{\text{Aotdr}})^2 + (u_r)^2 + (u_{\lambda\lambda})^2 + (u_{\text{Ar}})^2 + (u_{\text{sA}})^2}$$

The overall uncertainty of the coverage factor = 2 is calculated according to:

$$U_{\Delta S_A} = 2 \cdot u_{\Delta S_A}$$

The result for U_{sA} can be summarised in the following table where values for u_r are set to 0,005 dB but values for the random uncertainties u_{Aotdr} are excluded:

Wavelength nm	u_{Aotdr} dB	u_r dB	$u_{\lambda\lambda}$ dB	u_{Ar} dB	u_{sA} dB	$U_{\Delta S_A}$ ±dB
850		0,005	0,022	0,005	0,0240	0,067
1300		0,005	0,022	0,005	0,0081	0,049
1550		0,005	0,022	0,005	0,0081	0,049

7 Computer control

The number of parameters of certain instruments, the large number of measurement points and the calculation procedures mean that the calibration procedure should be computer controlled. Therefore a computer control program has been developed which reduces the calibration time and makes the instrument set-up more user-friendly. A further step should be to computer control the OTDR read-out but this requires a unique code for each type of OTDR.

7.1 Hardware

Each instrument has been equipped with an IEEE-488 interface. This is a parallel interface which is the standard control interface for most instruments. In this first step the digital delay generator, the time interval counter and both the optical attenuators were connected to the computer. The reason was that the counter value was needed for each measurement. The other instruments also required many changes of parameters. Because of the standard aspect of the interface, the OTDRs under calibration should also be able to be computer controlled.

The computer used is a IBM-compatible PC, Alfaskop Desktop 346 from Nokia. It is equipped with a 110 Mbyte hard-disc, mouse pointer and an IEEE-488 interface card from Capital Equipment Corp.

7.2 Programming language

The control program has been developed in Microsoft Visual Basic. This is an object-oriented, event-driven programming tool that runs under Microsoft Windows. The main reasons for the choice of Visual Basic rather than other programming languages are:

- 1) A graphical interface can easily be created. This makes the program more easy to use.
- 2) There is no problem when data must be shared with other programs under Microsoft Windows such as calculating programs, text editors etc.

A Visual Basic program consists of one or more forms (actually windows) in which the objects such as control buttons, text boxes or graphics are drawn. The properties for each object are then decided and the program code for each object is created. After this the program can be executed and each object will then respond in accordance with the code.

7.3 Program structure

The program consists of four different forms and three separate files with code. A short description of each part follows below:

OTDRGLOB.BAS	This file contains all global information, such as variables and constants needed in all forms.
IEEEVB.BAS	This file is delivered with the IEEE-488 interface card. It contains the general code necessary to control the interface.
GEMSUFU.BAS	This file contains subroutines and functions that are common for several forms.
INIT.FRM	This form starts the program. The calibration data are shown and the controlled instruments are initialised. From here the choice of distance calibration or loss calibration is done.
LÄNGD.FRM	This form contains the functions for distance calibration. When the trig level, pulse length and distance are given, a calibration routine according to 6.2.1 is performed. The distance scale deviation and location offset, both with their uncertainties, are then calculated and presented. There is also a routine for making a print-out of the results.
DÄMP.FRM	This form contains the functions for loss calibration. When the trig level, pulse length, distance range, dynamic range and number of measurement points are given, a calibration routine according to 6.3.1 is performed. The loss error is then calculated and presented. There is also a routine for making a printout of the results.
KALFIL.FRM	This form handles the functions for saving and recalling the calibration constants and measurement results.

7.4 Program control routines

In computer-controlled applications it is important that the program is able to check itself. Therefore, in both Längd.frm and Dämp.frm, a self-test routine has been incorporated. This routine sets its own start parameters, then it executes the normal calibration procedures and finally compares the displayed results with the expected ones. At some points the self-test routines temporarily stop and instruct the user to check the instrument settings. By help of this, the communication parts are tested.

8 Conclusion

A method to calibrate an OTDR is presented. The work shows that it is possible to calibrate an OTDR according to the proposed method named "external source method" according to IEC/TC86/WG4/SWG2 "Calibration of optical time-domain reflectometer". The instrument set-up simulates the length and attenuation of an optical fibre. This has been done with a set of instruments which have been evaluated in the report. An uncertainty calculation of the instrument set-up has been done. The measurement procedure has been described and an example of a measurement has been shown. To exemplify the total uncertainty of an instrument, figures from a typical OTDR have been taken and the total uncertainty is calculated..

The capability of the instrument set-up was described with the following uncertainties, coverage factor $k=2$:

Length simulation (L in km):

$$\begin{aligned} \text{For 850 nm} \quad U_{osL} &= \pm(0,11 \text{ [m]} + L \cdot 0,00012) \text{ [m/km]} \\ \text{For 1300/1550 nm} \quad U_{osL} &= \pm(0,10 \text{ [m]} + L \cdot 0,00012) \text{ [m/km]} \end{aligned}$$

Loss simulation (2-4 dB step):

$$\begin{aligned} 850 \text{ nm} \quad U_{osA} &= \pm 0,049 \text{ [dB]} \\ 1300/1550 \text{ nm} \quad U_{osA} &= \pm 0,017 \text{ [dB]} \end{aligned}$$

With the figures from the example in chapter 6, the following uncertainties were obtained of the total uncertainties of length-independent uncertainty $U_{\Delta Lo}$, length-dependent uncertainty $U_{\Delta sL}$, and loss uncertainty $U_{\Delta sA}$:

Wavelength nm	$U_{\Delta Lo}$ $\pm m$	$U_{\Delta sL}$ $\pm m/km$	$U_{\Delta sA}$ $\pm dB$
850	0,30	0,0060	0,067
1300	0,30	0,0060	0,049
1550	0,30	0,0060	0,049

8.1 Future work

The method for calibrating an OTDR has parameters which have influenced the measurement result. These can, for instance be temperature-dependence, ageing and polarisation effects. These have not been investigated within the scope of the project. Especially polarisation effects are of great importance to be investigated.

International and European work has now reached the point where inter-comparisons on OTDR are an actual issue. Euromet is an European collaboration between the primary laboratories. COST is another European constellation between different laboratories. The organisations have especially focused their work on inter-comparisons. SP will participate in inter-comparisons in both groups.

9 References

1. Stanford Research Systems: Manual for model SR620; Universal Time Interval Counter.
2. Calibration of optical time-domain reflectometer, IEC TC86/WG4/SWG2 (Hentchel)4.

