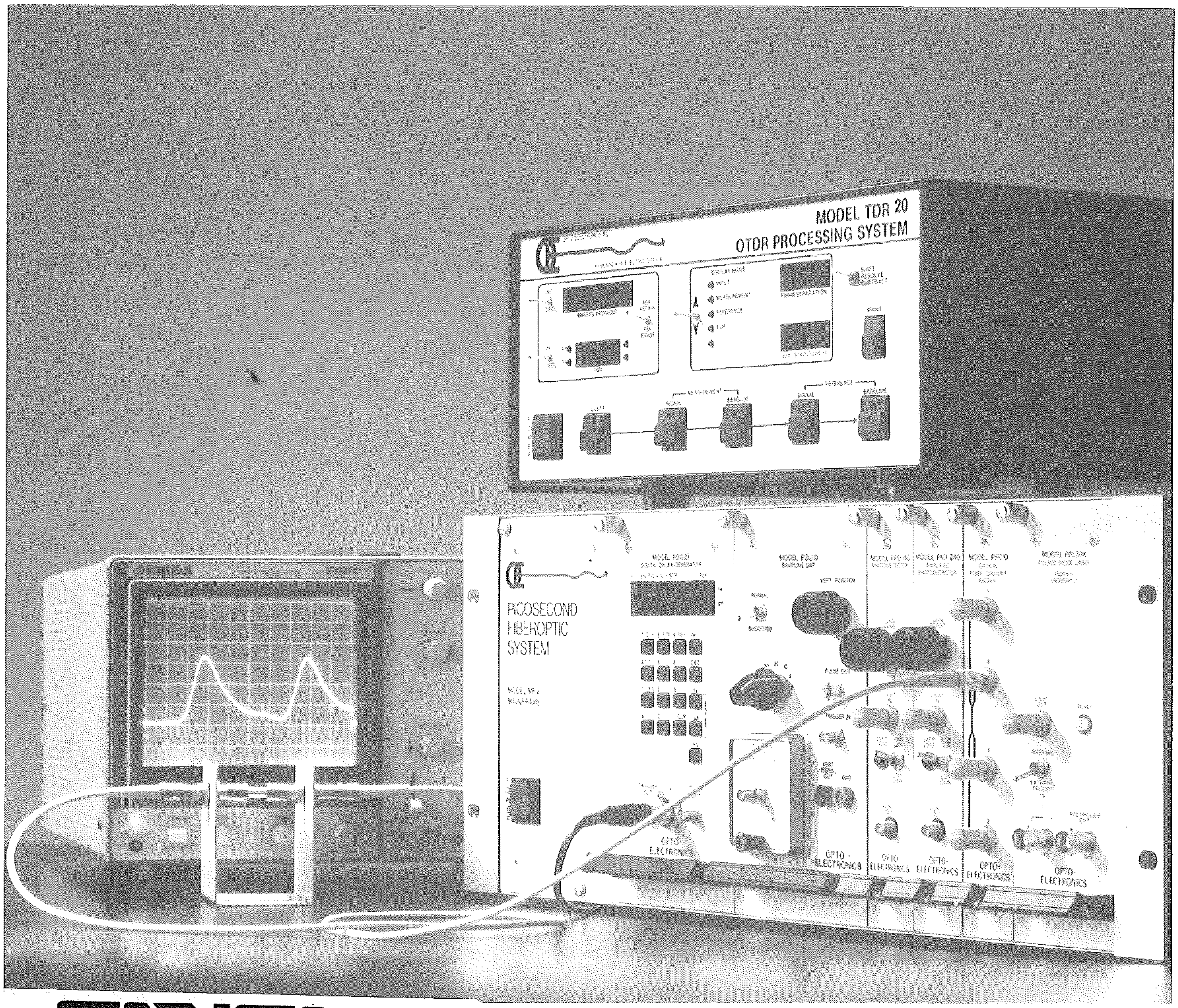
MILLIMETER RESOLUTION OTDR SYSTEM

RL 2015



SAVEN
MÄT • OPTO

SAVEN MÄT • OPTO AB • Enhagsvägen 7 • P.O.Box 504
S-183 25 Täby, Sweden • Tel. +46-8-473 50 00 • Fax. +46-8-768 03 83

OPTO-ELECTRONICS INC.
RESEARCH IN ELECTRO-OPTICS

OPTO ELECTRONICS INC.

MILLIMETER RESOLUTION
OTDR SYSTEM

INTERNATIONAL

Opto-Electronics Inc.
Unit 9, 2538 Speers Road
Oakville, Ontario L6L 5K9
Canada

USA

Opto-Electronics Inc.
Unit 202, Sidway Building
775 Main Street
Buffalo, New York 14202

Oakville, Canada
January, 1991

CONTENTS

1 INTRODUCTION

The Opto-Electronics MILLIMETER RESOLUTION OTDR SYSTEM is a unique new instrument with special capabilities not found in standard OTDR's. Specifically, the instrument measures time of flight of very short optical pulses with picosecond precision allowing for distance resolutions of less than one millimeter. This is coupled with a modular construction which allows for operation in transmission or reflection at a wide range of wavelengths into any fiber size. In short, each instrument can be configured to the operator`s requirements and can be reconfigured at will by the operator.

The millimeter resolution capabilities of the instrument do not restrict the operating distance or the dynamic range. On the contrary, operating distances up to 33 kilometers in singlemode fiber are realistic. In multimode fiber the operating distance is restricted to a few kilometers by modal dispersion. Freespace measurements with equally high resolution are also possible. Dynamic range varies with choice of modules and wavelength but by utilizing the best combination of wavelength and detection system dynamic ranges in excess of 100 dB can be achieved in transmission.

The Mainframe has been designed to accommodate a variety of modules as plug-in units. Multimode or singlemode operation at wavelengths from 680 to 1550 nanometers are provided by a variety of Transmitter/Receiver modules. Variable attenuators can be added for convenience and a variety of couplers is available as well. An operator can choose the best set of modules for a particular experiment or measurement. This set can be utilized for a multitude of other measurements as well. Conversely, additional modules serve to extend the capability of the system from Fresnel reflection measurements to Rayleigh backscatter measurements as well as to use the system as an electro-optic component tester or a bandwidth measurement test set.

The Opto-Electronics MILLIMETER RESOLUTION OTDR has been utilized for a large number of applications since its introduction in 1986. Most of these applications are shorthaul, and very shorthaul OTDR measurements. Some are fiber sensor related measurements , while others are electro-optic or microwave component testing measurements. Still others are concerned with bandwidth measurements. A number of these are outlined in the Applications section. They include; measuring absolute and relative distances in singlemode or multimode fibers from one millimeter to 30 kilometers without lead-ins or masking; locating the precise position of connectors, couplers, reflective splices and reflective breaks or other reflective faults in fibers and cables; testing, mapping and monitoring LANS in buildings, ships or airplanes; measuring the performance of sensors, connectors, couplers, attenuators, switches and integrated optics; measuring the precise strain, time delay changes and loss changes of fibers in cable pull testing, cable installations, fiber spooling and fiber payouts; measuring precise fiber group index, group index variations, strain and temperature coefficients of fiber group index; measuring the performance of optical, electro-optic, opto-electric, or microwave components in the time and frequency domain; measuring the pulse dispersion and bandwidth of components and fiberoptic systems and; measurements in many other applications where picosecond or submillimeter resolution and accuracy is required.

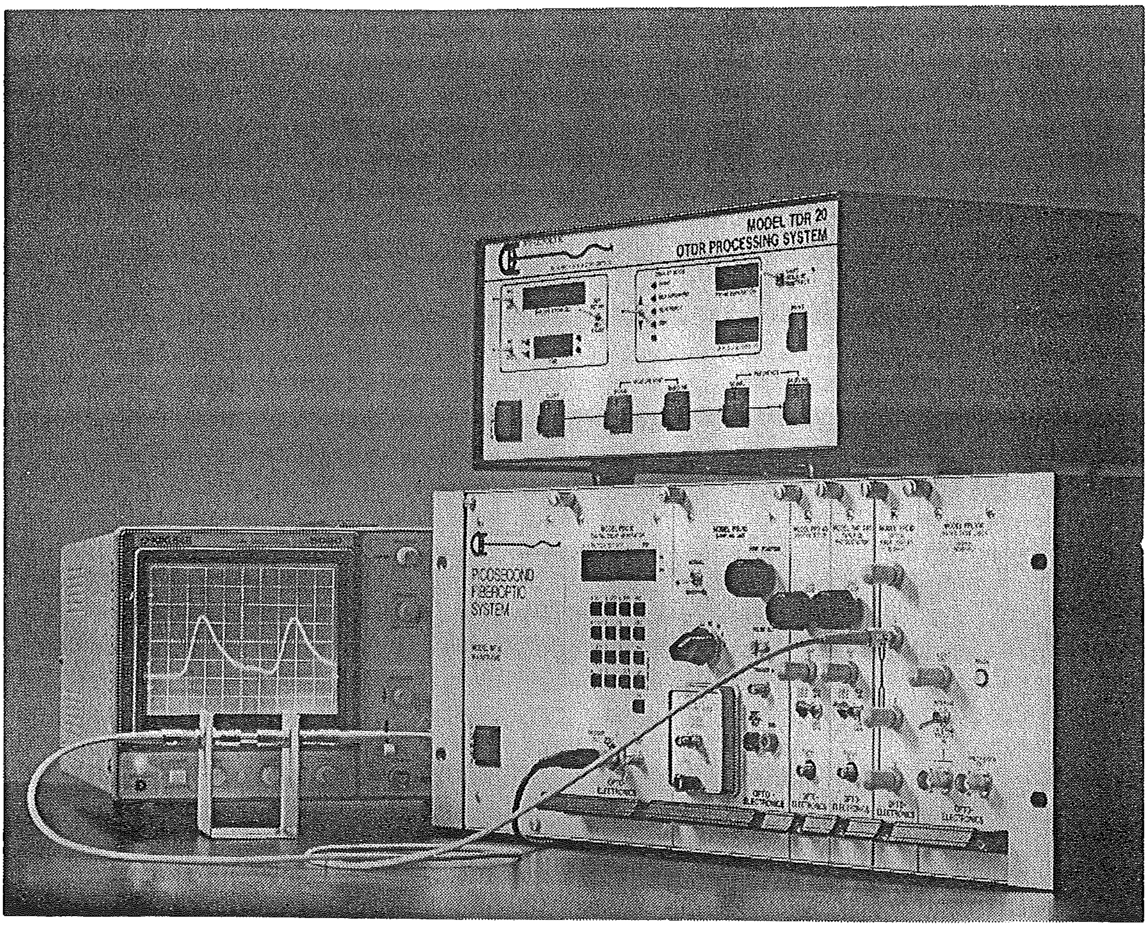


Figure 1-1

The Opto-Electronics MILLIMETER RESOLUTION OTDR system. The mainframe and the processor are placed on the bench along with a low frequency lab type oscilloscope which serves as the screen for the OTDR. The two pulses on the screen correspond to reflections from two closely spaced optical connectors shown in front of the screen. At the particular setting used in this example, the distance on the oscilloscope screen equals the distance in the fiber. The component boxes may be also rack mounted in a standard 19 inch frame.

2 GENERAL OTDR THEORY

A short summary is given of the underlying principles of OTDR measurements, OTDR backscatter and reflection signals, short and long pulse operation, deadzones, spatial resolution, loss budget, conventional OTDR instruments, and the essential differences between conventional OTDR's and the Opto-Electronics MILLIMETER RESOLUTION OTDR.

2.1 THE OTDR MEASUREMENT METHOD

In a basic OTDR measurement, a laser transmitter launches a short optical pulse into the fiber under test. The light returned from the fiber back to the OTDR is detected by a photodetector. The time delay between launch and detection is determined by the delay generator. Each value of this time delay, which can be varied by the operator, is uniquely related to a specific location along the fiber. Therefore, distance measurements can be made along the fiber.

The waveform of the returned light pulse from the fiber for each time delay is also measured and analysed. This gives information about fiber properties and features along its length. Important properties and features include losses, faults, and changes that occur along the fiber.

2.2 RAYLEIGH BACKSCATTER AND FRESNEL REFLECTION

The light from the fiber is returned by two different processes. One process is the backscattering from the microscopic density fluctuation, called the Rayleigh backscattering and the other is the reflection of light from abrupt macroscopic discontinuities in the fiber called the Fresnel reflection.

For a uniform undisturbed fiber, the Rayleigh backscattering is uniform along the whole length of the fiber. If a discontinuity is introduced, the returned waveform is modified and the disturbance may be analyzed. Losses, breaks, faults, changes and other features can be thus detected, measured and analysed. Unfortunately, the Rayleigh backscattered signal is a very small fraction of the probe pulse energy, therefore, very sensitive detection methods have to be employed for its measurement. For example, if a ten nanosecond wide light pulse is launched into a standard multimode communication fiber with a 3 dB/km transmission loss, the backscattered light from the first one meter length of the fiber is only one one-millionth (-60 dB) of the launched energy. For subsequent one meter lengths, this figure decreases; for singlemode fiber the backscattered signal is at least one order of magnitude smaller than that for multimode fiber. Furthermore, the Rayleigh backscattered fraction of the input pulse energy becomes smaller as the probe pulsewidth is reduced.

While Rayleigh backscattering originates from every point along the fiber, Fresnel reflections originate at points along the fiber where abrupt and discrete discontinuities occur in the index of refraction. One example of this is the cleaved end of a fiber. The index changes at this point from about 1.5 of the glass to 1.0 of the air, resulting in a Fresnel reflection with four percent (-14 dB) of the incident energy.

It should be noted at this point that the energy reflected from a Fresnel point, (-14 dB), and the energy backscattered from the first one meter length of a fiber, (-60 dB), differ by almost five orders of magnitude for a 10 ns long probe pulse. This difference in relative signal strengths causes serious difficulties for conventional OTDR's, as will be discussed later.

Various discontinuities produce Fresnel reflections of various intensities. An open fiber end with a flat perpendicular cleave or a flat polished end causes about -14 dB reflection. A good mechanical splice or a good pair of mated connectors cause from -30 to -40 dB reflection. A pigtailed detector or laser causes -4 to -20 dB reflection. Fresnel reflection from a mechanical break or crack may produce from -8 to -75 dB of signal. The lowest Fresnel reflectivities belong to macrobends, (-70 to -100 dB), low loss fusion splices, (-40 to -75 dB), good quality couplers, (-40 to -70 dB) and microbends, (-50 to -70 dB). The lowest level Fresnel signals from these features are seen to be comparable to the 10 nanosecond pulsewidth Rayleigh backscattered signals originating from short lengths of fiber, while the highest level Fresnel signals are more than six orders of magnitude greater than Rayleigh backscattered signals.

2.3 THE OTDR DEADZONE

The level of the Rayleigh backscattered signal for a given fiber at a given wavelength is proportional to the pulsewidth of the optical probe pulse from the OTDR. On the other hand the level of the Fresnel reflected signal is independent of the pulsewidth. It follows then, that the ratio of the Rayleigh signal to the Fresnel signal is pulsewidth dependent. The approximate ratios for standard multimode communication fibers at 850 nanometers for optical probe pulsewidths of 1, 10, 100 and 1000 nanoseconds are respectively -60 dB, -50 dB, -40 dB and -30 dB.

The detection system of an OTDR has to be sensitive enough to measure the small Rayleigh backscattered signals on the one hand, but this may result in saturation due to the presence of a nearby Fresnel reflection on the other. The impact of this saturation effect increases with decreasing pulsewidth due to the widening intensity difference between the two signals.

For conventional high resolution OTDR's utilizing standard detection methods, the saturation time due to a strong Fresnel reflection extends to about ten times the pulse width. High resolution OTDR's utilizing pulse widths in the range of 5 to 50 nanoseconds thus have saturation times of 50 to 500 nanoseconds.

Fiber lengths corresponding to these saturation times are called the deadzones of the OTDR. In the deadzone, no feature is detectable or measurable because the detection system cannot respond to any additional light signal. The saturation times mentioned above (50 to 500 ns) result in deadzones of 5 meters to 50 meters.

The first Fresnel reflection encountered in any OTDR measurement originates from the optical output connector on the bulkhead of the OTDR. This signal causes a deadzone of some few meters or few tens of meters extending from the OTDR into the fiber under test. This is an inevitable feature of conventional OTDR's. Bulkhead extender fibers or electronic masking functions may help the situation somewhat but a deadzone stubbornly exists at every Fresnel reflection along the fiber under test.

The presence of deadzones in fiber systems with long continuous runs without connectors and other sources of Fresnel reflections is not very serious. However, for short haul systems with short distances between connectors and other components, the presence of the repeating deadzones may render a conventional OTDR measurement impossible.

The highest resolution conventional OTDR's utilize three to five nanosecond wide probe light pulses with a resulting deadzone of three to five meters in multimode fibers at 850 nanometers. The corresponding deadzones for singlemode fibers at 1300 and 1550 nanometers are at least 30 to 50 meters.

2.4 ACCURACY AND RESOLUTION

The spatial accuracy of an OTDR is understood to mean the precision with which the OTDR can measure the absolute distance between two points along the fiber separated by distances much greater than the deadzone of the OTDR. The distance may be the length of a spool of fiber from the OTDR bulkhead to the far end of the spool, or the distance between two splices in a cable several hundreds or thousands of meters apart.

The spatial resolution of an OTDR is divided into single point resolution and two point resolution. The single point resolution is the smallest distance variation measurable by the OTDR, as for example, the smallest length of fiber cut off from the far end of a spool of fiber that can be measured by the OTDR. The two point resolution is the smallest distance between two distinct features along the fiber that can be resolved by the instrument as two separate features. An example for this may be two microbends separated by a small distance showing up on the OTDR screen as two separate features.

Both the spatial accuracy and the single and two point spatial resolutions depend on the time measuring accuracy, time jitter and stability of the OTDR. However, if these features are assumed to be state of the art, the dependency is on the pulsewidth of the probe light pulse and detector response time only. The wider the pulsewidth the lesser the accuracy and the two resolutions. The shorter the pulsewidth the greater the accuracy and the two resolutions.

As a rough rule of thumb for conventional OTDR's the accuracy and single point resolution is approximately equal to one half of the pulse width and the two point resolution is approximately equal to the full pulse width. This translates to accuracies and single point resolutions for conventional OTDR's with pulsewidths of 10 ns and 100 ns respectively to 50 cm and 5 m and two point resolutions of 1 m and 10 m. It should be remembered, however, that in order to realize these accuracies and resolutions, the features measured must be outside the deadzone caused by any other feature with Fresnel reflections. This naturally restricts the use of conventional OTDR's to medium and long haul applications, even if they have high accuracy and resolution.

2.5 THE LOSS BUDGET

The loss budget of an OTDR may be specified as a one way or two way insertion loss budget, or as a return loss budget. In general, the term is understood to mean the maximum loss in decibels that can be introduced into the fiber under test for which the returned OTDR signal maintains a value equal to the OTDR noise.

For example, to measure the insertion loss budget, insert an optical attenuator between the OTDR and the fiber under test and obtain an OTDR signal from the fiber. Increase the attenuation until the signal to noise ratio, (SNR), on the OTDR screen becomes one. The value shown on the attenuator is the one way insertion loss budget. The two way insertion loss budget is twice this value.

The loss budget depends on the laser output power of the OTDR, the sensitivity and SNR of its detection system and the width of the optical probe pulse. For maximum laser power and maximum detection sensitivity, the loss budget is therefore optical pulse width dependent. The loss budget is greater for long optical probe pulses and is lesser for shorter probe pulses. Now recall that long pulses cause long deadzones, therefore high loss budget OTDR's are useful for long haul applications only. This is appropriate because long lengths of fibers have more loss than short ones, consequently conventional OTDR's with long optical probe pulses are optimized for long haul applications.

On the other hand, short-pulse, low-loss budget, conventional OTDR's are not at all suited for short haul applications, not just because of the deadzone problem discussed above, but also because they have a low loss budget. Typical values for one way loss budgets for short pulse conventional OTDR's are 10 to 15 dB and those for long pulse conventional OTDR's are 30 to 45 dB. Usually in short haul networks there are a substantial number of connectors, splitters or star couplers that demand loss budgets tens of decibels beyond the available loss budget of conventional OTDR's.

2.6 THE CONVENTIONAL OTDR

A conventional OTDR is an electro-optic instrument consisting of a pulsed optical transmitter, a matched high impedance optical receiver and an electronic signal processing and displaying assembly. The transmitter launches optical pulses with widths ranging from microseconds (long haul) down to several nanoseconds (short haul) at repetition rates restricted by the maximum length of the fiber to be measured. The receiver is a direct detection photodetector (usually an APD) coupled to an OP AMP and other circuits with system response on the order of the transmitter pulsewidth. The signal processor is usually a dedicated computer system that translates, calculates, displays and stores the measurement data.

Conventional OTDR's are designed to detect the Rayleigh backscattered signals from fibers with great sensitivities and suffer from the high level of Fresnel reflection signals returned from inevitable connectors and other discontinuities along the fiber. Because of the high detector gain and low noise required by the detection of the Rayleigh backscatter signal, the detection system has to be kept at high impedance. The high impedance of the detection system forces a lower limit on the optical pulsewidth at around the five nanosecond mark. The five nanosecond pulsewidth limitation translates to the limitations in the loss budget, resolution, and the deadzone as discussed in previous paragraphs.

Using conventional OTDR technology the above mentioned limitations can not be overcome. Picosecond technology developed by Opto-Electronics Inc. opens up new territories for drastic improvements in OTDR resolution, loss budget and deadzone, for medium and short and very short haul applications.

2.7 THE OPTO-ELECTRONICS MILLIMETER RESOLUTION OTDR

The Opto-Electronics MILLIMETER RESOLUTION OTDR is similar in some respects to a conventional OTDR. It is also an electro-optic instrument consisting of a pulsed optical transmitter, a matched optical receiver and an electronic processing assembly, but the similarities end here. The differences are substantial. The pulsewidth of the optical probe pulse is less than 100 picoseconds, the detection system is a 50 ohm microwave electronic sampling system, the pulse repetition rate is constant, and the processor is designed to detect the Fresnel reflection signal in order to eliminate the deadzone. The Opto-Electronics picosecond OTDR is the ideal solution to OTDR measurement problems for medium, short and very short haul fiber optic measurement problems.

When applications demand Rayleigh backscattering over short fiber lengths of a few tens of meters, a few meters or tens of centimeters, the Opto-Electronics MILLIMETER RESOLUTION OTDR may be converted to a Rayleigh backscattering OTDR by the application of an ultra-sensitive picosecond photon counting detector. This detector extends the sensitivity of the system by an additional 30 dB and enables the detection of Rayleigh signals originating from fiber lengths as short as a few centimeters.

3 TECHNICAL DESCRIPTION

The Opto-Electronics MILLIMETER RESOLUTION OTDR is described along with its major components, its basic operation and its various performance modes and functions. The outputs and interfaces of the OTDR are also described.

3.1 MAJOR SYSTEM COMPONENTS

The Opto-Electronics OTDR components are similar to conventional OTDR's but its performance differs markedly. A typical system is shown in Figure 3-1 below while the block diagram is shown in Figure 3-2. The system also supports a number of external output and control devices. These are detailed elsewhere.

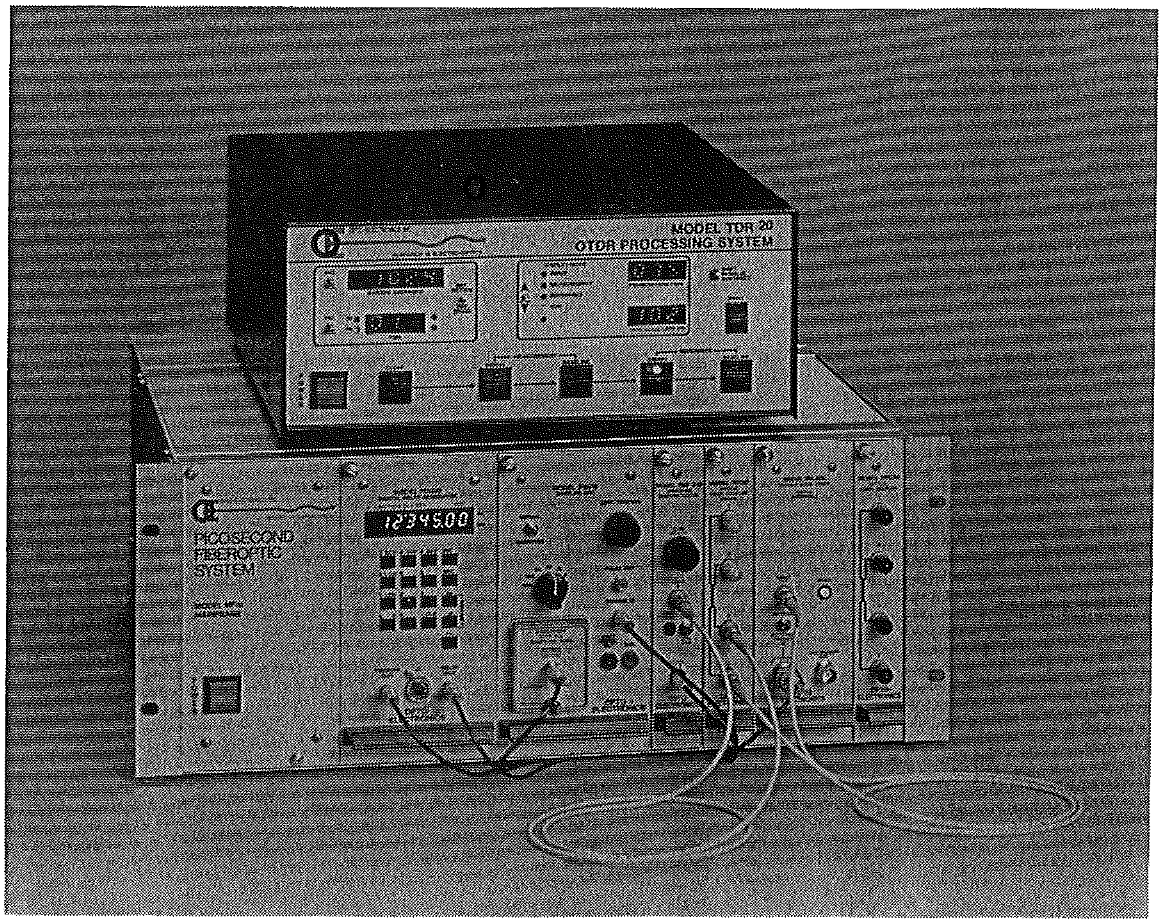


Figure 3-1

A typical configuration for the Opto-Electronics MILLIMETER RESOLUTION OTDR. The top box is the TDR20 Signal Processor and the bottom box is the Picosecond Fiberoptic System mainframe. The display scope is not shown in this photograph. The mainframe supports a variety of plug-in modules. Shown from right to left are: The Fiberoptic Coupler, the Laser Transmitter, another Fiberoptic Coupler, the Detector, the Sampling Unit, and the Time Delay Generator. The modules may be interconnected electrically and optically in a variety of ways to perform a number of different functions.

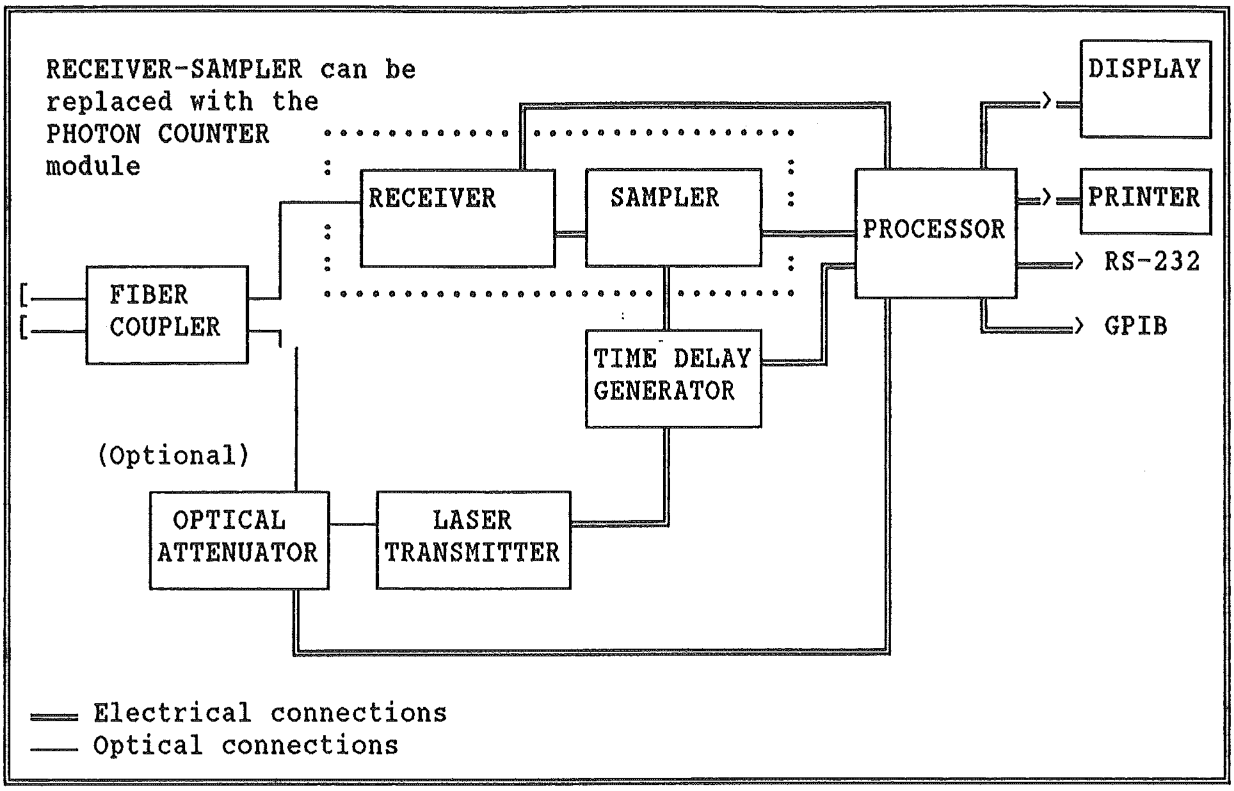


Figure 3-2

Block diagram of the Opto-Electronics MILLIMETER RESOLUTION OTDR.

3.1.1 THE LASER TRANSMITTER The laser transmitter outputs light pulses with pulsewidths of less than 100 picoseconds at peak powers of several tens of milliwatts (for 1300 of 1550 nm singlemode output) to several hundreds of milliwatts (for 820, 850 or 904 nm multimode outputs). The repetition rate of the pulses is 33 kHz or less, depending on the length of fiber to be scanned. The pulse width is approximately 100 times shorter and the peak power is considerably higher than the corresponding values found for conventional high resolution OTDR's.

3.1.2 THE TIME DELAY GENERATOR This module, which controls the timing of the laser probe output pulses and the delay of the detection system, has the lowest time jitter amongst commercially available time delay generators. It has been measured to be less than one picosecond RMS under normal operating conditions. This time corresponds to an OTDR distance variation of under 0.1 millimeters. The time delay generator controls the delay between laser pulse output and return pulse detection from zero picosecond (zero millimeter) to 0.3 milliseconds (30 kilometers) assuring very high accuracy of detection.

How The Delay Generator Works!
This is easiest understood by referring to Figure 3-3 below. The delay generator runs at a set repetition rate. If the time of the Trigger Pulse out is taken as zero, then a reference value can be set to any point in time within the absolute delay range. The DELAY can be positive or negative but the REFERENCE plus DELAY must fall within the ABSOLUTE DELAY RANGE. The Delay is measured from the REFERENCE point to the left side of the WINDOW. The WINDOW

size is determined from the Delay Generator T/DIV value, (WINDOW size = 10 x T/DIV). Again, REFERENCE plus DELAY plus WINDOW size cannot extend beyond the ABSOLUTE DELAY RANGE. An attempt to do so will cause the error indicator, (E), to light. The WINDOW position, (DELAY), can be moved by direct entry or stepped by the Delay Generator STP size value. When FN-REF-ENTER is pressed, the current DELAY is added to the current REFERENCE to give a new REFERENCE and a DELAY equal to zero while the WINDOW position remains unaltered in the ABSOLUTE DELAY RANGE.

```
 TRIGGER  OUTPUT at time t = 0 ns
 DELAY OUTPUT                                        ________
!---------------------------------------------------|        |----------------!
|<----------REFERENCE----------->|                  |________|
0                                |<-----DELAY----->|Window|           319995
!------------------------------------------------------------------------------!
|<-------------------- ABSOLUTE DELAY RANGE (ns) ----------------------->|
```

Figure 3-3

Schematic showing delay range of the Delay Generator.

3.1.3 <u>THE DETECTOR</u> The detector is a high gain APD or an amplified APD with optimized signal to noise ratio (SNR) having a response time on the order of 100 picoseconds. This speed matches the width of the laser pulse for the most efficient performance possible. The detector response time is also about 100 times faster than the response times of the fastest detectors used in conventional OTDR's.

3.1.4 <u>THE SAMPLING UNIT</u> The picosecond time scale electrical output of the photodetector can not be measured or displayed directly. Therefore, the waveform has to be sampled piecewise, utilizing an electronic sampler. The process of electronic sampling is commonly employed by gigahertz and picosecond sampling oscilloscopes. It requires steady optical pulses for low noise detection. This is provided by the low jitter delay generator in conjunction with the stabilized laser transmitter.

How The Sampling Unit Works!
The electrical signals are too short to be displayed in real time even with the fastest of oscilloscopes. Thus, a sampling technique is employed. To understand how this works, imagine the scope screen divided into 256 horizontal points. If the entire screen represents 500 ps (50 ps/Div) then each point represents about 2 ps. While it is not possible to follow a pulse in this time frame it is possible to sample the pulse voltage at point one, say, of the first pulse, then at point two, (one pulse plus 2 ps later) of the following pulse and so on. With this sampling technique, one sweep can be built up with 256 samples. It is obvious that the repetitive pulses must be identical and that one must have a delay generator with very low jitter. Furthermore, the process is slower than direct detection in that sampling is restricted to a rate of about 40 kHz.

3.1.5 THE PHOTON COUNTER A drastic increase in system sensitivity may be gained by replacing the detector and sampling units with the photon counter. The photon counter responds to individual photons in the picosecond light pulse and is the ultimate in low light level measurements. The photon counter enables the Opto-Electronics MILLIMETER RESOLUTION OTDR to measure the very low light level Rayleigh backscattered signals from very short lengths of fibers.

How The Photon Counter Works!
There are 256 horizontal points on the display screen. Each point represents a sequential point in time at which the photon counter is turned ON. The length of the Photon Counter ON time is a function of the SENSITIVITY setting on the PPC10. For example, with the SENSITIVITY setting at MED the photon counter ON time is 0.8 ns. Thus the photon counter will count only if a photon arrives within this 0.8 ns window. For delay times less than 2 microseconds the delay generator operates at about a 33 kHz repetition rate. This is the rate at which the laser source is triggered and emits optical pulses.

The delayed electrical pulse triggers the photon counter at a precisely determined time. The PPC10 will look for and count, if present, a photon returned from each pulse. The count is one or zero. If two or more photons arrive at the same time the count is still one. At each of the 256 points the PPC10 waits for four pulses. Thus the display has five levels. The baseline represents zero counts out of four pulses. The first level represents one count out of four and so forth. When a solid line is observed at the four count level, this indicates that the counter is being saturated, ie. more than one photon is arriving at each count.

In real time, one sees a lot of dots on the screen, therefore, averaging is required. If the Processor is set to run 512 averages for example, then it takes 512x256 or 131,072 pulses to construct a sweep as displayed on the screen. This represents a little over 4 seconds in time. As there are 256 points in the vertical sense as well, a reasonable number of averages will produce a well defined pulse shape.

For best results, the light should be attenuated at the laser output until the feature being viewed shows 1 to 3 counts in real time. This indicates a return of photons, but prevents saturation.

3.1.6 THE FIBEROPTIC COUPLER This is a four port device designed to direct the optical probe pulse, to the fiber under test and the returned pulse from the fiber to the detector. The four ports allow two parallel outputs for the OTDR to measure two fibers or networks in parallel. The two output ports of the coupler are usually matched in length to provide overlapping return pulses from the bulkhead of the OTDR. Both outputs may be used independently or simultaneously and both represent zero distance from the OTDR within one millimeter.

3.1.7 THE OPTICAL ATTENUATOR In many instances, the returned optical signal is much too strong for the detector. For these cases, a calibrated, processor controlled attenuator reduces the optical signal, keeping it well within the detectors linear response range. Thus, the attenuator gives the instrument a much increased dynamic range.

3.1.8 THE SIGNAL PROCESSOR The processor has many functions. It manages the other components in the OTDR as well as the various inputs and outputs. These include the management of inputs from the front panel or from the GPIB port, and the management of outputs to the built in CRT screen, the external dot matrix printer or the external PC via RS-232 or IEEE-488 ports. In addition the Processor performs signal averaging, does various calculations and stores data. More details about the various functions of the processor are given elsewhere.

3.1.9 THE DISPLAY SCOPE A low frequency, inexpensive oscilloscope is required as a display to observe the various waveforms generated by the OTDR system. Most laboratories have general purpose oscilloscopes which are quite suitable. Therefore, Opto-Electronics does not include the oscilloscope in the OTDR package.

3.2 RANGE OF OPTIONS

LASER TRANSMITTER

Wavelength (nm)	Standard:	680, 820, 850, 904, 1300, 1550
	* Special *	750, 785, 800 to 860, 1060, 1200,
Fiber Core Size (µm)	Standard:	4, 9, 50, 62.5, 100, 200, 400
	* Special *	polarization maintaining fiber.

ATTENUATOR

Fiber Core Size (nm)	Standard:	4, 9, 50
	* Special *	100
Calibration	Standard:	one wavelength
	* Special *	two wavelengths

COUPLER

Fiber Core Size (µm)	Standard:	4	for 680 to 850 nm
		9	for 1300 or 1550 nm
		50, 62.5, 100	for 680 to 1550 nm
		200	for 680 to 1550 nm
		400	for 680 to 1550 nm
Splitting Ratios	Standard:	1:1	
	* Special *	2:1, 10:1	

DETECTOR

Material and Type	Standard:	Si APD or Si APD Amplified;	400 - 1080 nm
		Si Photon Counter;	400 - 1080
		Ge APD or Ge APD Amplified;	600 - 1750 nm
Fiber Core Size (µm)	Standard:	100	
	* Special *	200, 400	

It should be noted that the OTDR system can be optimized to solve a particular problem or it can be optimized for general use. There are many trade-offs so that the factory should be consulted to pick those options which give best results for most applicatoins of the user.

4 SYSTEM PERFORMANCE

The Opto-Electronics MILLIMETER RESOLUTION OTDR may be used as a reflectometer in the Fresnel mode or as a backscatterer in the Rayleigh mode, depending on weather a photodetector/sampler combination is used or the photon counter is utilized. The system may also be used in transmission for a variety of applications.

4.1 MODES OF OPERATION

4.1.1 FRESNEL OPERATION In this mode the OTDR utilizes the probe pulse itself for the measurements. The quantities measured are the pulse time delay, (distance), the pulse area under the curve, (energy), and the pulse width, (FWHM). For most measurements an input "REFERENCE" pulse and a returned "MEASUREMENT" pulse are required. Data from the two pulses are then used to calculate the relative distance, the relative energy and the relative pulse width. Using these results, absolute and relative distance and time delay measurements can be made, insertion and return loss values can be obtained, pulse dispersion values can be calculated and overlapping double pulses can be deconvolved.

The OTDR Processor, whose front panel is shown in Figure 4-1, has three settings, SHIFT, RESOLVE and SUBTRACT. Most measurements require the SHIFT setting. In the RESOLVE setting the Processor will deconvolve the MEASUREMENT pulse in terms of the REFERENCE pulse, if the MEASUREMENT pulse contains two overlapping pulses and will present the two component pulses separately. In the SUBTRACT setting, the Processor will subtract the REFERENCE pulse from the MEASUREMENT pulse and will present the residual pulse.

The numerical results of the calculations appear in the various windows on the Processor front window.

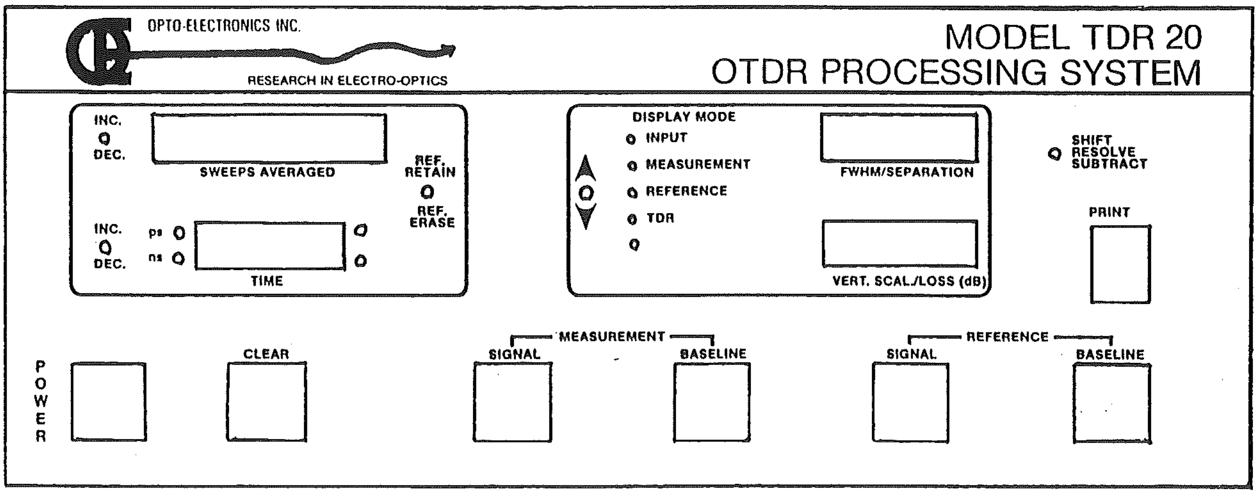


Figure 4-1

Schematic of the front panel of the Model TDR20 Processor

4.1.2 RAYLEIGH OPERATION In this mode the OTDR utilizes the backscattered energy from the probe pulse from every point along the fiber. This results in a display of a sloping or a horizontal waveform, depending on whether the fiber under test is long or short. For standard 50/125 core/clad graded index communications fiber the Rayleigh loss slope becomes discernible for lengths of10 meter or longer. For shorter fibers or for singlemode fibers, the display is a flat horizontal line, provided the fiber is not disturbed or is not faulty.

The quantities measured here are the length of the fiber, the position of any feature and the backscattered energy. From these measured values, fault location, insertion loss and return loss are calculated by the TDR Processor in the SHIFT setting. The numerical results are again displayed in the various windows on the front panel of the Processor.

The Rayleigh mode of operation requires the use of the photon counter for increased detection sensitivity. When using the photon counter the operator may work in the Fresnel mode, as well, and detect return pulses from features along the fiber that reflect a very small fraction of the probe pulse energy. Such features are fusion splices, couplers, ultralow return loss connectors, microbends, cracks and breaks and other features not detectable by any other method.

The Opto-Electronics MILLIMETER RESOLUTION OTDR, when used in the Rayleigh mode, is also subject to the *deadzone* phenomenon discussed in 2.3 above. However, this OTDR, having a pulse width that is approximately 100 times shorter than that of a conventional OTDR, has a *deadzone* that is approximately 100 times shorter than that of conventional OTDR's. This short deadzone, combined with the very large loss budget enables the Opto-Electronics OTDR to make reliable measurements in the first few tens of meters, the first few meters, or even in the first few centimeters of a fiber.

4.1.3 TRANSMISSION OPERATION If the fiber optic coupler module is bypassed, the MILLIMETER RESOLUTION system may be used in transmission. In this mode the light from the laser transmitter module is coupled directly into the fiber under test, allowed to propagate to the far end, where the detector module is coupled to the fiber to complete the circuit.

In this way, link losses, link dispersion, bandwidth and other properties may be measured with millimeter resolution. The loss budget is approximately 25 dB greater than that of the corresponding reflection method. If the photon counter is paired with an 850 nm laser transmitter, the operator may have a loss budget up to 110 dB. This opens up new opportunities in fiberoptic distributed sensing, multipoint sensing and in the probing of very lossy systems.

4.2. DISTANCE and TIME RESOLUTION

Accuracy and resolution for conventional OTDR's was discussed in general in section 2.4. The accuracy was stated to mean the precision with which an OTDR can measure the absolute distance (or time delay) between two points along the fiber which are separated by distances much greater than the dead zone of the OTDR.

For the Opto-Electronics MILLIMETER RESOLUTION OTDR, the accuracy of distance and time measurement is not limited by the deadzone of the instrument because it has no deadzone in the Fresnel mode of operation. In this case, the measurement accuracy is determined by the accuracy with which the peak position of the returned pulse is located on the screen. This in turn depends on the pulsewidth and on the SNR of the returned signal. For a SNR above 10, the measurement accuracy is better than 0.5 millimeters. The measurement accuracy decreases if longer distance fibers are measured over which the picosecond probe pulses widen appreciably.

Generally, the pulse widening for the MILLIMETER RESOLUTION OTDR is negligible up to a few kilometer lengths of singlemode fiber at 1300 or 1550 nanometers, up to a few kilometer lengths of 50 micrometer multimode core graded index fiber, up to several hundred meters of 100 micrometer core graded index fiber or up to several tens of meters of larger core size step index fibers. For fiber links up to these lengths, the measurements accuracies are better than 1 millimeter. For link lengths longer than these, the accuracies decrease proportionately.

The resolution was stated in section 2.4 to be either single point or two point resolution. It was stated that the single point resolution is the smallest distance variation (or time delay variation) measurable, for example, the smallest length of fiber cut off from the far end of a spool of fiber that can be measured by the OTDR. For the MILLIMETER RESOLUTION OTDR, the single point resolution is on the millimeter scale and it is a function of the SNR of the returned signal. The single point distance and time resolutions for the Opto-Electronics OTDR are plotted as functions of the SNR and the probe pulse width of the returned signal in Figure 4-2.

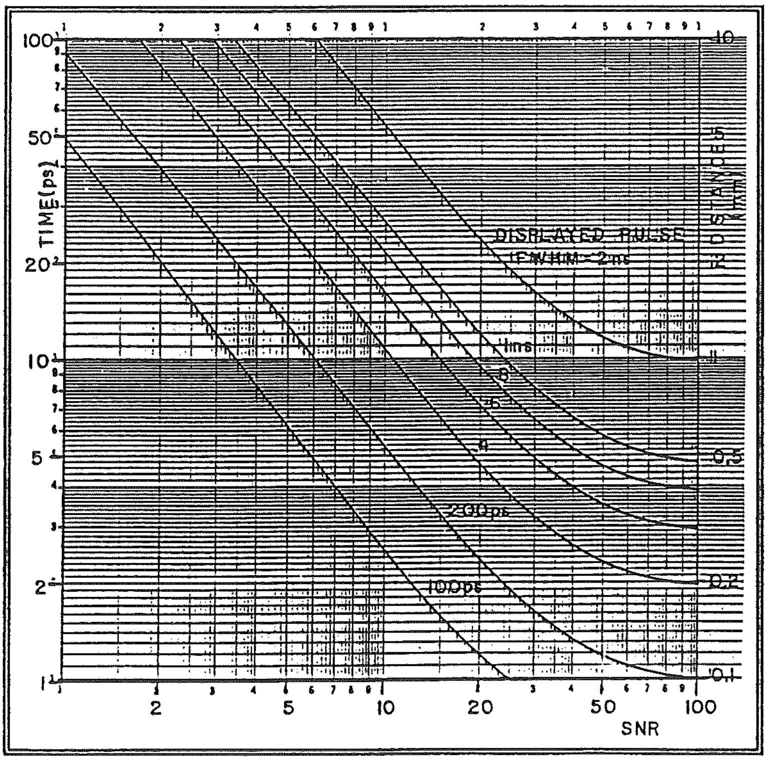
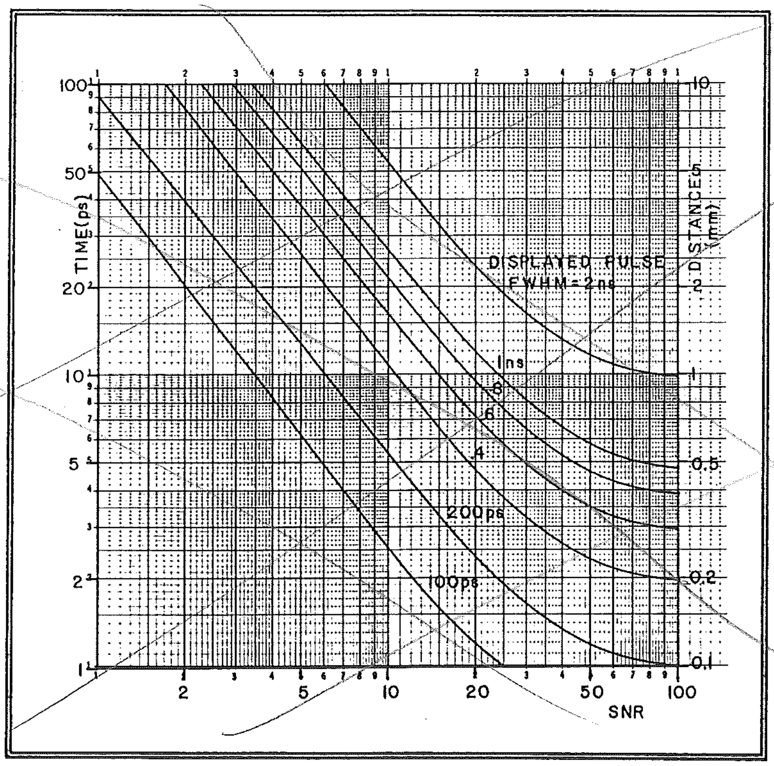


Figure 4-2
Single point distance and time resolutions of the MM RESOLUTION OTDR as functions of the SNR and pulsewidth of the return pulse.

The two point resolution, for non-overlapping pulses is measured in the SHIFT mode while that for overlapping pulses is measured in the RESOLVE mode. The Resolution depends on the SNR of the returned pulse, similar to the single point resolution and also on the relative intensities of the two adjacent pulses. The best two point resolution is obtained for two adjacent overlapping pulses with similar amplitudes and pulsewidths. As the ratio between the pulse heights deviate from one, the two point resolution decreases. If the ratio of pulse heights are above the 10 to 1 range, overlapping pulses may not be resolved. For non-overlapping pulses the pulse height ratio may be as high as 100:1 or more, depending on their separation distance; in this case the single point resolution applies.

The two point distance and time resolutions for the MILLIMETER RESOLUTION OTDR is plotted in Figure 4-3 as functions of the SNR of the returned signal and the pulse height ratios of the adjacent overlapping pulses for a pulsewidth of 150 ps.



See in another manual.

Figure 4-3
Two point distance and time resolutions of the MM RESOLUTION OTDR as functions of the SNR of the return pulse and the ratio of the component pulse heights. The pulse width is assumed to be 150 ps.

An example of the deconvolution of two adjacent pulses is shown in Figure 4-4 below. The distance between the two reflective features in the fiber from which the two pulses were returned is approximately 14 millimeters. The pulse height ratio is approximately 2:1.

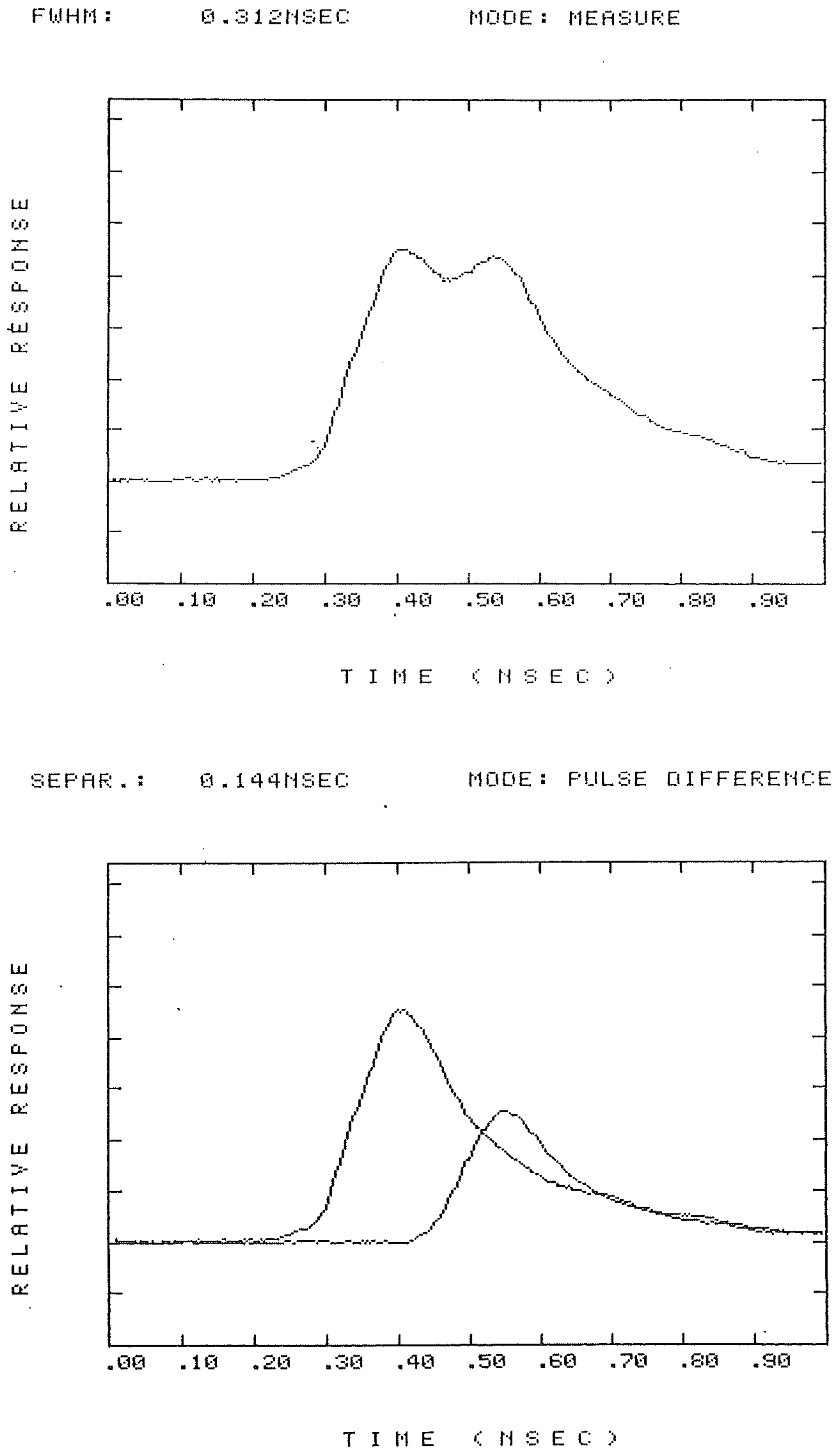


Figure 4-4
Two point measurement in a fiber link showing two reflective features separated by 144 ps or 14.4 mm. Top as measured, bottom as calculated by the Processor RESOLVE mode.

4.3 SENSITIVITY and LOSS BUDGET

The sensitivity of the Opto-Electronics MILLIMETER RESOLUTION OTDR depends on the wavelength of the laser transmitter, the size of the fiber used and the type of detector employed. The loss budget depends on the sensitivity of the system as well as on the mode of operation of the system. The loss budget is greatest for transmission operation, is less for Fresnel operation and it is the smallest for Rayleigh operation.

In specifying the loss budget, distinction has to be made between each operating mode, as well as between insertion loss and return loss. By definition, both insertion and return loss values are positive dB numbers. They are defined by the equations below;

INSERTION LOSS $I = 10 \cdot \mathrm{LOG}(1/i)$ (4-1)

RETURN LOSS $R = 10 \cdot \mathrm{LOG}(1/r)$ (4-2)

where i and r are the transmittance and reflectance of the feature or component under test respectively.

As both i and r are always less than one, I and R are always positive.

4.3.1 SYSTEM SENSITIVITY The sensitivity of the MILLIMETER RESOLUTION OTDR may be calculated from the laser pulse power values, detector sensitivities and the attenuation values of couplers and attenuators if these are used for the particular operating mode. The values are listed below in Table 4-1 in units of dBm or dB. Detector sensitivities are given for both 2 second long averaging, (approximately 100 averages) and for 2 long minute averaging, (approximately 10,000 averages). The detector sensitivity values are given for a signal to noise ratio (S/N) of one.

Wavelength (nm)	680	800-860	904	1300	1550
LASER POWER (P)					
SM	--	+23	--	+14	+11
MM-50,-62.5,-100,	+17	+23	+27	+17	+14
MM-200,400	+17	+23	+27	+17	+14
DETECTOR SENSITIVITY (D)					
(2 second averaging)					
Si APD MM100	-36	-37	-36	--	--
Si AMP APD MM100	-52	-53	-52	--	--
PHOTON COUNTER. MM100	-79	-80	-79		
Ge APD MM100	--	-24	-24	-27	-28
Ge AMP APD MM100	--	-40	-40	-43	-44
(2 minute averaging)					
Si APD MM100	-46	-47	-46	--	--
Si AMP APD MM100	-62	-63	-62	--	--
PHOTON COUNTER. MM100	-89	-90	-89		
Ge APD MM100	--	-34	-34	-37	-38
Ge AMP APD MM100	--	-50	-50	-53	-54
FOR MM200 ADD	+ 0	+ 0	+ 0	+ 6	+ 6
FOR MM400 ADD	+ 6	+ 6	+ 6	+12	+12
COUPLER ATTENUATION (C)					
SM	--	+10	--	+ 9	+ 9
MM-50,-62.5-100	+12	+ 8	+ 9	+ 8	+ 8
MM-200 (1 port)	--	+ 5	+ 5	--	--
MM-400 (1 port)	--	+ 5	+ 5	--	--
ATTENUATOR ATTENUATION (A)					
SM	--	+ 3	--	+ 2	+ 2
MM-50,-62.5,-100	--	+ 2	+ 2	+ 2	+ 2
CONNECTOR ATTENUATION (CO)					
SM	+ 1	+ 1	+ 1	+ 1	+ 1
MM	+ 0.5	+ 0.5	+ 0.5	+ 0.5	+ 0.5

TABLE 4-1
The power output, sensitivities and insertion loss figures in dBm and dB values for the various components utilized in the MILLIMETER RESOLUTION OTDR system. Receiver values are for a signal to noise ratio of one.

4.3.2 LOSS BUDGET FOR TRANSMISSION OPERATION In this mode, the laser launches the probe pulse into the fiber under test and the detector detects the light at the other end as shown in Figure 4-5 below. In free space applications the fiber is replaced with relevant optics.

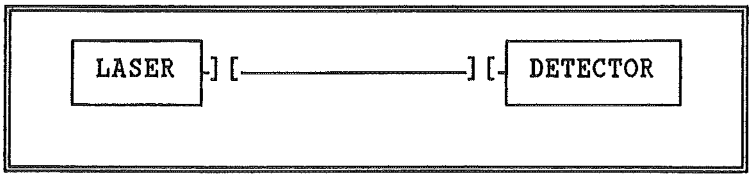


Figure 4-5

Transmission operation through a fiber,
a network, a component or in free space.
No fiber coupler is required.

The transmission loss budget is calculated directly from the values in Table 1-4 using Equation (4-3) below;

Transmission Loss Budget TLB = P-D-2CO (4-3)

where P is the laser pulse power, D is the detector sensitivity and CO is the connector insertion loss.

The smallest TLB value of 39 dB is calculated from Table 4-1 to be for a singlemode 1300 nm laser combined with a Ge APD after 2 seconds averaging. The highest TLB value of 110 dB is obtained for a multimode 904 nm laser combined with the photon counting detector after 2 minutes of averaging.

4.3.3 LOSS BUDGET FOR REFLECTION OPERATION In this mode, the laser launches the probe pulse into the coupler, the coupler transmits to the fiber under test and the returned pulse is directed by the coupler to the detector as shown in Figure 4-6 below.

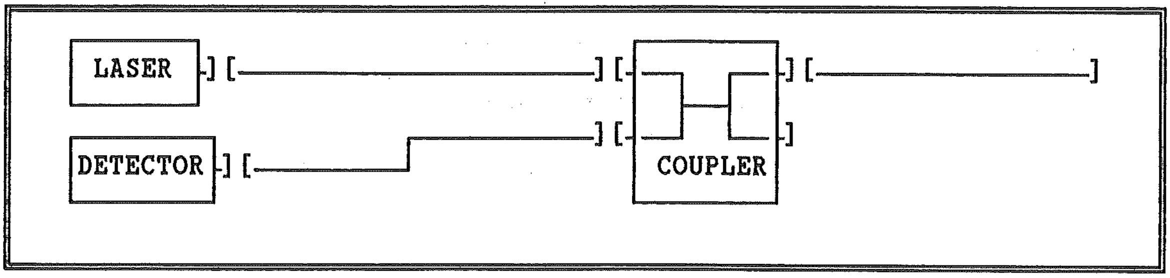


Figure 4-6

Reflection operation using a coupler to
probe a fiber under test from a single end.

In the Fresnel mode, both return loss and insertion loss may be measured. The return loss budget is calculated from the values in Table 4-1 using Equation (4-4) below;

Return Loss Budget $$RLB = P-D-C-4CO \qquad (4\text{-}4)$$

where P, D, C, and CO are the laser pulse power, detector sensitivity, coupler attenuation and connector insertion loss respectively.
Some typical RLB values can be calculated from Table 4-1 to be 51 dB for a 1300 nm singlemode laser, combined with an amplified Ge APD with 2 minutes averaging and 75 dB for an 850 nm multimode laser combined with an amplified Si APD with 2 minutes averaging.

The insertion loss is calculated from the values in Table 4-1 using the Equation (4-5) below;

Insertion Loss Budget $$ILB = 0.5 \cdot (P - D - C - 4CO - 14) \qquad (4\text{-}5)$$

where the symbols take the usual meanings.

The 14 dB term in Equation (4-5) is a reminder that both MEASUREMENT and REFERENCE are pulses returned by flat polished open connectors, or cleaved fiber ends with reflectivities of 4% or a return loss of 14 dB. If this is not the case, but, for example, two mirrored ends are used as MEASUREMENT and REFERENCE, then the 14 dB term would become zero.

The 0.5 term in Equation (4-5) is a reminder that the insertion loss is specified as a one way loss.

Some typical ILB values can be calculated from Table 4-1 to be 20 dB for a 1300 nm singlemode laser combined with an amplified Ge APD with 2 minutes averaging and 30 dB for an 850 nm multimode laser combined with an amplified Si APD with two minutes averaging.

A summary for the Fresnel reflection, insertion and return loss budgets is given in the graphs in Figures 4-7 and 4-8 below. The loss budget graphs give typical Opto-Electronics MILLIMETER RESOLUTION OTDR performance for variously configured OTDR's. The horizontal axis is the signal to noise ratio of the OTDR signal. The SNR = 1 values are those calculated from Table 4-1 by Equation (4-4) and Equation (4-5).

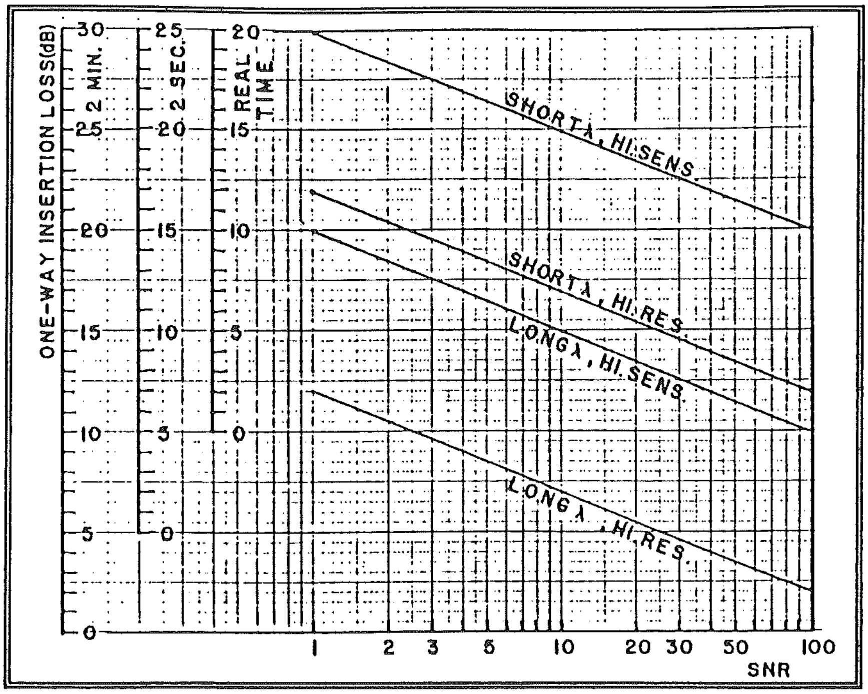


Figure 4-7
Return loss budgets calculated, using Equation (4-4) for four typical MILLIMETER RESOLUTION OTDR configurations as functions of the returned signal SNR and as functions of the averaging time.

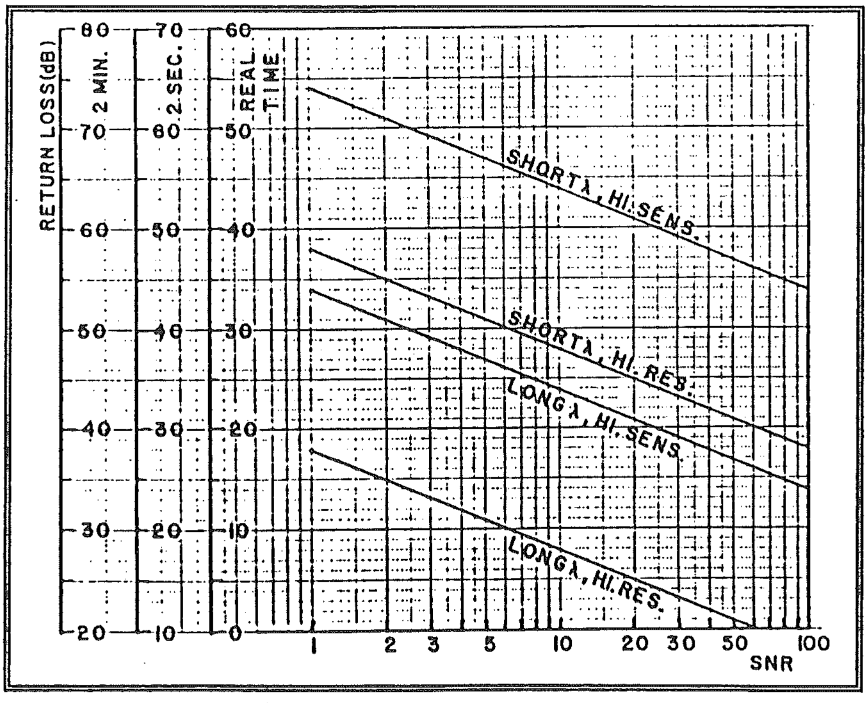


Figure 4-8
One way insertion loss budgets calculated, using Equation (4-5) for the four typical MILLIMETER RESOLUTION OTDR configurations. as functions of the returned signal SNR and as functions of the averaging time.

In Figure 4-9 below, return loss budgets of the four example OTDR's and a photon counting model are contrasted with return loss values of typical features and components commonly found in most fiberoptic systems. This figure gives a good idea of how far "down" the Opto-Electronics MILLIMETER RESOLUTION OTDR can reach to detect and measure these features.

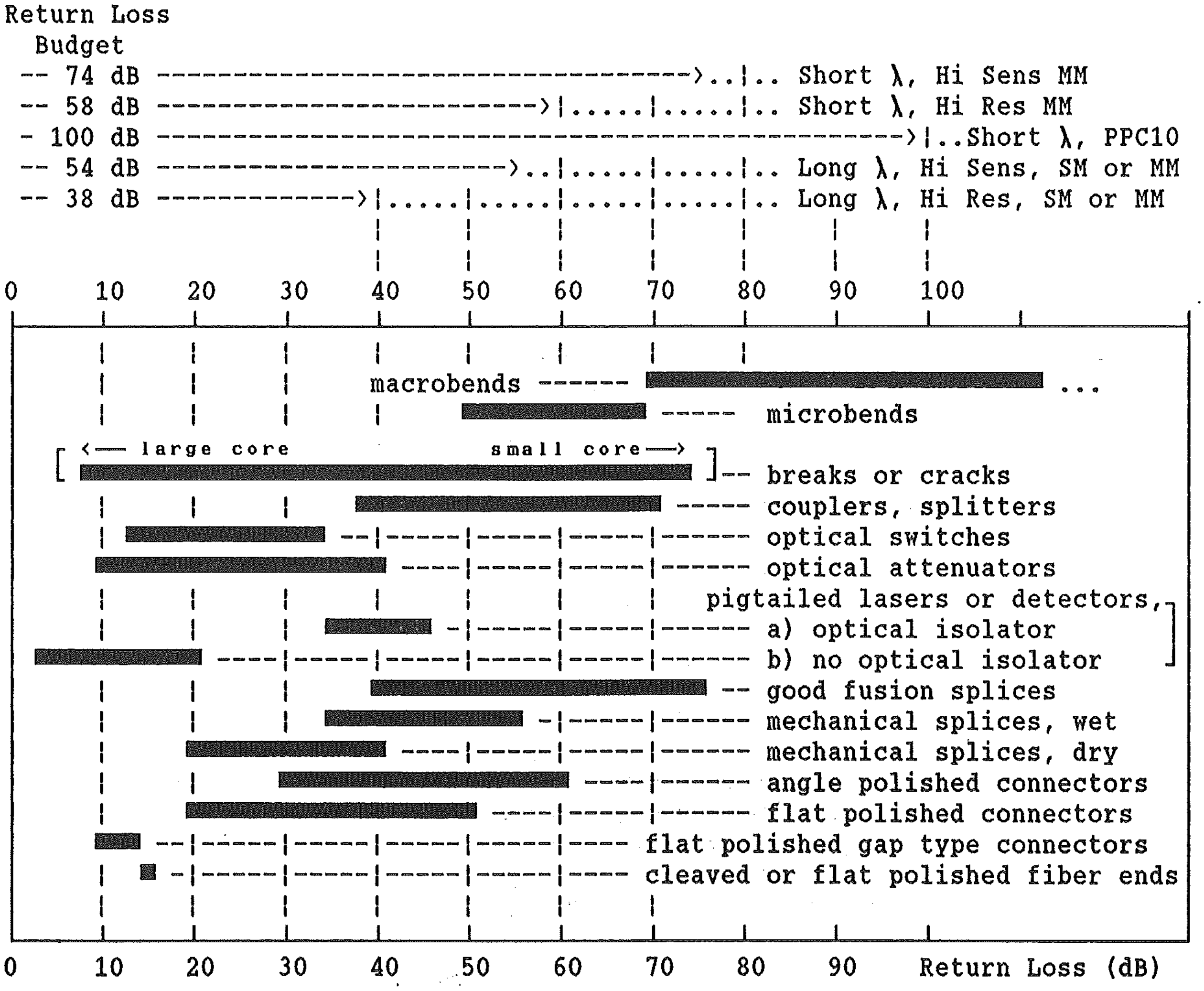


Figure 4-9

The loss budgets of four typical configurations of the Opto-Electronics MILLIMETER RESOLUTION OTDR and that of a photon counting model are contrasted with the return loss values of common fiberoptic features, components and faults. It is seen that some models have limited capabilities while the photon counting configuration can detect every feature that is commonly found in a fiber optic link or system. The loss budget values are at SNR = 1, with 2 minute averaging.

4.3.4 LOSS BUDGET FOR RAYLEIGH BACKSCATTER OPERATION

For this mode of operation a short wavelength laser is combined with the photon counting detector. Otherwise, the system is configured similar to Fresnel reflection mode except, a calibrated attenuator is placed between the laser and the coupler. The optical circuit for the Rayleigh backscatter operation is shown in Figure 4-10 below.

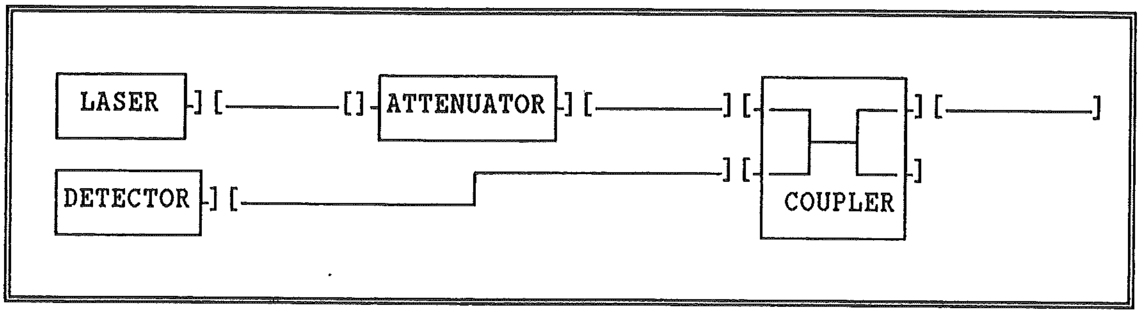


Figure 4-10

Rayleigh backscatter operation using a photon counting detector to probe the fiber under test from a single end.

In the Rayleigh backscatter mode the insertion loss is measured. The loss budget is calculated from the values in Table 4-1 using Equation (4-6) below;

Rayleigh Insertion Loss Budget

$$RILB = 0.5(P - D - A - 6CO - X) \tag{4-6}$$

Where P is the laser power, D is the detector sensitivity, A and C are the attenuations of the attenuator and the coupler, respectively, CO is the insertion loss of the connector and X is the "Return Loss" of the length of fiber illuminated by the laser pulse.

The value of X for the ultrashort pulse widths of the Opto-Electronics MILLIMETER RESOLUTION OTDR varies over a wide range depending on the wavelength of the laser transmitter and the type and core size of the fiber.

Typically, at 850 nm, the value of X for 50/125 graded index communications fiber is approximately 70 dB and for 9/125 step index communication fiber, X is approximately 80 dB.

Taking the 2 minute averaged values at 850 nm from Table 4-1, the Rayleigh insertion loss budgets for 50/125 and 9/125 fibers may be calculated to be 16 dB and 7 dB respectively.

If the insertion loss of both fibers are assumed to be 3 dB / km, the range over which Rayleigh detections and measurements may be made is approximately 5 km and 2 km for the two fibers respectively.

These ranges are quite adequate for most millimeter resolution measurements as they are usually carried out in lengths of fiber from a few meters to a maximum of a few 100's of meters.

4.4 AVERAGING and CALCULATIONS

4.4.1 SIGNAL AVERAGING Part of the OTDR Processor is a digital instrument with analog interfaces designed specifically to mathematically average low level signals from the sampler or photon counter. Signal averaging is a conceptually simple yet very powerful technique that can be used to improve the SNR of repetitive signals. Signal averaging works because the repetitive signal of interest has the same fixed amplitude each sweep and the accumulation process reinforces the signal, while the random noise will vary about the mean, averaging to zero. The OTDR Processor uses linear summation averaging which gives the largest improvement possible in SNR for a given number of averages. For linear summation averaging, the signal Y(N) at a given point after N averages is given by

$$Y(N)=S\sum_{J=1}^{N}Y(J) \qquad (4\text{-}7)$$

where S is the scaling factor and Y(J) is the Jth sample taken at this point. For a white noise background, the SNR improvement is theoretically the square root of N and the OTDR Processor achieves better than 90% of the theoretical improvement. In order to correct for coherent background noise, such as repetitive variation in the sampling baseline, the OTDR Processor takes a background average which is subtracted from the signal before display. The combination of these two techniques enables expansion of the effective sensitivity of the detection system by over 20 dB.

4.4.2 OTDR PROCESSOR INTERFACES The Sampler or the Photon Counter takes a new sample of the input waveform each time it receives a trigger pulse. Each time a new sample is taken, a pulse is delivered to the OTDR Processor which uses the pulse as an indicator that a new data point can be taken.

The Sampling unit or Photon Counter takes a sample at a time delay governed by the PDG20 delay and sweep control. The OTDR Processor controls the sampling position using an 8 bit digital-to-analog converter, giving 256 points across the screen. The vertical signal out from the sampling unit is proportional to the sampled signal amplitude, and is fed to an 8 bit analog-to-digital converter in the OTDR Processor. The OTDR Processor waits for and converts four samples per horizontal point before moving to the next point, and thus the number of scans that the sampler makes is one fourth the number of averages. This gives a screen output update of approximately 25 Hz.

The vertical input range of the OTDR Processor is set to correspond to the 8 division high oscilloscope screen plus a one division overrange margin above and below the screen. The best performance is obtained when the maximum possible input range is used, so the sampler should always be set on the most sensitive scale possible, consistent with keeping the signal plus noise on the screen. Similarly, the output to the display oscilloscope corresponds to a 10 division high display at the proper vertical sensitivity so that a display scaling factor of one produces a displayed signal having the same height as the sampled trace. The display scaling factor effectively multiplies the displayed data, thus enabling calibrated measurements to be taken on signals which would otherwise be too small to see.

4.4.3 PULSEWIDTH (FWHM) CALCULATIONS The FWHM display on the OTDR Processor can be a very useful feature. However, to get reliable results it is necessary to know something about how the calculations are done. The algorithm used was designed to give accurate results with the widest possible range of pulses and step functions. All the risetime and pulsewidth calculations are done on the same data which is fed to the display scope.

To calculate pulsewidth (full width at half maximum) it is first necessary to have values for the 0% and 100% level. To obtain a 0% level, the OTDR Processor averages the fifth through eighteenth points from the left hand edge of the scope screen and calls this the zero level. The first few points are skipped to avoid any error due to the scope retrace. To obtain the 100% value, the OTDR Processor searches the display data for the maximum value on the screen. It then does a thirteen point parabolic fit about this point, and determines the 100% value from this fit. The combination of the thirteen point baseline average and the parabolic fit to the peak gives accurate results on signals that still have some degree of noise. The OTDR Processor now calculates the FWHM by doing an eight point running average starting at the baseline, looking for the 50% value. If the displayed signal is especially noisy, the FWHM will not be calculated.

Once a valid MEASUREMENT and REFERENCE set of data become available, the OTDR Processor proceeds according to the setting of the calculation mode switch. These modes are described below.

Shift Mode

In the shift mode, the peaks of the MEASUREMENT and REFERENCE are found by doing a parabolic fit around the maximum as described for the FWHM above. The time separation of the two peaks is the calculated and displayed value in the units previously set up. In addition, for loss measurements the areas under the curves are calculated from which the loss is determined and displayed in units of dB.

Resolve Mode

It is assumed here that the MEASUREMENT data set consists of two pulses, of shape identical to that of the reference pulse. The two pulses may partially overlap. The algorithm then resolves the composite MEASUREMENT pulse into the two component pulses, calculates and displays the time separation. The accuracy of resolution depends on the peak amplitude ratio of the two pulses as well as on their actual separation. The ratio should be better than 10:1 and the separation should be greater than 1/2 FWHM. See Figure 4-3 in section 4.2.

28

Note that the amplitude and position of the reference pulse are irrelevant, since only the functional shape of the pulse is used in the calculation. However as noted earlier it is best to fill the screen especially if the pulse is noisy.

Subtract Mode

This mode is used where the signal is a double pulse, but one of the two constituent pulses is available as REFERENCE. Here, the second pulse may be accurately calculated by subtracting the REFERENCE from the MEASUREMENT data. The positions of the peak of the REFERENCE and DIFFERENCE pulses are then calculated, and their time separation is displayed.

Note that here the amplitude and position of the REFERENCE are important. Any drift or amplitude change from acquisition of one set of data to the other will affect the accuracy of the results. This mode is very accurate, allowing separation of pulses with any degree of overlap.

5 APPLICATIONS

The MILLIMETER RESOLUTION FRESNEL REFLECTION OTDR is typically used in areas where conventional OTDR's fail due to their large dead zone, lack of dynamic range or lack of resolution. These areas occur in medium, short and very short haul fiberoptic harnesses, links, systems and networks, in fiberoptic components and sensors and in optical waveguides.

The MILLIMETER RESOLUTION RAYLEIGH BACKSCATTER OTDR is used where extremely small perturbations in fibers need to be detected or measured with very high spatial sensitivity or with very high spatial separation or resolution. Typical applications include microbends, splice losses, cracks or breaks in fibers and a host of fiberoptic point and distributive sensing.

The ultra high resolution OTDR is used by research and development workers, by fiberoptic engineering designers, by fiberoptic sensor developers, by outside plant people, by people who monitor and check installed fiberoptic systems such as aircraft or weapons readiness, computer interconnections or secure links and many other areas.

In this summary, typical applications are briefly discussed relating to modality, distance, time, fault, strain, temperature, loss, sensor, mapping, monitoring, dispersion and bandwidth measurements.

5.1 MODALITY RELATED APPLICATIONS

The OTDR must be fitted with the correct core size output fiber for each particular application. For every core size the output fiber has equilibrium mode distribution to assure accurate measurement results.

5.1.1 SINGLE MODE APPLICATIONS Measurements on single mode fibers require the OTDR to have the proper 5 or 9 micrometer core size fiber output. However, measurements on singlemode fibers can also be made with an OTDR fitted with larger core fibers such as 50 or 100 micrometers. The larger core output would launch light into the singlemode core plus the cladding and the cladding modes would be stripped out by the buffer over a length of a few centimeters from the input end. The only consequence of using a multimode OTDR on a singlemode fiber is the launching loss. In the case of the 50 to 9 micrometer mismatch the loss would be about 15 dB and in the case of the 100 to 9 micrometer mismatch the launching loss would be about 21 dB.

The returned pulse does not suffer any extra attenuation when coming from the 9 micrometer fiber into the larger core. Therefore, the above mentioned mismatch losses of 15 dB and 21 dB should be considered as one way losses for the purpose of calculating the reduced loss budget of the OTDR.

5.1.2 MULTIMODE APPLICATIONS Measurements on multimode fibers require the OTDR to have the output fiber core size the same as , or larger than, that of the fiber to be measured. In case of "the same as" there is no mismatch loss but in the case of "larger than" the loss is similar to the singlemode case. For a rough estimate of the mismatch loss between fibers with diameters d and D, Equation (5-1) may be used to determine the loss.

$$\text{Mismatch Loss} = -10\cdot\log(d/D)^2 \qquad (5\text{-}1)$$

Using an OTDR fitted with small core size output to measure a larger core fiber is not advised. This configuration causes the lower order modes only to be excited in the larger core fiber. This can lead to inaccuracies in some measurements. If, for example, a singlemode OTDR was used to measure a multimode fiber link, the results would deviate from the true values for length, time of flight, insertion loss, connector insertion loss and return losses, splitting ratios of a coupler, fiber dispersion and fiber bandwidth.

For this reason, the OTDR should not be used to measure fibers with core sizes larger than its output core size unless the effects of modality need to be investigated in fibers or components.

The mismatch loss is also present in this configuration with approximate values given by Equation (5-1) except the loss occurs on the way back when the returned pulse is launched onto the smaller OTDR core from the larger core sample fiber.

5.2 DISTANCE RELATED APPLICATION

5.2.1 EFFECTIVE GROUP INDEX MEASUREMENTS The ultra high resolution OTDR, as all other OTDR's, is a time-of-flight measuring instrument. In order for it to measure distance or length, the effective group index (n_e) of the fiber has to be known to several decimal places. The value of n_e is usually not known with an accuracy better than 0.1%. Therefore, distance measurements cannot be made with better accuracy then this figure no matter how accurately the time of flight is measured, unless an improved value of n_e is determined.

The difficulty in measuring a precise value of n_e with conventional OTDR's is that a long fiber, usually one kilometer or longer needs to be used. The OTDR is used for the time of flight measurement, some other means is used for the physical length measurement and then n_e is calculated using Equation (5-2) below;

$$n_e = Ct/2L \tag{5-2}$$

where C is the velocity of light in vacuum, t is the two way time of flight of the optical pulse in the fiber and L is the length of fiber.

The source of greatest uncertainty in the method is the physical length measurement and the unknown degree of fiber strain. The Opto-Electronics MILLIMETER RESOLUTION OTDR can easily solve the above mentioned length measurement and strain problem as it can measure time of flight within one picosecond, therefore, n_e may be determined using short lengths of fiber. For example, the typical ±0.1% accuracy for n_e can be achieved using a 1 meter length of fiber whose length is measured easily with ±1 millimeter accuracy. For greater n_e accuracies, longer fibers are needed. If 10 meter and 100 meter lengths are used, whose lengths are also measurable to ±1 millimeter, n_e may be determined to be within 1 part per ten thousand and one part per hundred thousand respectively.

When making these measurements, the longitudinal strain of the fiber can also be eliminated by monitoring the position of the returned pulse on the screen. An elongation of one millimeter over the 1, 10 or 100 meter sample is easily detected by the OTDR. More details are given about strain below.

5.2.2 ABSOLUTE LENGTH MEASUREMENTS Having established the value of n_e, it is entered in the OTDR memory. Now time-of-flight measurements can be converted into distance.

Length is always measured between two reflective features. The nearer feature to the OTDR is usually called REFERENCE and the farther one is called MEASUREMENT. The REFERENCE feature may be the bulkhead connector of the OTDR, the far end of the output pigtail, or the input end of the sample spool,etc. The MEASUREMENT may be the far end of the sample spool, a connector in the link, or a laser at the far end of its pigtail. These are a few of many possibilities.

In other situations there may be several reflective features along the fiber link or network. Here, length measurements may be made between any two features or a series of measurements between two adjacent features. In this case a REFERENCE may be chosen again, usually to be the input end of the link or network and the downstream features become successive measurements.

Length measurements may be made in real time with sub-centimeter accuracy in "real-time" or with millimeter accuracy by running some averages over a few seconds. In the MILLIMETER RESOLUTION OTDR the measured waveforms of REFERENCE and MEASUREMENT and their associated values are stored in memory for subsequent recall or for further calculation.

5.2.3 RELATIVE LENGTH MEASUREMENTS There are many examples for relative distance measurements. First there may be a need to measure the relative distance between two connectors at the end of a long link without wanting to know the link length, or to determine the position of a break relative to a splice with known position regardless of its distance from the OTDR. In this class of measurements, as in absolute distance measurements above, the use of a REFERENCE for the unknown feature and the use of MEASUREMENT for the unknown feature is recommended. Measurements are possible again in real-time or can be averaged.

In another class of problems MEASUREMENT lengths of fibers may be compared with, or trimmed to the length of a REFERENCE fiber without having to know their overall lengths. In this case both parallel outputs of the OTDR are used. The REFERENCE length is plugged into one port permanently and the returned pulse from the far end is placed in the middle of the screen. This data is stored . A MEASUREMENT fiber can now be connected to the other output port and the returned pulse from its far end can be measured to determine the differential length. Trimming may be carried out until the two return pulses overlap. Sub-millimeter length matching can be achieved in this way.

In yet another class of problems the REFERENCE length may change in time due to strain, temperature or other effects so that MEASUREMENT measurements are required to determine the changes. These changes may be measured down to one millimeter with frequency up to one measurement per second. Real-time monitoring of the pulse position on the screen is also possible to check for fiber strain during cable pulling, wind and ice loads on aerial cables or strain on the fiber of fiber tethered devices, etc. More details are given about this in Strain Related Applications below.

5.2.4 DISTANCE MEASUREMENTS IN FREE SPACE The MILLIMETER RESOLUTION OTDR may be used to measure distance in free space, air of any other non-scattering medium as well as in fiber. To carry out free space distance measurements, the output connector of the OTDR is fitted to the focal plane of a small telescope and the telescope is focused onto a reflective tape, a corner cube or a "Cat's Eye" reflector placed at the far end position. The distance between the output connector and the far end reflector may be measured with millimeter accuracy over distances of up to a hundred meters in air. The measurement requires the appropriate atmospheric index of refraction to be known for the distance calculation.

Such a through the air measurement in conjunction with a through the fiber measurement can be utilized to measure the index of refraction of a piece of fiber. In this method, absolute length measurements are not needed as the time of flight ratio between air and glass is measured directly and this is, by definition, the index of refraction.

If the photon counting detector is used, the greatly increased sensitivity permits free space distance measurements to be made without a telescope or reflecting tape, etc. A simple arrangement of two fibers strapped together and cleaved at the far ends can serve as the transmitter and receiver apertures. Distances from this probe to objects with reasonable reflectances can be measured with millimeter accuracy over several meters.

5.3 TIME RELATED APPLICATIONS

In many applications the important property of the fiber link or network is the time of flight rather than the physical distance. Measuring the time of flight is a simple procedure with the OTDR. For time measurements the effective group index of the fiber is not required.

It should be noted that the time delay displayed is the time-of-flight of the optical pulse from the OTDR (or from REFERENCE) to the MEASUREMENT feature and back to the OTDR (or to REFERENCE) i.e. the round trip time delay. From Equation (5-2), the relationship between round trip time delay and fiber distance is shown in Figure 5-1 for n_e = 1.5 and C = 300,000 km/s. The values of n_e and C were chosen to give an easily remembered and approximately correct relationship between distance and time, i.e. distance in meters is one tenth of the round trip time in nanoseconds.

Measurements of time with the OTDR proceed exactly as measurements of length or distance described in the previous section, utilizing REFERENCE and MEASUREMENT. The operator may measure absolute time delay or relative time delay in real time or averaged with the results stored in memory and can measure delay time in fibers or in free space similar to distance measurements. In all cases , however, the delay times shown are the two-way time-of-flight figures.

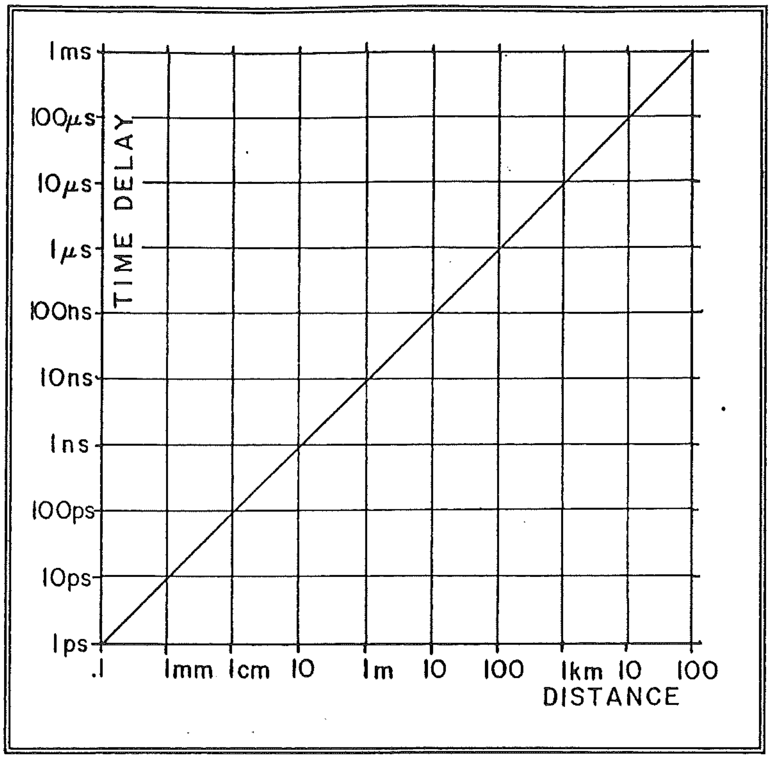


Figure 5-1
Approximate round trip time of the optical pulse in a fiber with effective group index $n_e = 1.5$ as a function of fiber length.

5.3.1 DELAY LINE CALIBRATION One special application of time related measurements is delay line calibration or testing. Here the REFERENCE feature is the input connector to the delay line fiber and MEASUREMENT is the output (far end) of the delay line fiber. The measurement is straightforward but, because of the very high accuracy of the OTDR, some important caveats are necessary. One: Observe the wavelength carefully. For shorter wavelengths such as 850 nm, a deviation from the specified wavelength by five or ten nanometers may result in an appreciable time delay error. Two: Ambient temperature has to be measured and recorded, as a 1 °C temperature change may change the time delay of a 1 km long delay line (5 microsecond delay) by up to 50 picoseconds. Three: The fiber should be free of mechanical strain because strain influences the effective group index of the fiber, and thus, the time delay.

5.3.2 FIBER INTERFEROMETER CALIBRATION In certain fiber interferometer circuits the two fiber arms of the interferometer have to be made equal in time delay to be within one cycle of the optical wavelength. Using the high resolution OTDR the two arms can be trimmed to such lengths and existing devices can be tested for such a condition.

To trim two fibers within a few millimeters was described in relative length measurements above. In time, the same procedure is followed. When the two fibers are within 10 or so picoseconds, the returned pulse on the screen will start showing an intensity variation due to the beating of the two component pulses. A slight stretching of the shorter fiber will increase the beating until the largest fringe occurs. When the pulse reaches the highest amplitude the two fibers have the same optical length within a small fraction of the wavelength. Now the shorter arm may be relaxed and the longer arm may be polished down to achieve the same maximum pulse amplitude condition. At this point, the two arms have the same optical length.

5.4 FAULT RELATED APPLICATIONS

Faults in fiber optic harnesses, networks, links or pigtailed modules and components are associated with either the fiber itself or with the modules and components in the network or link. Common faults may be breaks, cracks and microbends in fibers, damaged connectors or splices, and high insertion, return or scattering losses in modules and components. Faults may also develop in the transmitter or receiver ends of a link due to optical or electronic causes. Faults may be present from the time of installation of a system or may develop gradually or suddenly.

Fault detection in short haul and very short haul systems with lengths of a few centimeters to a few tens or hundreds of meters is very difficult or impossible using conventional OTDR's even if they are the so-called high resolution types. This is especially true if there are closely spaced or numerous connectors or components in the system. The narrowest pulsewidth used in conventional high resolution OTDR's is 3 nanoseconds. This pulse hides a length of fiber approximately 5 meters long in the Rayleigh backscatter mode or over 1 meter in Fresnel reflection mode.

On the other hand, the Opto-Electronics MILLIMETER RESOLUTION OTDR with their 100 picosecond pulsewidth are ideally suited to detect the precise location of a fault and to indicate its nature. This is due to the high resolution, zero deadzone and high loss budget of the instrument.

5.4.1 GENERAL FAULT LOCATION If a fault in a link is suspected, the WINDOW SIZE of the OTDR is opened to the link length and the returned waveform is viewed. The location of the fault is estimated from the last return pulse on the screen. The WINDOW SIZE is now decreased to the normal 0.5 meters and the RANGE is set to the distance estimated at the last return pulse. The screen can now be advanced downstream by stepping the time delay generator until a return pulse is found which corresponds to the fault. This could be a break, a crack or a microbend.

5.4.2 FIBER BREAKS and CRACKS An open break or crack in a fiber may reflect much or little light incident upon it, depending on many factors. Generally, the larger the core diameter of the fiber, the greater the reflected power is, i.e. the smaller the numerical value of the return loss is. The normal range of return loss values for fiber breaks and cracks is plotted in Figure 4-9 ON PAGE 4-11. It is seen from the figure that not all breaks and cracks are detectable by all the OTDR models, so a careful consideration is needed to choose the right model for any specific fiber.

Breaks and cracks can be detected next to connectors and splices within the loss budget of the OTDR. The minimum detectable separation depends on the relative intensities of the return pulses from the connector and the break as discussed in Section 4-2.

5.4.3 MICROBENDS and MACROBENDS Figure 4-9 on page 4-11 shows the range of return loss for micro and macrobends. Microbends, which are responsible for moderate to severe insertion losses (faults) have lower return loss values and are more easily detected by the high resolution OTDR than macrobends. Macrobends are seldom considered as faults because they generally produce very small insertion losses.

5.4.4 FAULTY CONNECTORS and SPLICES The range of return loss values of various connectors and splices are shown in Figure 4-9 on page 4-11. In order to determine connector integrity in a system with a number of connectors, the WINDOW SIZE is opened to the link length and the return pulses from the string of connectors are displayed on the screen. A faulty connector usually shoes up as a strong reflection followed by very small intensity return pulses from connectors downstream from the faulty connector.

5.4.5 SPLITTERS and COUPLERS Excess loss and coupling ratio of these devices are important parameters in links, especially in star networks using multiport couplers. In this situation a MAP function may be set up using a PC connected to the OTDR by GPIB. The PC may now record all possible input and output combination losses and splitting ratios. When a problem occurs, a simple and quick TEST reveals the source of the problem.

The loss budget of the Opto-Electronics MILLIMETER RESOLUTION OTDR permits the testing of star couplers with up to 16x16 ports for 850 nanometer multimode systems. More details about this will be given in Section 5.8 below.

5.4.6 OTHER FAULTY COMPONENTS Switches, attenuators, pigtailed lasers and detectors may develop faults due to pigtail breaks or cracks, pigtail alignment shifts or other reasons. To detect these faults it is most helpful to take a signature of the component when it is functioning properly. When a fault is suspected, a new measurement of the component is made and is compared with the original signature. In most cases this reveals the source of the failure. For example, the two signatures may be subtracted to find the residual pulse, which corresponds to the failure point. In other cases the DECONVOLVE function is used to reveal the problem.

5.5 STRAIN and TEMPERATURE RELATED APPLICATIONS

Longitudinal, shear, radial or torsional stresses cause corresponding strains in fibers. These affect various characteristics of the fibers. The temperature of the fiber also affects its propagation characteristics in various ways. These changes can easily be measured by the MILLIMETER RESOLUTION OTDR. Typical examples are given below.

5.5.1 LONGITUDINAL FIBER STRAIN When a length of fiber is pulled, it stretches. The maximum stretch before the fiber breaks is typically 1% to 3% of its original length. the Young's modulus of quartz based fiber is constant up to the breaking point. This results in a linear relationship between the pulling force (stress) and the resulting elongation (strain). Accurate knowledge of the stress-strain relationship in a fiber and its effect on its optical properties is important.

Using the MILLIMETER RESOLUTION OTDR, these measurements may be carried out accurately on short lengths of fiber where the strain is on the millimeter or centimeter scale and where physical length measurements are easily performed. A typical measurement of a stress-strain relationship is carried out in the MEASUREMENT mode by measuring the far end of the test fiber without stress applied, then by repeating the measurement for stress 1, stress 2 etc., until the fiber breaks. When the OTDR length readings are plotted against the stress values a linear relationship is usually obtained.

When making this measurement it is important do so in nanoseconds rather than in meters as the effective group index changes during the straining.

The change of the effective group index n_e with strain is referred to as the "ELASTO-OPTIC EFFECT" in a fiber and it is due to the decrease of density of the quartz with increasing longitudinal strain. The decrease of density leads to a decrease of the index n_e. The net effect of the index change is that when a given fiber is stretched by say 1% of its original length, the apparent length change, as measured by an OTDR using a distance scale, may be 0.88%. For example, if a 10 m long fiber is stretched to the physical length of 10.1 m, (stretched by 10 cm) the OTDR would indicate an elongation of 8.8 cm only. The difference is due to the change in n_e between the fiber when it was 10 m long and the fiber when it became 10.1 m long.

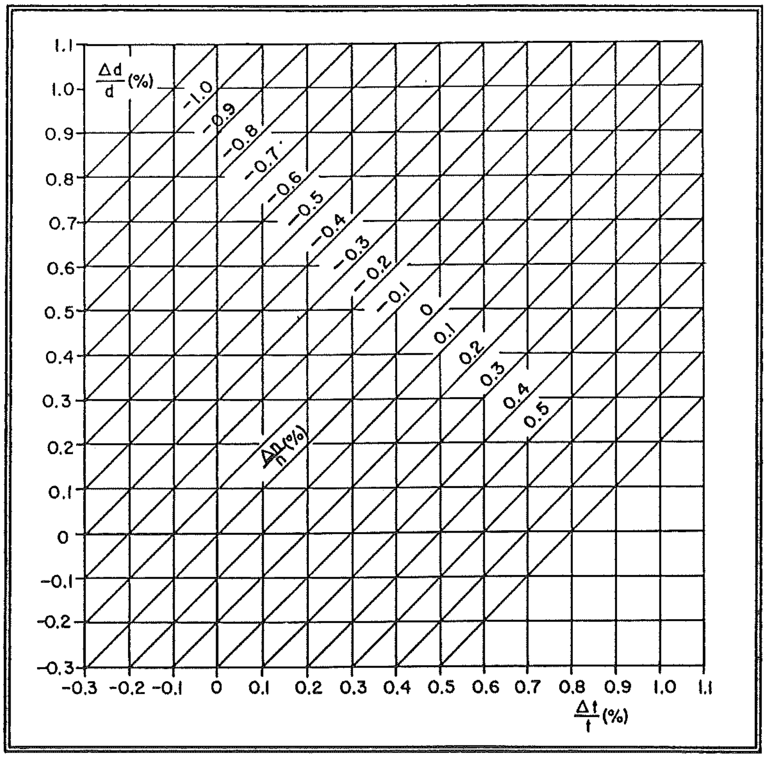


Figure 5-2
Plot of Equation (5-3) used to determine the strain coefficient of the effective group index.

The effective group index change δn_e with strain is measurable using the OTDR on short fiber samples, (1 to 3 m) by measuring the unstrained length d and the length change δd mechanically and by measuring the time delay t of the unstrained fiber and the time delay change δt. The relationship is given in Equation (5-3) below and is plotted in Figure 5-2.

$$\delta n_e / n_e = \delta t/t - \delta d/d \qquad (5\text{-}3)$$

5.5.2 <u>SHEAR FIBER STRAIN</u> When shear stress is applied to a fiber at a single point, a microbend results. Depending on the severity of this microbend, light from the core may escape into the cladding and possibly beyond and the transmitted light intensity decreases. This is then a fault, as discussed previously.

The location of a shear strain can be detected and its severity can be measured by the OTDR down to intensities indicated in Figure 4-9. Shear strain in fibers can be therefore monitored at various locations which is useful for strain monitoring in mechanical structures and smart skins. This will be further discussed in Sensor Applications below.

5.5.3 <u>RADIAL FIBER STRAIN</u> Radial fiber strain has to be severe to cause any measurable effect in commonly used fibers. Specialty fibers with very small core/cladding differential index may be effected by radial strain. In this case light would escape the core into the cladding and result in a transmission loss. Even in this case, there would be very little backscattered light. Therefore radial fiber strain is not normally detectable by an OTDR either in the Fresnel or in the Rayleigh mode.

5.5.4 <u>TORSIONAL FIBER STRAIN</u> A fiber may be readily twisted, which for commonly used fibers, does not result in any transmission loss or other noticeable effects, therefore its location can not be detected. However, there is one interesting application of torsional fiber strain, which is to use it to rotate the direction of polarization of the linearly polarized light output of the OTDR singlemode model for specialty measurements. These specialty measurements include the measurement of beat length in polarization preserving fibers, measurement of extinction ratios in polarization preserving fibers, measurement of gap sizes between optical fibers for fusion splicing and in many other measurements where linearly polarized output is required for the Millimeter Resolution OTDR.

5.5.5 <u>CABLE PULL TESTING</u> Ideally, a cabled fiber should not be strained when the cable itself is strained. This is usually true up to a certain degree of cable strain. Beyond this threshold strain, the fiber elongates along with the cable. An accurate knowledge of the threshold strain and the relationship between cable and fiber stretching is important for cable manufacturers, cable installers and cable users. A strained fiber is known to fail in use over a shorter period than an unstrained one.

The MILLIMETER RESOLUTION OTDR system is ideally suited for cable stretch measurements because it can accurately measure very small length changes. It can measure precisely the threshold point of a cable in the manufacturer's quality control lab during pull testing, provide accurate values for cable/fiber elongation relations and can monitor the severity of pulling forces and the effect of sharp bends during cable pulling in new installations. The system can also be successfully employed in the monitoring of fiber strain for installed aerial cables due to wind and ice loads and to provide useful long term data.

The measurements here are similar to those for longitudinal fiber strain. The return pulse from the far end of the unstrained fiber is brought onto the screen and used as the reference. Strain is measured by taking repeated MEASUREMENTS during the pulling process. The values of the measurements may be downloaded to a PC via GPIB for storage or further processing.

5.5.6 FIBER PAYOUT STRAIN MONITORING In fiber guided devices the fiber is sometimes paid out rapidly from a spool causing a variable degree of strain in the fiber. The OTDR can monitor the integrated value of this strain in real-time as well as monitor the transmission losses associated with the rapid payout.

Singlemode fiber lengths up to 10 km can be measured with resolution on the order of several millimeters.

5.5.7 TEMPERATURE RELATED APPLICATIONS The temperature coefficient of the effective group index of fibers varies with the type of dopant used in the fiber. Standard communications fibers exhibit an index change resulting in approximately 40 picoseconds per kilometer time delay change per degree C.

The MILLIMETER RESOLUTION OTDR can accurately measure this temperature coefficient on lengths of fibers only a few hundred meters in length. Alternatively, if the fiber is connected to the arms of a 2x2 fiber coupler to form a race track circuit, these measurements may be performed on fibers as short as a few meters.

The racetrack configuration combined with high temperature coefficient fibers and the high resolution OTDR lends itself to temperature sensor application. This is further discussed in section 7 below.

If a cleaved or polished fiber end is terminated in air, it reflects about 4% of the incident light and the reflection is temperature independent. However, if the fiber end is immersed in a medium whose index of refraction changes with temperature, the fiber end becomes a very accurate temperature probe of the medium. If, moreover, the fiber end is terminated with an organic polymer plug having a high temperature coefficient of index of refraction, the assembly becomes a point temperature sensor. More details will be given about temperature sensor applications in section 5-7 below.

5.6 LOSS RELATED APPLICATIONS

Optical losses in fiber optics may be classified into return loss, insertion loss, scattering loss and absorption loss. From the principle of energy conservation it follows that at any point, for any component, in any link or any system

$$r + i + s + a = 1 \qquad (5\text{-}4)$$

where r, i, s, and a are respectively, the reflection, transmission, scattering, and absorption coefficients of the incident pulse energy.

The loss quantities listed above are ten times the logarithm of the reciprocals of the above coefficients, or

$$R = 10 \cdot \log(1/r) \tag{5-5}$$
$$I = 10 \cdot \log(1/i) \tag{5-6}$$
$$S = 10 \cdot \log(1/s) \tag{5-7}$$
$$A = 10 \cdot \log(1/a) \tag{5-8}$$

As an example, if a component in a fiber optic link transmits 90% of the incident energy ($i=0.9$), reflects 4% ($r=0.04$), scatters 5% ($s=0.05$) and absorbs 1% ($a=0.01$), of the incident energy, then the values of the loss quantities are $I=0.5$ dB, $R=14$ dB, $S=13$ dB and $A=20$ dB.

The relationship between the (linear) pulse energy coefficients and the (logarithmic loss values are tabulated below for some often used values in rounded figures.

Coefficient (%)	Loss Values (dB)	Coefficient (%)	Loss Values (dB)
100	0	10	10
99.9	0.004	5	13
99	0.04	2	17
90	0.5	1	20
80	1	0.1	30
50	3	0.01	40
20	7	0.001	50

5.6.1 <u>RETURN LOSS MEASUREMENT</u> Return loss measurements performed with the MILLIMETER RESOLUTION OTDR system are straight forward. Once the OTDR is calibrated, the return loss of any feature or component may be measured within the loss budget directly.

At this point, a little known fact should be noted about the existence of a high limit of return loss values beyond which an OTDR can not measure. This limit depends, among other factors, on the width of the probe pulse. The shorter the pulse, the higher the detection limit. This property is due to the pulsewidth dependency of the Rayleigh backscattered signal, as discussed in Section 2.2. If the Rayleigh signal is comparable to the return loss signal it may swamp out the return loss signal measurement. In such a case the pulsewidth has to be decreased to decrease the relative size of the Rayleigh background. The MILLIMETER RESOLUTION OTDR operates with pulsewidths on the 100 picosecond time scale, which is more than thirty times shorter than the shortest pulsewidth employed by "HIGH RESOLUTION" conventional OTDR's. For this reason the Opto-Electronics' OTDR is ideally suited for the measurements of high return losses. Typical ranges of return loss values are shown in Figure 4-9 on page 4-11. in Section 4 along with loss budgets of the various Opto-Electronic OTDR configurations.

Connector return loss measurements are important in high frequency, high data rate or coherent communication systems. These measurements are simply made using the MILLIMETER RESOLUTION OTDR system. Non-contact type connectors have the lowest return loss, while contact type connectors, expanded beam connectors and angle polished connectors have progressively higher return losses. Connectors mated with index matching gel or liquid (wet connectors) may have very high values of return loss. It should be noted, however, that the index of refraction of most matching substances is temperature and wavelength dependent. The gel that helps to increase the return loss of a connector to say, 60 dB at 25 °C, may change this value to 40 dB at 15 °C or 35 °C. Also, a good match for 1300 nm operation is not necessarily a good match at 850 nm. Another fact worth mentioning is that graded index multimode connectors can not be matched out to high return loss values due to the radial variation of the core index.

Cleave return loss measurements help evaluate the performance of the cleaver, (both the machine and the operator). The fiber under test is connected to the output port of the OTDR and the far end is cleaved. The return pulse from the cleave is positioned on the screen and a MEASUREMENT taken. The return loss is noted, a new cleave is made next to the first one, the measurement is repeated and the new return loss is noted. The process may be repeated any number of times if a histogram is desired. Individual return loss values may also be compared with interference microscope measurements to obtain a relationship between return loss and cleave angle values.

Mechanical splice return loss measurements are necessary for the reason mentioned for connectors and also to evaluate the performance of a particular splice relative to others. The temperature and wavelength dependence of the epoxy used in the splice may also be measured. The measurement proceeds by taking a REFERENCE of the open ended cleaved fiber, followed by a MEASUREMENT of the finished splice. The return loss can then be calculated.

Fusion splice return loss measurements may be used to evaluate the fusion splicing process and the quality of the splice. First a good cleave is needed at both fiber ends. These may be evaluated by the cleave return loss measurement discussed above, as well as by the return pulse behavior when the two cleaved fiber ends are brought together in the fusion splicer. If the cleaves are perfect, the two fiber ends form an ideal Fabry-Perot interferometer. As the ends are brought together in the splicer, the return pulse intensity will start varying by the interferometric effect. If the pulse height of the return pulse from the single cleave in the fusion splicer was "A" and the Fabry-Perot cavity is near ideal, then the pulse height variation with distance will be between 0 and 4A. This variation is observed for the last fringe, just before contact is made between the two cleaved fiber ends. If the pulse height variation is less than 0 to 4A then the cavity is not perfect. This can be due to a non-perpendicular cleave, a non-planar cleave, a damaged surface, a dirty surface, or a slightly misaligned condition of the two fibers. The misalignment can be easily checked by X and Y adjustments in the fusion splicer at fiber end separation corresponding to the last maximum fringe condition at which the peak height of the OTDR pulse was supposed to be 4A. The X and Y adjustments for maximum pulse height at this fringe condition also serves to align the two fiber cores with a precision much greater than any other method employed by fusion splicers. The measurements are made in real-time or can be averaged and stored. After correcting any possible cleave, damage or dirt problem and making the necessary X and Y adjustments, the fusion splice is made. At this time the return pulse disappears from the screen. To measure the return loss of the splice the OTDR sensitivity must be increased, possibly to maximum. The return loss of a fusion splice is closely related to its insertion loss. The lower the return loss, the lower the insertion loss. This is discussed further in the Insertion Loss Section below.

Coupler, switch, isolator, modulator, multiplexer, laser and detector return losses are measured by the OTDR in a similar fashion to the connectors and splices discussed above. These measurements give information to the designer and the user about the components in question. Each component has an OTDR signature which may be measured by the OTDR when it is installed in the system or link and then stored. When a problem occurs in the system or link, a new MEASUREMENT of the component is made and then compared with its stored signature to check its integrity.

5.6.2 INSERTION LOSS MEASUREMENTS Insertion loss of a component or a link may be measured by the Fresnel Reflection method by comparing a reflection upstream from the component or link with a reflection downstream from the component or link. The upstream and downstream reflections should have the same return loss, that is, they should come from the same type of feature. These may be two good cleaves, two open connectors of the same kind or gap type connectors of the same type, etc. The measurement is carried out by taking a REFERENCE of the upstream pulse, taking a MEASUREMENT of the downstream pulse and allowing the OTDR Processor to calculate the one way insertion loss.

The accuracy of the insertion loss measurement depends on the SNR of the return pulse signal and on the uncertainty of the return loss values of the two features (upstream and downstream) used in the measurement. The insertion loss measurement accuracy for a SNR of 10 is tabulated as a function of the uncertainty of the up-down stream return loss values below.

Up-Down Stream Return Loss Uncertainty	1.0 20	0.5 10	0.2 5	0.1 2	dB %
Insertion Loss Accuracy	0.5	0.25	0.10	0.05	dB

Experience shows that good cleaves, open connectors and gap type mated connectors have an uncertainty in their return loss of 0.5 dB (10%) or less. Therefore, if these are available for the measurement of insertion loss of a component or a link, then the accuracy of the insertion loss is 0.25 dB or less.

If the insertion loss is very small, ie less than 0.1 dB, the uncertainties mentioned above make insertion loss measurements impractical by this method. Insertion loss measurements are also not possible for short lines below 0.1 dB using conventional high resolution OTDR's as the offset between the upstream and downstream Rayleigh backscattered signals is too small to be measured meaningfully. However, the Opto-Electronics' OTDR can help in some cases to give a close estimate of the insertion loss of components or short links below 0.1 dB by measuring the return loss. This is discussed below in the Scattering loss Section.

5.6.3 SCATTERING LOSS MEASUREMENTS Scattering loss can not be measured directly in optical fibers or fiberoptic components unless the light is detected or collected outside the fiber. The scattering loss is usually calculated using Equation (5-4) above by assuming that the absorption loss is negligible. This assumption is reasonable for modern communication fibers and components.

If the absorption loss can be ignored, Equation (5-4) requires the measurement of two losses, (return and insertion) to determine the third (scattering). In practice it is found that the return, insertion and scattering losses are often related.

For components having a discrete interface, such as a dry connector, the insertion loss can not be lowered below a minimum value which is determined by the value of the return loss. For example if a dry connector has a return loss of 14 dB (4%), it can not have an insertion loss lower than 0.18 dB (96%) even if it has no scattering loss. On the other hand, the insertion loss of components with no discrete interface are controlled by the scattering loss only. Examples for this are index matched connectors, (wet connectors), epoxied mechanical splices and fusion splices. Here, the insertion losses can be small enough not to be measurable by conventional methods as mentioned in the Insertion Loss Measurements Section above.

5.6.4 ABSORPTION LOSS MEASUREMENTS For modern communication fiber and fiberoptic components the absorption loss is negligible relative to other losses. For specialty fibers used in sensor applications, for example, absorption may may be high. The same is true for attenuators, where absorption is introduced on the optical path in a controlled fashion.

Absorption loss can not be measured directly using the method of Fresnel reflection, and neither can it be measured directly using Rayleigh backscattered signal. It can only be calculated from Equation (5-4) if there is no scattering. If both scattering and absorption are present, the two can not be separated by OTDR measurements.

5.7 SENSOR RELATED APPLICATIONS

There are many different types of fiberoptic sensors designed to detect, measure or monitor a large number of physical or chemical quantities. The sensors convert the values of these quantities to some property of the light signal in the fiber. The measured quantity may be made to influence the light intensity, time delay, pulse shape, phase or other property at a single position along the fiber or at various multiple positions. Fiberoptic sensors may be single point, multipoint or distributed.

The Opto-Electronics MILLIMETER RESOLUTION OTDR is ideally suited for use in the fiberoptic sensor field due to its lack of deadzone, wide dynamic range, high loss budget, picosecond and millimeter resolution, interference fringe measuring capability and its linearly polarized output for the single mode models. The OTDR is capable of real-time measurements or it can accumulate and store data for downloading at a later time.

Some examples of fiber sensors that utilize the special capabilities of the MILLIMETER RESOLUTION OTDR are given below.

5.7.1 DISTANCE SENSING Distance sensing may involve the measurement of absolute distance, distance change, length change, movement, displacement, rotation, vibration etc. The OTDR is used in this area by launching pulses into either an optical fiber, another medium or into free space through a collimator. The property measured is the two way time of flight of the pulse for distances greater than one millimeter or by interference fringes for distances less than one millimeter. Another property, the pulsewidth, may also be utilized to measure the amplitude of rapid distance changes such as in vibration or rotation sensing. The measurements proceed as described in 5.2 and 5.3 above.

5.7.2 TEMPERATURE SENSING Generally, the refractive index of solids and liquids change with temperature. This can be utilized by the OTDR in two ways to measure temperature. First, if a cleaved or polished fiber end is immersed or embedded in a liquid or solid whose refractive index has a stable and hysteresis free temperature dependence, then the return loss variation with temperature provides the means to measure the temperature of the region around the fiber end. This was mentioned already in Section 5.5 above. Such a scheme is good for single point or multipoint measurements for moderate temperature ranges. In a multipoint situation each probe is given a different distance from the OTDR in order to separate the positions of their respective return pulses on the screen. The return loss of each probe can be measured in sequence or simultaneously and the temperature can be calculated for each point. The OTDR loss budget allows the measurement of a chain of such temperature sensors with up to several dozen probes in the chain.

Another method of temperature measurement utilizes the change of n_e in the fiber itself with temperature. The change of n_e leads to a change in the time of flight of the probe pulse from the OTDR, thus, time shift of the pulse on the screen can be related to temperature change. If specially doped fibers are used, the time shift may be substantial and a short piece of fiber may be utilized as a temperature probe. Moreover, if this fiber is placed onto a circulator or racetrack circuit the time shift may be increased many fold. This was already mentioned in Section 5.5 above. Such a scheme may be used for singlepoint or multipoint temperature sensing with a sensor having the size of a postage stamp. Here again, the OTDR loss budget allows the measurement of a chain of these sensors with up to several dozen probes in the chain, the temperature range for this method is limited only by the coating used on the fiber. For metal or metal oxide coated fibers the measurement of temperature up to several hundred degrees is possible.

Distributed temperature sensing is also possible using the Opto-Electronic MILLIMETER RESOLUTION OTDR with a specially prepared fiber. The fiber is made with a small, temperature sensitive, region introduced at regular intervals and the return loss and insertion loss values of the sections are monitored. If the whole length of the fiber is at a uniform temperature, the OTDR trace is an exponential curve with a slight downward slope in the direction of increasing distances. If the temperature is kept uniform, but it is changed, the slope changes. If the temperature deviates from the uniform value in any one section, the OTDR trace deviates from the exponential form at that point. The changes can be monitored in terms of temperature. This method is useful for moderate temperature ranges.

5.7.3 STRAIN SENSING Measuring fiber strain with the OTDR was discussed in Section 5.5 above. Conventional or specialty fibers can be used as strain sensing elements and the strain can be monitored by the MILLIMETER RESOLUTION OTDR. The applications are wide ranging from the monitoring of dimensions of mechanical structures to earthquake prediction to damage assessments and to smart skins.

Some application involve longitudinal fiber strain, such as in measuring the expansion and contraction of large oil and gas tanks, structural steel elements, railway rails, bridges etc., while other application involve transverse of shear stain, such as in sharp bending or shear of plates, skins or composite materials.

In measuring strain with fiber, just as in measuring temperature with fiber, there are singlepoint, multipoint and distributed measurements. For all these applications the fiber may be used to measure the shift in time due to strain or to measure the return loss from a microbend due to strain. Specialty fibers may also be used where the fiber is MARKED at regular intervals with very small reflective features and the return loss of these is measured. Changes in the return loss signature of a section can be related to a particular strain.

5.7.4 LIQUID SENSING Many properties of liquids can be measured with fiber using the MILLIMETER RESOLUTION OTDR. Sensors may be devised to measure just the presence of a liquid, such as in liquid level indicators or in liquid leak sensors. In such cases the presence of liquid would cause the fiber probe to change its reflective or transmission property and the OTDR would detect the change in the value of the return or the insertion loss. This may also be done using a string of sensors at several dozen points to monitor liquid levels or check leaks in various installations.

5.7.5 INTERFEROMETRIC SENSING Fiber interferometric sensing is a very popular method due to its extreme sensitivity. An example for this was already mentioned in Section 5.6 above involving fusion splicing. In that example the quality of cleave of the two fiber ends and their mutual core alignment was evaluated in a Fabry-Perot configuration.

The same method may be used to evaluate the quality of fiber ends in connectors, mechanical splices and other terminations where flat polish is employed. When two such ends are brought together they form a Fabry-Perot cavity. The measurement is made by bringing the return pulse from one of the fiber ends to the screen of the OTDR and taking a REFERENCE. After this step the other fiber end is brought close to the first one and the increase of pulse height on the screen is observed. When the distance between the two fiber ends is decreased to approximately one millimeter the pulse height will change cyclically between a low and a high value due to interference. Just before contact, the pulse height will reach its highest value. A MEASUREMENT is taken and the difference between measurement and reference is found. If the two fiber ends were perfectly flat, with a perfect polish and were parallel to each other, the return loss of the MEASUREMENT would be 6.0 dB below the return loss of the REFERENCE. If some of the features mentioned above are not perfect, the return loss difference is less than 6.0 dB. This difference can then be related to the mechanical quality of the termination.

Another example was mentioned in Section 5.3 above, involving the matching of the two arms of a fiber interferometer. The MILLIMETER RESOLUTION OTDR can help to accomplish this quickly and easily by the combination of its picosecond time of flight measuring capability, its two parallel optical output ports and its interferometric measuring capability.

The MILLIMETER RESOLUTION OTDR is also used extensively to perform measurements on gyroscopes, Mach-Zehnder type interferometers, Fabry-Perot type interferometers and other interferometric circuits where millimeter resolution and linearly polarized probe pulse is required.

5.8 MAPPING and MONITORING APPLICATIONS

Mapping and monitoring can be done with the MILLIMETER RESOLUTION OTDR and a PC connected to the OTDR by GPIB. Some typical applications are outlined below.

5.8.1 SINGLE COMPONENT A single component such as a pigtailed laser, a pigtailed detector, a coupler, a pigtailed switch etc. can be tested relative to a reference component whose performance is within specifications. The reference component is measured and stored. The data stored consists of the pulse shape of the return probe pulse, its FWHM, pulse energy and the length of the pigtail. The test sample can be measured relative to the reference component and the differences can be displayed.

5.8.2 SINGLE LINK A single link may contain many components, such as connectors, splices, attenuators, etc. When this link is installed it is checked out for satisfactory performance and if it passes the test it can be MAPped by the OTDR. This is done by examining the features one at a time and storing the data in the PC. Subsequently, if there is any sign of problem with the link, the OTDR can TEST it against the stored MAP information. Using a simple macro program in the PC, the OTDR will find and measure the features automatically and compare each result in turn with the stored data. When there are discrepancies, this will be brought to the attention of the operator.

The testing can be done semi-automatically as well. In this instance the features are found in sequence, measured and compared with the MAP data, and the OTDR is stepped to the next feature.

5.8.3 HARNESS A harness may be made up of several single links. These may be MAPped and TESTed individually as single links, or if the links are joined together in some configuration when the harness is installed, the MAPping and TESTing should be done in that configuration. A harness may be TESTed after assembly, as a Q.C. procedure and/or after its installation. In both cases a TEST can be run against a MAP taken from a reference harness which meets all specifications or from the installed harness when it was performing according to all specifications.

The measurement steps are the same as those outlined for the single link. Here again, the measurement can be fully automated for red-light/green-light testing.

5.8.4 STAR NETWORKS In a star network, one or more star couplers split a single input into a number of arms. These arms may contain connectors and other components. A star network may be MAPped by the OTDR as long as there are no overlapping features in the various arms within the two point resolution of the OTDR. The network can be easily designed to satisfy this condition. The OTDR MAP of a star network is easily understood from the illustration in Figure 5-3 below.

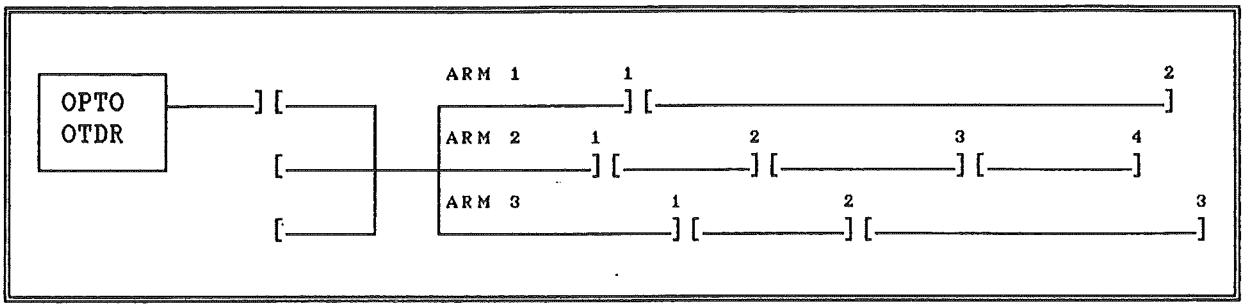


Figure 5-3

A 3x3 star network being MAPped by the MILLIMETER RESOLUTION OTDR. The first return pulse comes back from connector 1 in arm 2, the second one from connector 1 in arm 1, the third from connector 1 in arm 3, the fourth from connector 2 in arm 2 etc. The last return pulse comes from the third and final connector in arm 3. The OTDR will MAP altogether 9 features in this example.

To avoid confusion in identifying the features and the arms, each feature may be labeled with its position number starting at the star coupler with the arm number as the subscript. For example, the first connector in the second arm in Figure (5-3) would be labeled 1_2. With such labeling the OTDR MAP record for this example would be a string of return pulses and their associated values from connectors 1_2, 1_1, 1_3, 2_2, 2_3, 3_2, 4_2, 2_1, 3_3.

Routine testing or testing for fault proceeds normally as described for the single link. However, care must be taken in interpreting the test result by realizing that adjacent pulses in the string do not necessarily come from adjacent features in the same arm.

The loss budget of the MILLIMETER RESOLUTION OTDR's allows the MAPping and TESTing of star networks containing couplers with up to 16x16 ports.

5.8.5 SECURE LINKS These links normally contain no connectors, splices or components. MAPping by the MILLIMETER RESOLUTION OTDR takes place at maximum sensitivity to record every possible imperfection in the link. TESTing may be done at the desired intervals or continuously. In either case the OTDR sensitivity is set to maximum or the photon counting detector is used to detect the smallest deviation from the MAPped data.

In this application a fully automatic mode is usually required. This can be accomplished by using an external PC via the GPIB link.

5.9 DISPERSION and BANDWIDTH RELATED APPLICATIONS.

Pulse dispersion (pulse widening) and bandwidth limitation in fibers are caused by chromatic effects (finite spectral width of the optical transmitter pulse) and intermodal effects (each mode in a multimode fiber propagates with different velocity). These two effects are referred to as Chromatic Dispersion and Intermodal Dispersion. The measurements of dispersion and bandwidth are conventionally carried out using either modulated cw light or nanosecond pulsed light in transmission (two ended measurement) on several kilometer lengths of fiber. By using the picosecond pulsed OTDR these measurements can be carried out in reflection (one ended measurement) on much shorter lengths of fiber. The measurements of chromatic and intermodal dispersions by the MILLIMETER RESOLUTION OTDR are outlined below.

5.9.1 CHROMATIC DISPERSION MEASUREMENTS The chromatic dispersion in a singlemode fiber for a given spectral width of the optical transmitter is minimum in the area of 1300 to 1500 nanometers. Above and below this wavelength region the chromatic dispersion is greater. This behavior is due to the specific wavelength dependence of the value of n_e of fibers. Below 1300 nanometers the value of n_e decreases with increasing wavelength, it flattens out in the 1300 to 1500 nanometer region and increases again for longer wavelengths. Thus, the chromatic dispersion is both wavelength and transmitter spectral width dependent.

The MILLIMETER RESOLUTION OTDR may be used to measure the chromatic dispersion of a single mode fiber in the OTDR mode (one ended reflection measurement) at any one of the wavelengths at which laser diodes are available. For these measurements the knowledge of the values of λ and $\delta\lambda$ are necessary. The signal from the far end of the launch pigtail is used as the REFERENCE signal and the return pulse from the far end of the test fiber is used as the MEASUREMENT signal. The pulse widths are determined with the OTDR and the chromatic dispersion D_c in units of ps/km·ns is calculated using Equation (5-9) below;

$$D_c = (FWHM_S{}^2 - FWHM_R{}^2)^{1/2}/2L\delta\lambda \quad (ps/km \cdot ns) \qquad (5\text{-}9)$$

where $FWHM_S$ and $FWHM_R$ are the sample and reference pulsewidths in picoseconds respectively. L is the fiber length in km and $\delta\lambda$ is the spectral width in nanoseconds of the OTDR optical pulse.

If the REFERENCE pulse width is taken to be $FWHM_R$ = 100 ps, the fiber length to be L = 10 km, the spectral width of the optical pulse to be $\delta\lambda$ = 10 nm and if singlemode dispersion values are taken at 850 nm and 1300 nm as $D_c(850)$ = 100 ps/km·ns and $D_c(1300)$ = 5 ps/km·ns respectively, then the values of the expected sample pulse widths calculated from Equation (5-9) are $FWHM_S(850)$ = 2000 ps and $FWHM_S(1300)$ = 140 ps. Because the FWHM values can be measured with an accuracy of ±1 ps by the OTDR, the dispersion value for 1300 nm can be established with an accuracy of ±2% for the above example.

A summary for the above example is tabulated below for 850 and 1300 nm. It is seen that a chromatic dispersion measurement accuracy of ±2% is possible at 1300 nm using a 1 km long fiber and the same ±2% accuracy is possible at 850 nm using a 50 m long fiber. Greater accuracies are obtained from measurements on longer fibers.

λ (nm)	L (m)	$FWHM_R$ (ps)	$FWHM_S$ (ps)	$\delta\lambda$ (nm)	D_C (ps/km•ns)
850	50	100 ±1	140 ±1	10	100 ±2
1300	1000	100 ±1	140 ±1	10	5 ±0.1

Having obtained the chromatic dispersion by measuring the FWHM values and calculating D_C from Equation (5-9), the chromatic bandwidth B_C (3 dB value) may be calculated, in units of GHZ•km•ns, using equation (5-10) below;

$$B_C = 400/D_C \quad (\text{GHz}\cdot\text{km}\cdot\text{ns}) \qquad (5\text{-}10)$$

Typical bandwidth values for singlemode fibers at 850 nm and 1300 nm wavelengths are 4 GHz•km•ns and 80 GHz•km•ns respectively.

5.9.2 INTERMODAL DISPERSION MEASUREMENTS For singlemode fibers there is no intermodal dispersion because only one mode propagates in the fiber. In multimode fibers many modes propagate, each with a slightly different group velocity, leading to pulse widening. This type of dispersion is known as Intermodal Dispersion. In multimode fibers, each mode is subject to chromatic dispersion as well, just as in the singlemode case. The overall dispersion in multimode fibers therefore is the sum of chromatic and intermodal dispersions. If one of the two is small, then the other dominates.

Intermodal dispersion is lesser for smaller diameter fibers (lower number of modes) and is greater for larger diameter fiber (higher number of modes). It is also lesser for graded index fibers and is greater for step index fibers. Intermodal dispersion does not have a strong wavelength dependence.

The measurement of multimode dispersion using the Opto-Electronics MILLIMETER RESOLUTION OTDR requires the same procedure as was discussed for singlemode fibers. However, care must be taken to fill all the modes of the fiber at equilibrium distribution for accurate results. This was already discussed above. Measurements at long wavelengths (1300 to 1500 nm) yield the intermodal dispersion of the fiber while measurements at short wavelengths (850 nm region) yield the sum of modal and chromatic dispersions. Intermodal dispersion D_M is calculated in units of ps/km, from the measured FWHM values and the fiber length L using Equation (5-11) below;

$$D_M = (FWHM_S{}^2 - FWHM_R{}^2)^{½}/2L \quad (\text{ps/km}) \qquad (5\text{-}11)$$

The bandwidth is calculated in units of GHz•km using Equation (5-12) below;

$$B_C = 400/D_M \quad (\text{GHz}\cdot\text{km}) \qquad (5\text{-}12)$$

Some typical values of dispersions measured at 850 nm for various multimode fibers are tabulated below.

FIBER CORE SIZE (µm)	DISPERSION MEASURED AT 850 nm (ns/km)	PROPORTION OF CHROMATIC DISPERSION (per cent)
50 graded	0.45	25
100 step	5	2
400 step	40	0.2

It is seen from the table that Chromatic Dispersion plays an important part only for fibers with small Intermodal Dispersion.

It is also seen from the table that intermodal dispersion increases rapidly with increasing fiber diameter. A 10 m length of step index fiber with 400 µm core size disperses the short probe pulse of the OTDR approximately 500 ps one way, or to approximately 1 ns in a round trip. Dispersion limits the measurement accuracy and resolution of the OTDR as was discussed above. It is reasonable to expect millimeter resolution at 850 nm at the end of a 1 km graded index 50/125 µm fiber or at the end of a 10 m length of step index 400 µm fiber. For increasing lengths, the resolution will gradually decrease. For numerical results consult Figure 4.2 in section 4.

5.9.3 <u>A SPECIAL CASE</u> If an 850 nm pulse is launched by the OTDR into a 9 µm core step index fiber (which is normally used for singlemode 1300 to 1500 nm transmission), two modes will propagate in the fiber. The two modes will gradually separate in time and become two distinct pulses after a certain length of travel. At the same time both will widen due to the chromatic dispersion of the fiber. In standard fibers the pulse separation after 1 km travel is approximately 1.5 ns. This enables the OTDR to detect and measure the two propagating modes, their chromatic dispersion and their modal dispersion on a fiber sample as short as 50 m. This is useful to measure fiber properties as well as the effect of strain, temperature etc. on the fiber. The second (slower) mode is easily eliminated by a macrobend. This behavior also enables the OTDR to probe a 1300 nm singlemode fiber with 850 nm singlemode pulses, which is sometimes useful when the loss budget of the 1300 nm model is insufficient for a particularly difficult measurement.

6 SPECIFICATIONS and PERFORMANCE

6.1 SPECIFICATIONS

MECHANICAL
MF20 Mainframe
Size : 19"W x 14 1/4"L x 7"H
Weight : 6 1/4 kg (14 lbs)
Capacity : 11 Single module bays
Mounting : Standard 19" rack or bench top
TDR Processor
Size : 12"W x 13"L x 5 1/2"H
Weight : 4 kg (9 lbs)
Mounting : Standard 19" rack or bench top

ENVIRONMENTAL
Temperature : +10C to +40C operating
: -15C to +60C storage
Laser Safety : Meets Class I laser product safety

ELECTRICAL
Power : 110/220 V, 50/60 Hz line

OPTICAL CONNECTORS
General : standard ST with bulkhead adapters Custom biconic, FC, D4, SMA
Transmitter : As specified, SM or MM (4 to 400 um core size)
Receiver : Generally MM up to 400 um core size. This is suitable for both SM and MM operation.
Coupler : SM or MM, compatible with system
Jumpers : SM or MM, compatible with system

INTERFACES
Display
Oscilloscope : Requires a single channel low frequency lab type oscilloscope.
Printer : Auxiliary Epson style dot matrix with graphics capability.
RS232 : Data port to dump stored data from TDR Processor.
GPIB : Enables fully automatic remote operation of OTDR and data transfer.

6.2 PERFORMANCE

DISTANCE RANGE:Singlemode 1mm to 30km
:Multimode 1mm to 3-5km
(dispersion limited)

DYNAMIC RANGE :Defined as the maximum one way insertion loss (dB) for a 4% Fresnel reflection at a SNR=1.

A. SEARCH OPERATION, NO AVERAGING (dB)

Fiber Type	Multimode			Singlemode		
Detector	APD	AMP APD	PC	APD	AMP APD	PC
Wavelength (nm)						
850	12	20	45	10	18	33
1300	2	10	--	0	8	--

B. MEASURE OPERATION, 65,536 AVERAGES (dB)

Fiber Type	Multimode			Singlemode		
Detector	APD	AMP APD	PC	APD	AMP APD	PC
Wavelength (nm)						
850	24	32	57	22	30	45
1300	14	22	--	12	20	--

RESOLUTION

Single point resolution is defined as the measurement of a single pulse from a single reflection. Two point resolution is defined as the measurement of two pulses, or one composite pulse, from two reflections. Values shown are for negligible pulse dispersion.

A. SINGLE POINT RESOLUTION (ps/mm)

SNR	50	20	10	5
DETECTOR				
APD	1/0.1	2/0.2	4/0.4	10/1.0
AMP APD	3/0.3	5/0.5	10/1.0	25/2.5

B. TWO POINT RESOLUTION (ps/mm)

SNR	50	20	10	5
PULSE RATIO				
APD 1:1	2/0.2	3/0.3	5/0.5	12/1.2
APD 2:1	3/0.3	5/0.5	11/1.1	25/2.2
APD 5:1	5/0.5	10/1.0	22/2.2	50/5.0

7 ORDERING INFORMATION

7.1 STANDARD OTDR SYSTEMS

Table 7-1 below indicates the 6 "standard" systems currently available. The one to nine types of modules (required and optional) are listed vertically with the system compatible options for each module. Further options are available but these become specials.

Detailed information required for the ordering of each module is outlined in section 7.2 below.

SYSTEM	SAMPLING SYSTEM				PHOTON COUNTING SYSTEM	
	1	2	3	4	5	6
MODE WAVELENGTH RANGE	SINGLE MODE SHORT λ	LONG λ	MULTIMODE SHORT λ	LONG λ	SINGLEMODE SHORT λ	MULTIMODE SHORT λ
1. MAINFRAME	MF20	MF20	MF20	MF20	MF20	MF20
2. DELAY GENERATOR	PDG20	PDG20	PDG20	PDG20	PDG20	PDG20
3. PROCESSOR	TDR20	TDR20	TDR20	TDR20	TDR30	TDR30
4. SAMPLER	PSU20	PSU20	PSU20	PSU20	N/A	N/A
5. DETECTOR	PPD30 PAD230	PPD40 PAD240	PPD30 PAD230	PPD40 PAD240	N/A	N/A
6. PHOTON COUNTER	N/A	N/A	N/A	N/A	PPC10	PPC10
7. TRANSMITTER	PPL30K- λSM		PPL30K- λMM___		PPL30K- λSM	PPL30K-λMM
a. WAVELENGTH -λ (nm)	820 850	1300 1550	680 750 785 800-860 904	1060 1200 1300 1550	820 850	680 750 785 800-860 904
b. FIBER SIZE -SM (μm) -MM___ (μm)	4	9	50/125 62½/125 100/140 200 400	50/125 62½/125 100/140 200 400	4	50/125 62½/125 100/140 200 400
8. ATTENUATOR	POA6	POA9	POA50	POA50	POA6	POA50
9. COUPLER (4 PORT) (3 PORT)	PFC6	PFC9	PFC50 PFC62 PFC100 PFC200 PFC400	PFC50 PFC62 PFC100	PFC6	PFC50 PFC62 PFC100 PFC200 PFC400

Table 7-1
The standard OTDR systems can be found in the vertical columns.

7.2 DETAILED ORDERING INFORMATION

1. Mainframe .... MF20 - ___ V
   insert operating voltage,
   110 or 220 V

2. DELAY GENERATOR .. PDG20

3. PROCESSOR ....[✓ TDR] ___
   [✓ 20] For operation with sampling system.
   [✓ 30] For operation with photon counting and sampling system.

4. SAMPLER .... PSU20 For operation with the sampling system.

5. DETECTOR ... PPD30 For operation at short wavelength and high resolution.
   ... PAD230 For operation at short wavelength and high sensitivity.
   ... PPD40 For operation at long wavelength and high resolution.
   ... PAD240 For operation at long wavelength and high sensitivity.

   ... PPC10 For photon counting at short wavelength.

6. PHOTON COUNTER ... PPC10

7. TRANSMITTER ...... PPL30K-___-_M___
   Indicate fiber core size
   Indicate single or multimode
   Indicate wavelength

8. ATTENUATOR .... PAO ___
   Indicate fiber core size.

9. COUPLER .... PFC ___
   Indicate fiber core size, this should match the test fiber size for optimum conditions.

7.3 WARRANTY

Opto-Electronics warrants all its OTDR models for parts and labor in normal operation for a period of 12 months from the time of shipment. The cost of shipment to Opto-Electronics and back to the customer is to be borne by the customer.

8 OPERATING INSTRUCTIONS and TRAINING

8.1 OPERATING INSTRUCTIONS

It should be remembered that the OTDR techniques employed by the Opto-Electronics MILLIMETER RESOLUTION OTDR system is not at all like that of conventional Rayleigh backscatter OTDR's. Conventional Rayleigh OTDR users may have to rethink the conventional Rayleigh OTDR philosophy. To aid in this respect, this booklet has outlined the differences. In addition, the system comes with three manuals; the first, details the particular modules making up the chosen system; the second, outlines the interaction of the modules in the system and the system operation; the third, is an instruction manual which takes the operator through a step by step procedure to teach the functions of each module as well as the setup and the operation of the system. This latter manual, constitutes a "home training course" which can take from two to five days depending on how many of the suggested exercises are completed.

8.2 TRAINING

Opto-Electronics offers a two day training course, for up to three persons, free of charge, with all OTDR system purchases. Traveling and accommodations must be borne by the trainee(s) but help in arranging accommodations is available. Training takes place at the Oakville Ontario plant, (One half hour travel by car from Toronto International airport.), and must be arranged at least four weeks in advance.