# DTS Training Course

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# Aim of the Training Course

- To give you a better understanding of DTS
- For you to be able to educate other people how a DTS works

# LESSON 1

# Basic Optical Principle

- Optical fibres are long strands of transparent material typically glass $SiO_2$
- The light travels along the fibre bouncing off the mirror-like outer cladding

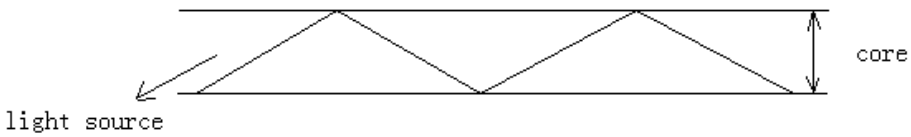



Figure 1. Light travels in a fibre

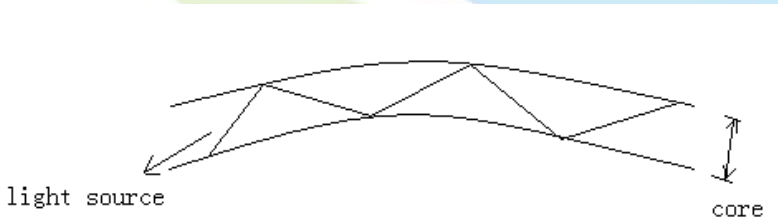
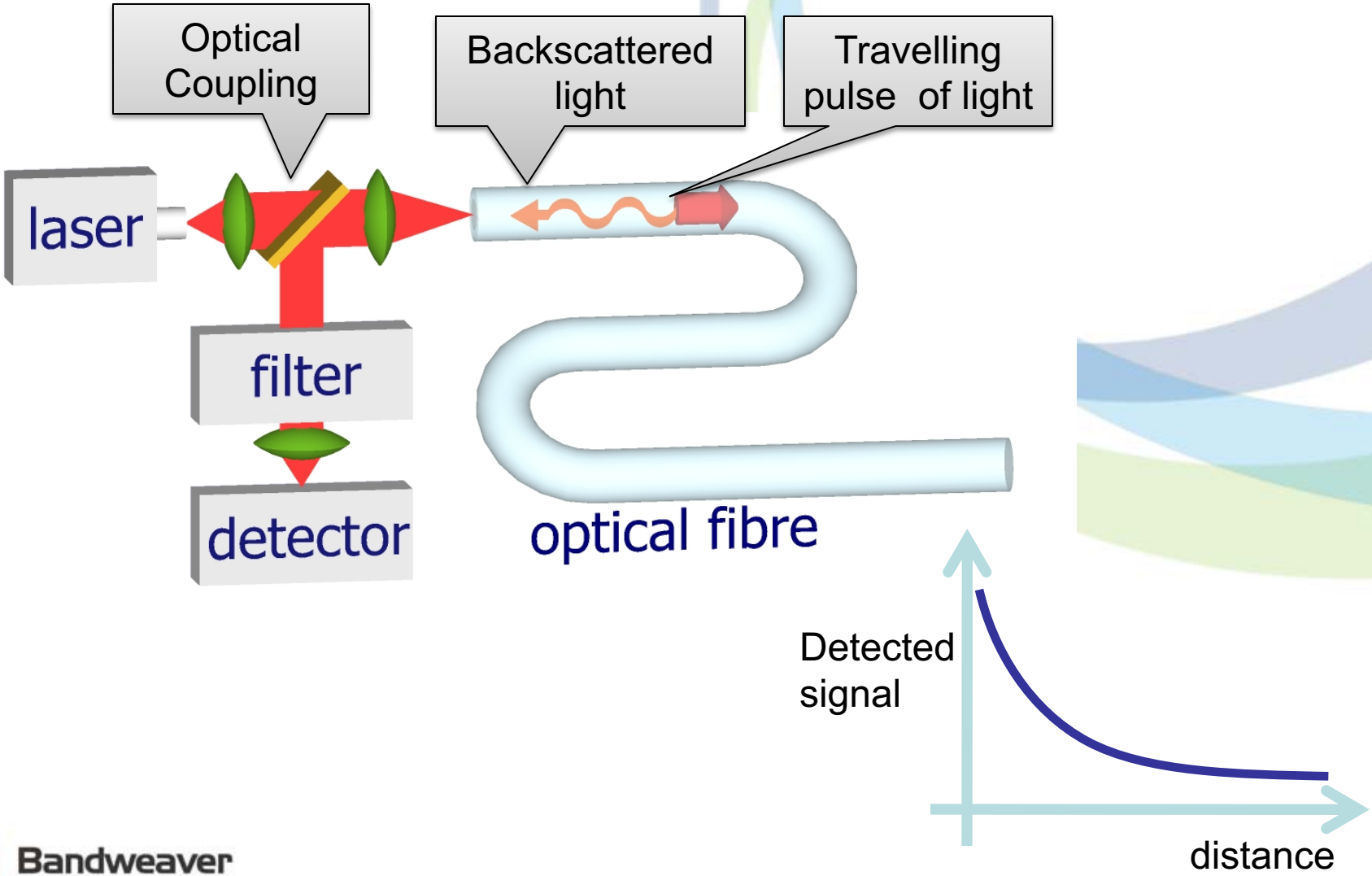
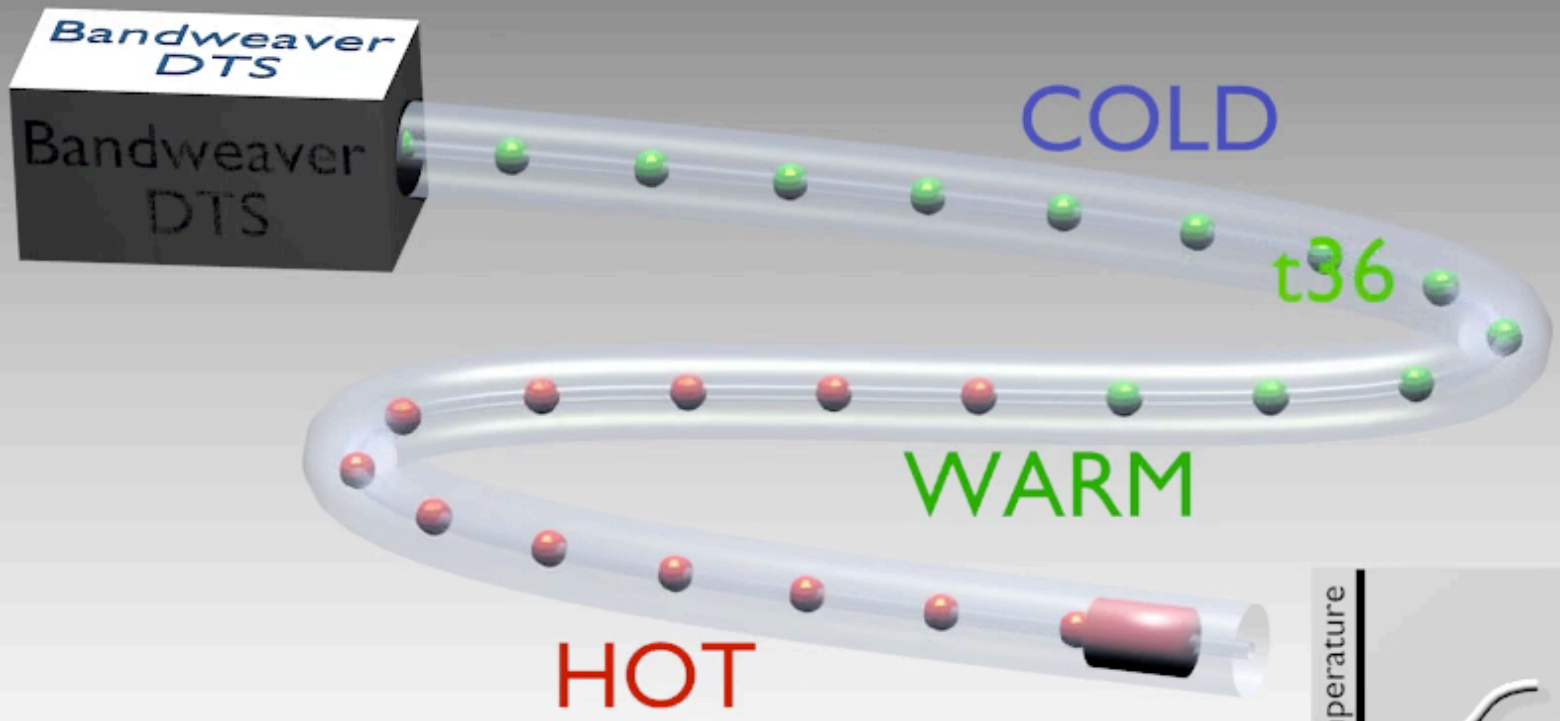



Figure 2. Light travels in a bent fibre

# Simplified DTS operation



# DTS Theory



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# Backscatter

- As the pulse moves forward some light is reflected backwards, optical glass is not a perfectly transparent material
- The amount of backscatter is very small
- The pulse generates a continuous backscatter signal
- Analogy: Every point of the optical fibre acts like a weakly reflecting mirror

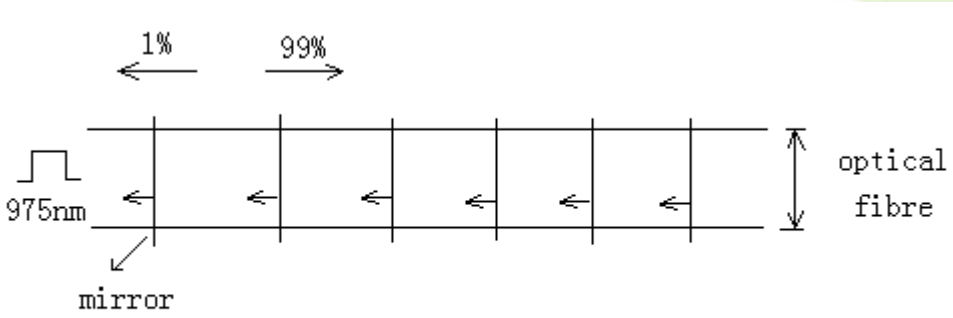
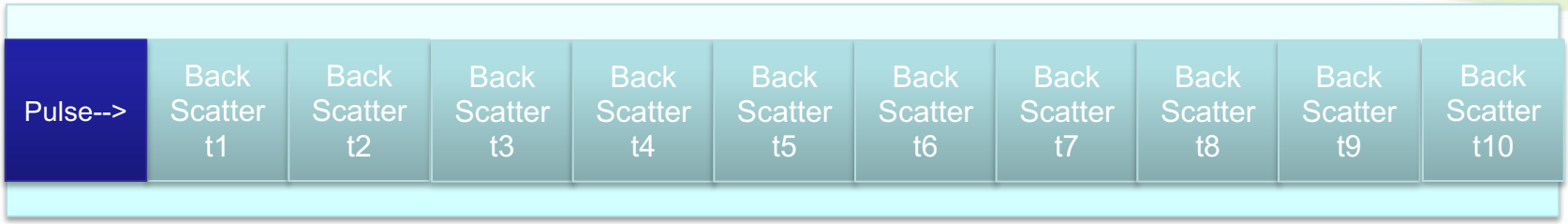



Figure 5.Every point of optical fibre acts like a mirror

# Backscatter animation

- Laser is introduced on the left hand side and travels down the fibre
- Backscatter travels in the opposite direction
- Backscatter signal is continuous



# The Importance of Backscatter

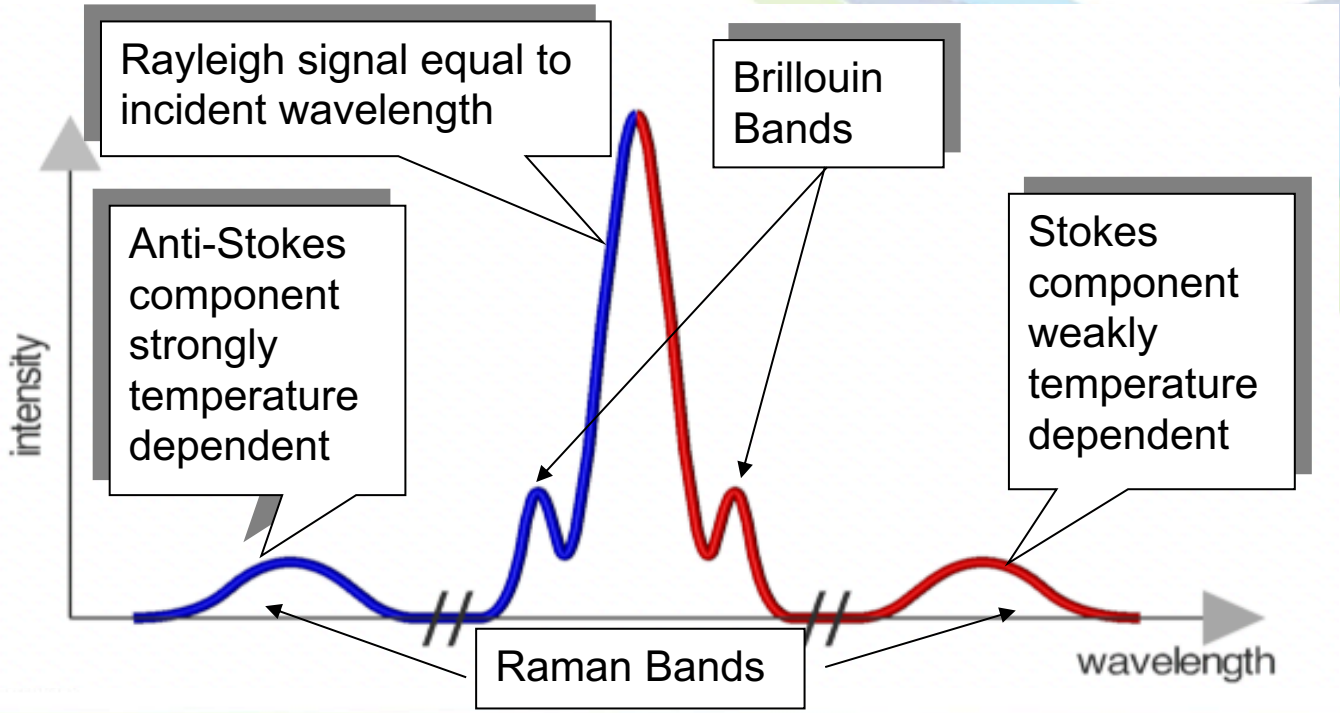
- Gives a snapshot of what is happening in the fibre without cutting it
- If the time and speed of the pulse is known then the position can be calculated
- This allows a distributed measurement

# Nature of light

- How do we measure light?
  - Colours have a wavelength (nano meters, nm, $10^{-9}$m)
  - Red 680nm
  - Blue 470nm
- Current DTS wavelengths 975nm, 1064nm and 1550nm
  - Invisible to the human eye

# Backscatter Spectrum

- Every point of fibre cause a backscatter signal
- The scattered light has many components due to the light interacting with the glass



# Main Peaks

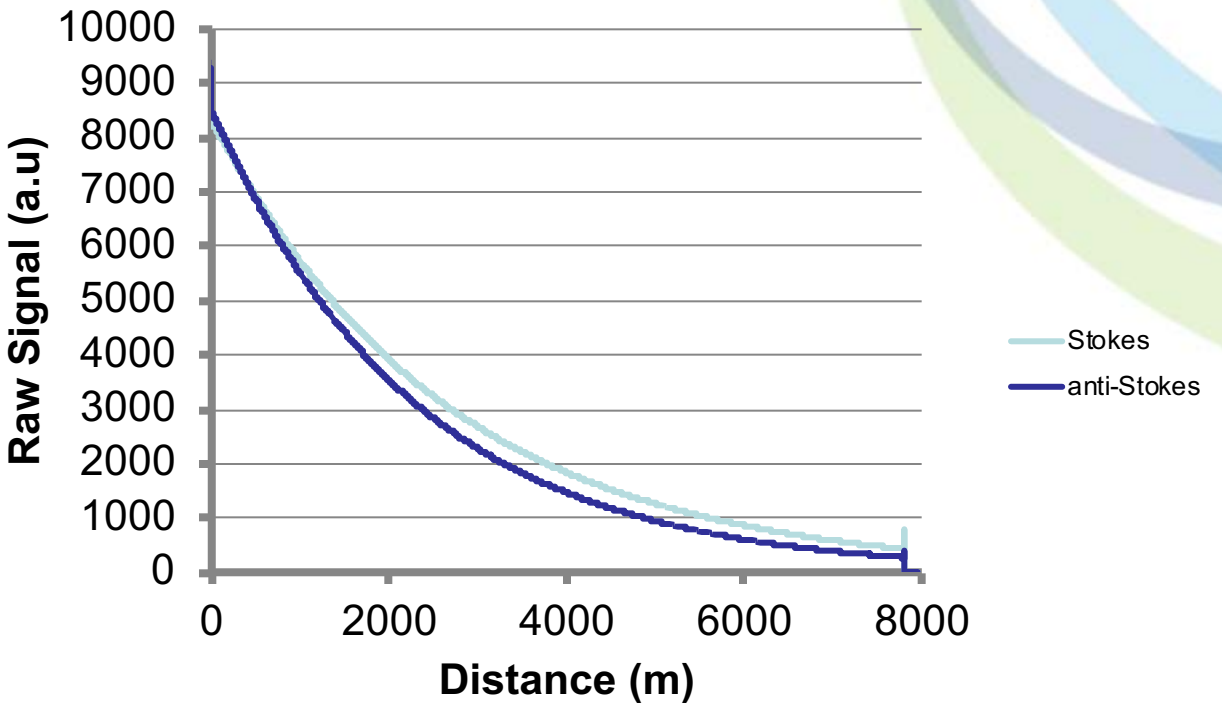
- Rayleigh
  - Same wavelength as incident power
  - Photon energy does not change
- Brillouin
  - Two peaks very close to Rayleigh peak, sensitive to temperature and strain
- Raman
  - Two peaks far from Rayleigh peak, sensitive to temperature only

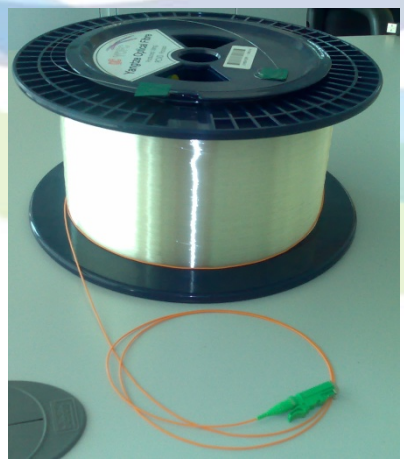
# Raman Peaks

- At Raman wavelengths two peaks occur: they are called the Stokes and Anti-Stokes
- Energy of the photon is absorbed and reemitted at a higher or lower wavelength
  - Stokes longer wavelength – lower energy
  - Anti-Stokes shorter wavelength – higher energy
  - Anti-Stokes is more sensitive to temperature than Stokes
- When the temperature increases the signal power increases

# Example Raw Data

- Raw Stokes and Anti-Stokes data from a long length of standard multimode fibre
- Signals decay exponentially



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# Pulse of light

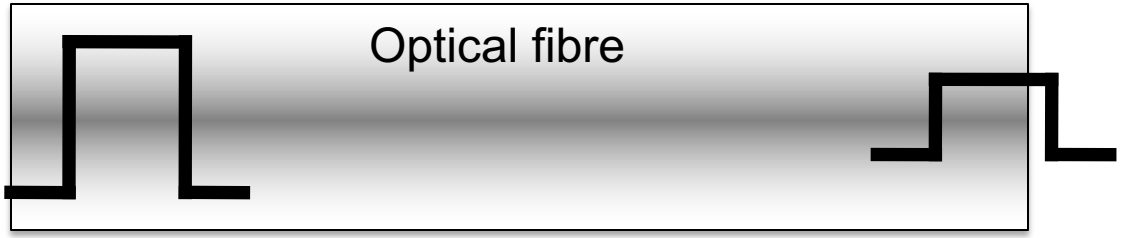
- A DTS typically uses a 10ns pulse to illuminate the glass core
- As the pulse travels down, power is lost

$$P_Z = P_0 \exp(-\alpha z)$$

$P_0 = \text{initial power}$

$\alpha = \text{loss parameter (dB/km)}$

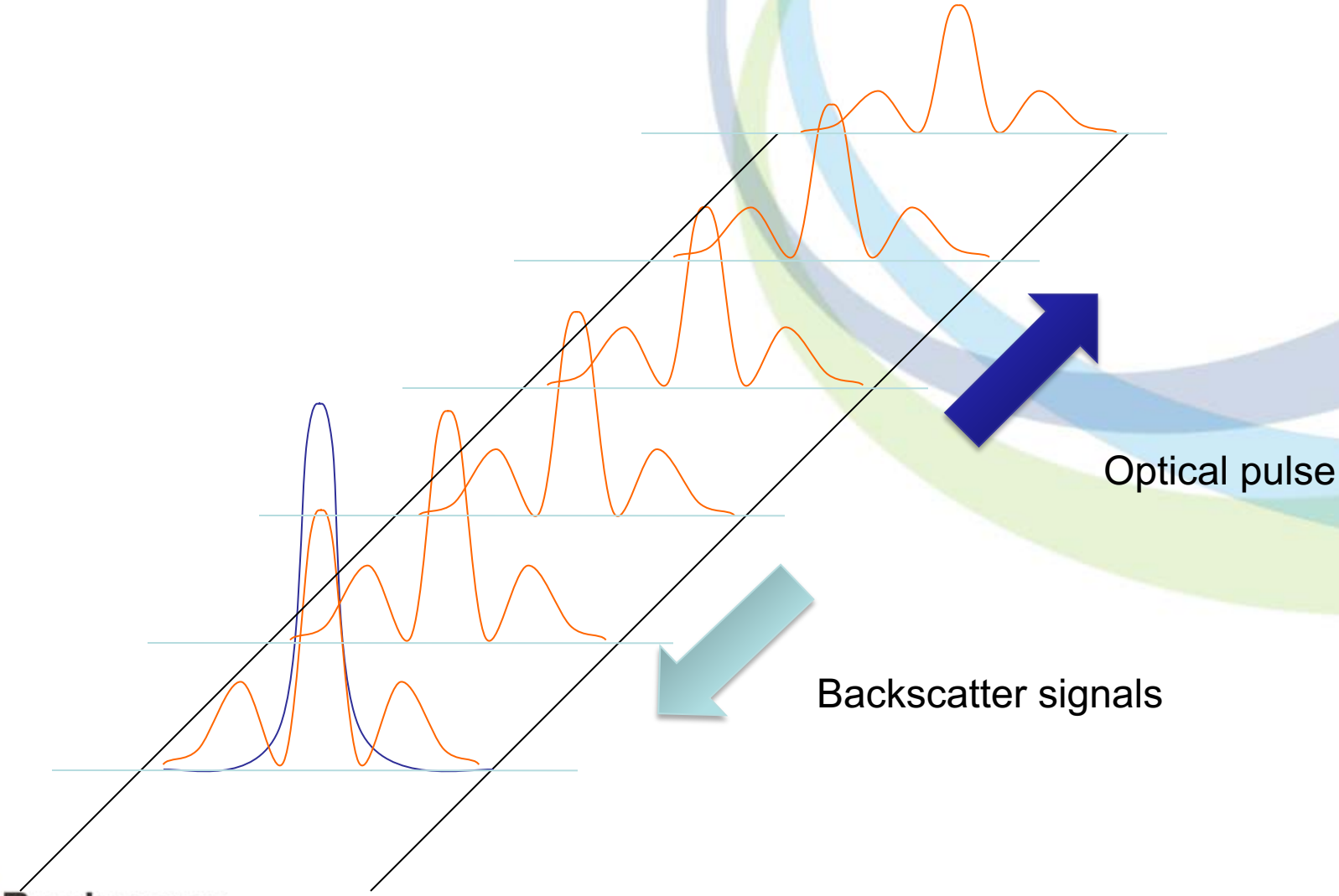
$z = \text{distance}$



# Example Raw Data Revisited

- The laser pulse decreases in power exponentially ($e^x$) with length
- Therefore the backscatter power will also decrease in power exponentially with length
- The loss is exponential as described by the Law of Beer-Lambert

# Backscatter Simulation



# Signal loss in optical fib

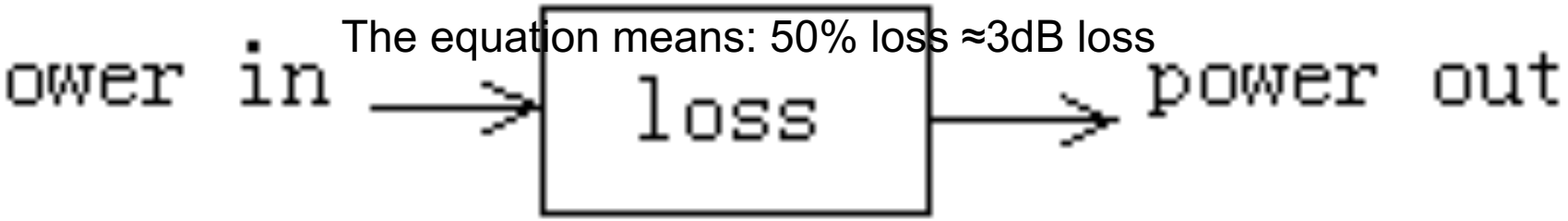
- All optical fibres experience a marginal loss of signal
  - absorption
  - radiation scattering
  - reflection
- The loss of signal is most common on or around joints or bends
  - Don’t exceed the bend radius
- The loss is defined as dB or dB/km

# Optical loss example 1

- Example1:There is 1km fibre, Power in is 1unit, and Power out is 0.5.

loss=10*log[0.5]=-3.01dB

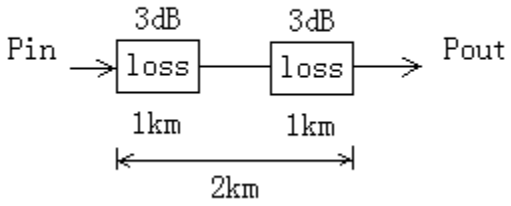
The equation means: 50% loss ≈3dB loss




$$\mathrm{Loss[dB]} = 10 * \log[\frac{P_{out}}{P_{in}}]$$

# Optical loss example 2

- Example 2：There is 2km fibre, the power loss is 3dB/km.




From the picture above the total loss is 6dB, 75% power loss.

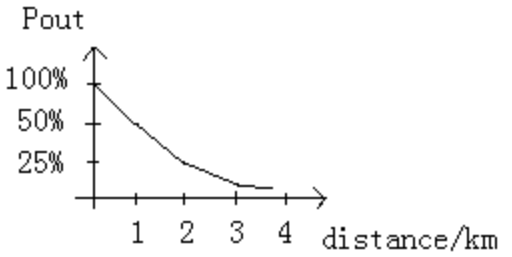
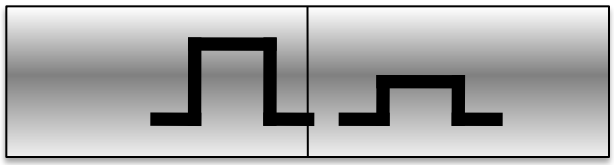



figure 4.Power decreases with the distance

# Loss at a Point

- Due to absorption, radiation scattering and/or reflection, there is signal loss at the joint
  - Connectors
  - Fusion Splices
- Backscatter signal shows a distinct power drop

Large optical loss at joint



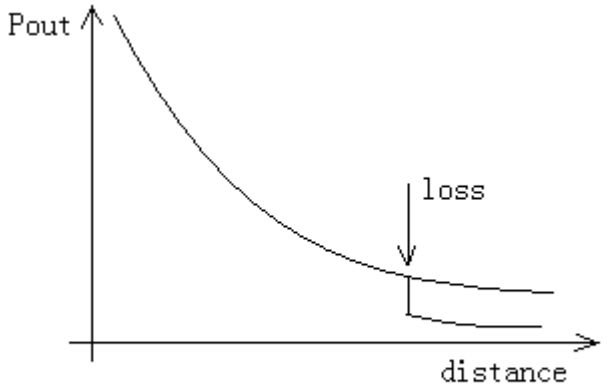
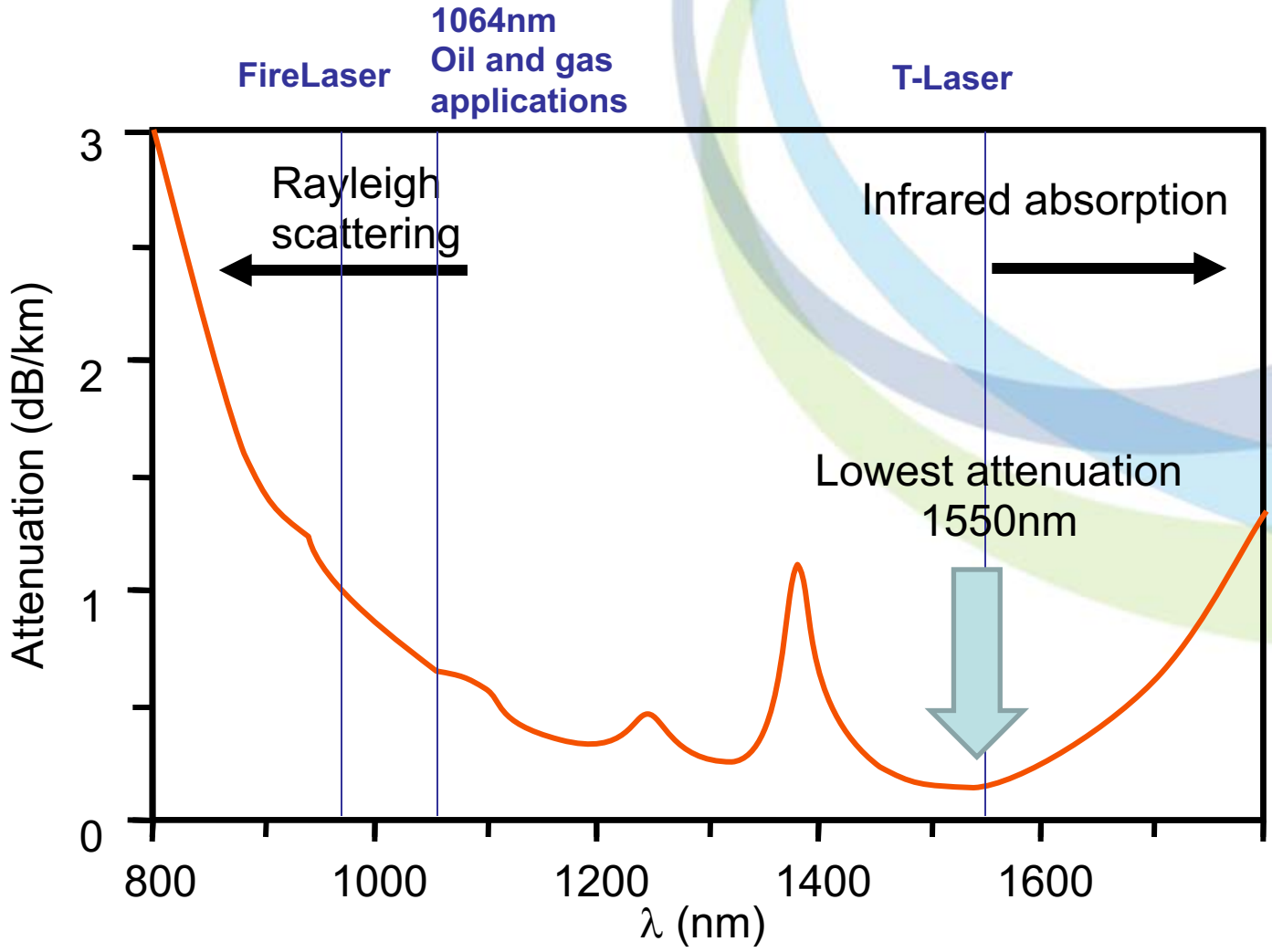



Figure 7. Power loss at the joint

# Optical Loss vs Wavelength

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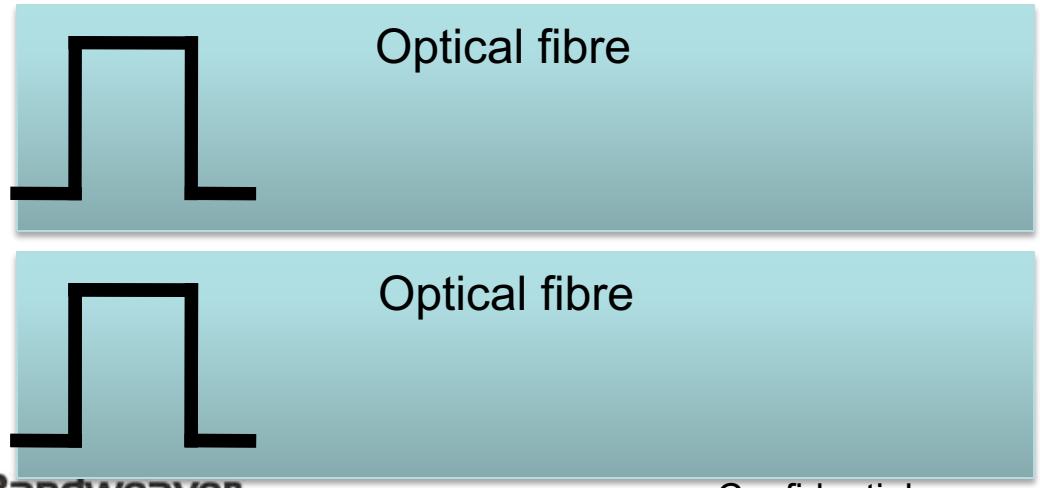
# DTS System Ranges

- 975nm
  - FireLaser 4km
- 1550nm
  - T-Laser
  - lower wavelengths the power decreases faster with distance, therefore the overall range is smaller

# Laser Frequency Maximum Fibre Length

- One pulse in not enough for a measurement, many pulses are needed
- Only one pulse at a time in the fibre otherwise back scatter will occur from two or more locations




Normal

Incorrect

# Laser Frequency Maximum Fibre Length

- Laser repetition rate 10kHz (100us)
  - A DTS will use more than 100,000 pulses
- Speed of light $3x10^8$m/s (299792458m/s)
- Refractive index of glass ~1.5 (1.465)
- Maximum fibre length 10km (d)
  - Calculation uses twice the distance (x2) forward pulse and backscatter travel distance
- Don't exceed fibre lengths for a DTS
- Max length also depends on maximum acquisition length of hardware

$2 \times d = c / n \times t$

- c: speed of light in vacuum
- t: total time
- n: refractive index

# General Safety!

- Never look directly into an optical fibre when it is connected to a DTS
- The laser light is invisible to the naked eye
- The laser has a high peak power and can destroy the retina
- Always turn off the laser when changing fibres

# END OF FIRST LESSON

# Lesson Two topics

- General advantages of DTS when compared with other sensors
- Total internal reflection
- Singlemode vs Multimode fibre
  - Dispersion - Graded index fibre
  - Spatial resolution
- Temperature from Light
- Raw data and slope - Differential loss
- Temperature resolutions

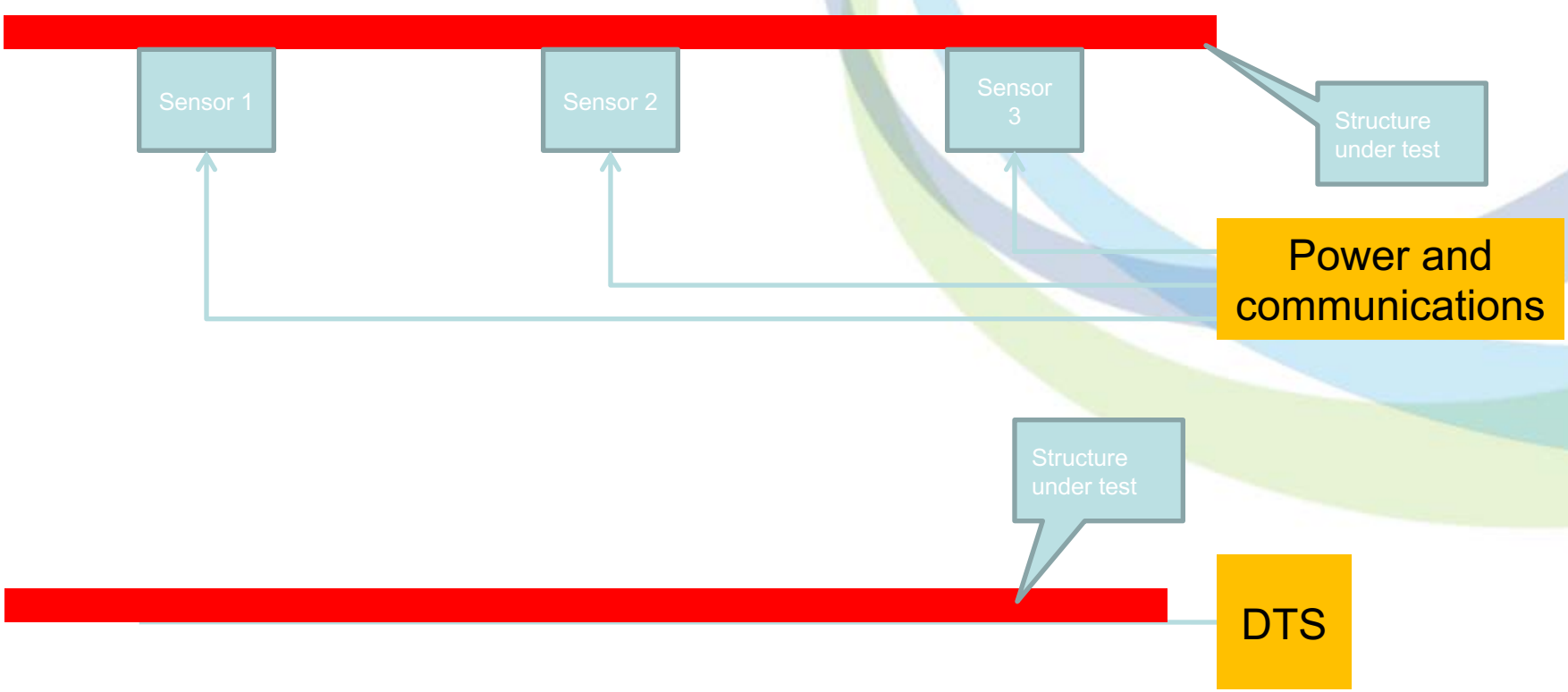
# General advantages of fibre

- Immune to EM radiation
- Standard optical communications fibre
- Fibre is the sensor, information returns to the machine via the sensor
- Distributed nature
  - No need to locate potential fault
  - One fibre
  - Discrete sensors may need their own power
- However discrete sensors are more sensitive

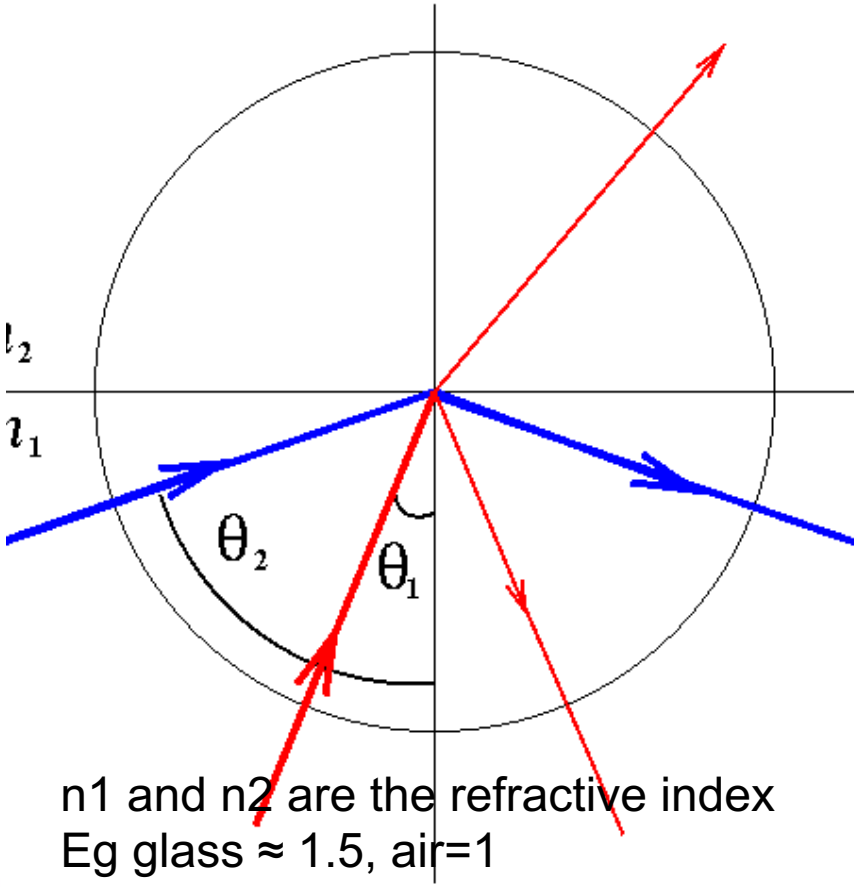
# Example

- Fibre installation in building foundations

# Fibre Optic vs Traditional Sensor



# Total Internal Reflection




n1 and n2 are the refractive index
Eg glass ≈ 1.5, air=1

- Light crossing between two different materials
- Critical angle for total internal reflection

$$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right)$$

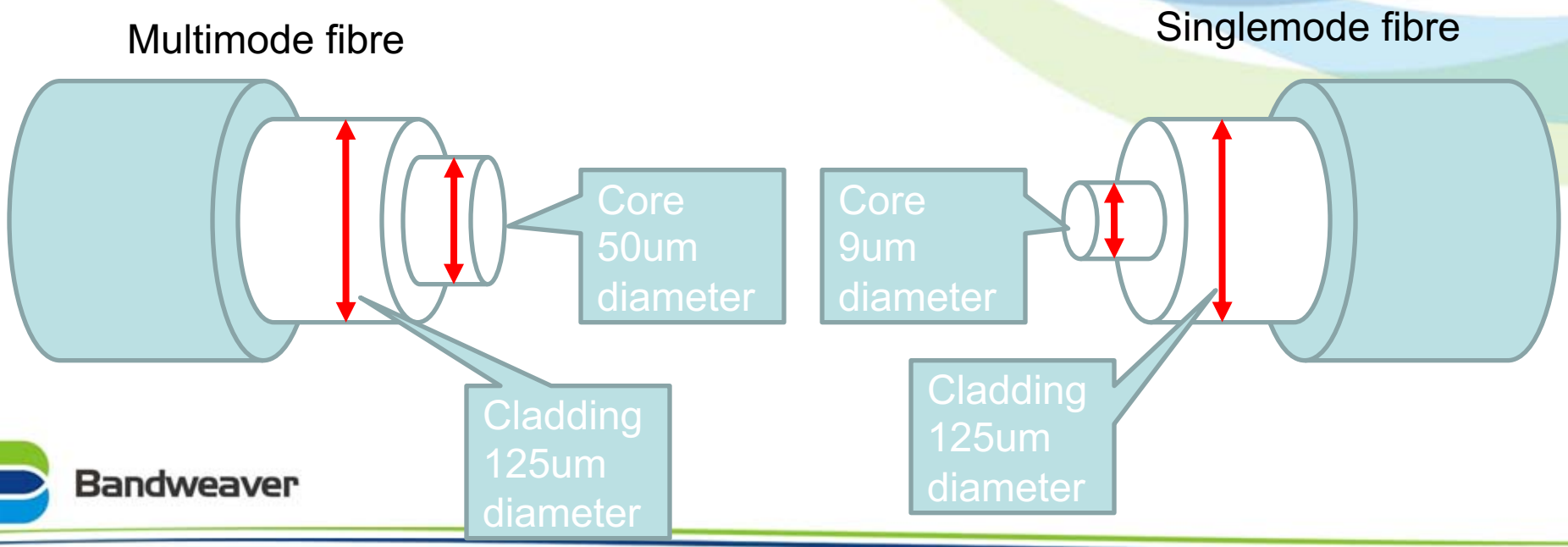
$$\text{if } \theta > \theta_c \text{ light is guided in fibre}$$

# Types of Fibre

- Most common types
  - Single mode fibre
    - Only one propagation mode can travel in the fibre
  - Multimode fibre
    - Many propagation modes can travel in the fibre
- Light travels in fibre by total internal reflection
- Simple term: Larger core size more modes

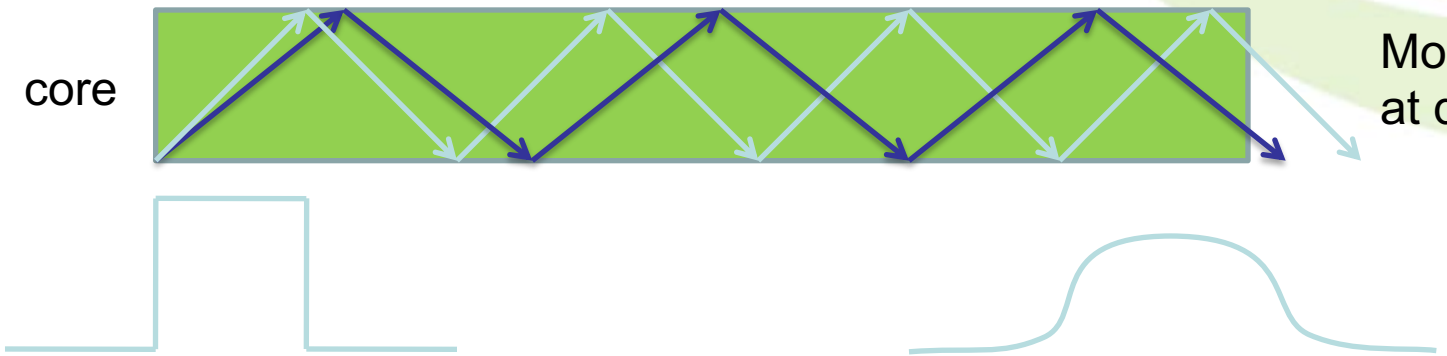
# Fibre Description

- Two general fibre types
  - Single mode fibre and Multimode fibre
  - Core and cladding have different refractive indices ($SiO_2$)



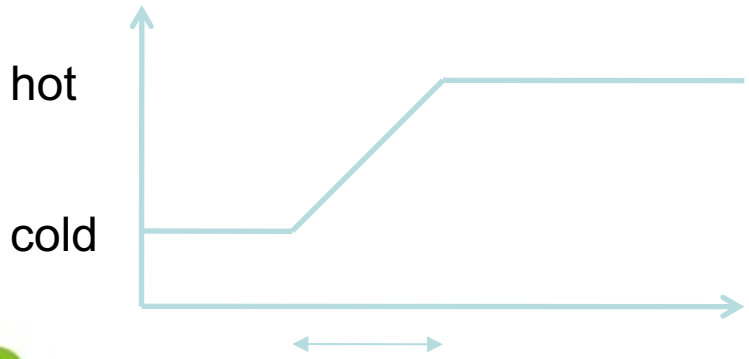
# Multimode Step Index Fibre Problem

- In multimode fibre light can propagate at different angles
- Each path has a different length
  - Pulse spreading can occur



# Dispersion Problem

- As the pulse becomes wider spatial resolution becomes worse
- Spatial Resolution
  - The shortest distance required to distinguish between two temperatures




Short spatial resolution

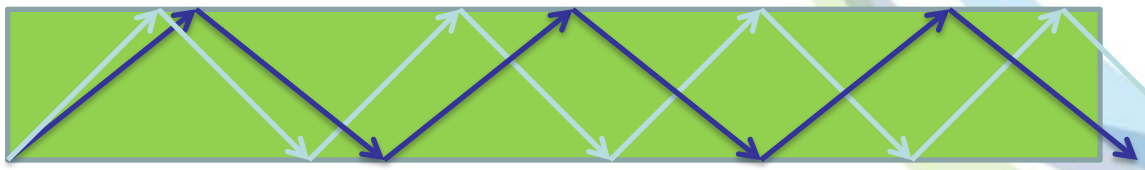
Long spatial resolution

# Step Index vs Graded Index Fibre

Refractive index

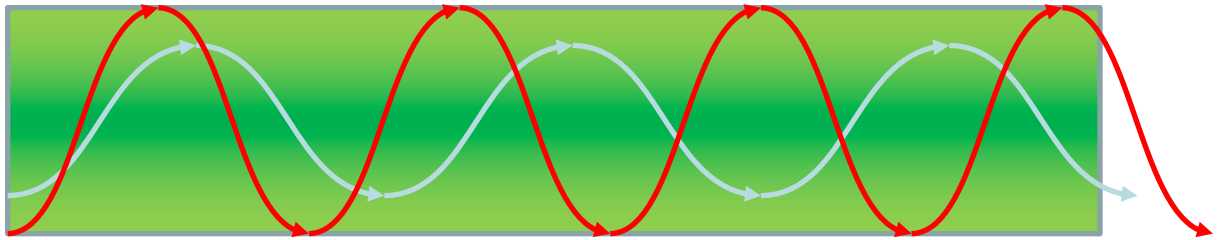
Total distance travelled by waves are different more dispersion

core



Total distance travelled by waves are similar and light travelling away from the centre of the core travels faster=>less dispersion

core



Refractive index between core and cladding is graded

# Modal Dispersion

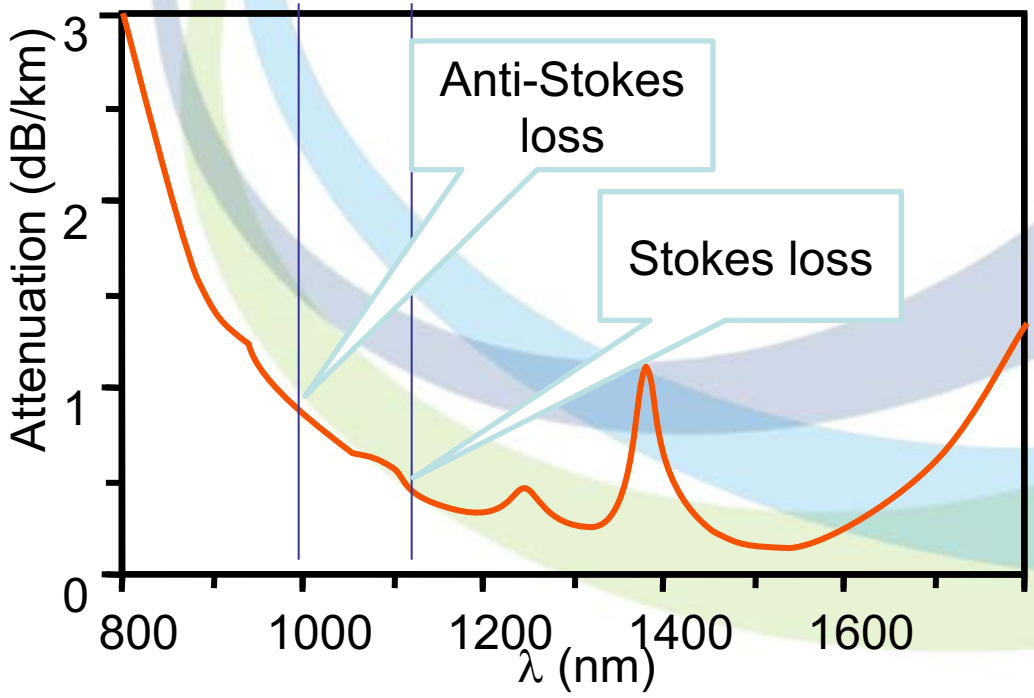
- Different modes travel at different speeds
  - Pulse spreading with distance
  - Spatial resolution becomes worse
- Use Graded index multimode fibre
  - Reduced pulse spreading
  - This type of multimode fibre is always used for DTS measurements
- 50um or 62.5um GI MM = 50um 62.5um core graded index multimode fibre

# Multimode vs Singlemode Fibre

- Multimode advantages
- Larger core size → more power in → more backscatter signal
  - Better signal to noise ratio
  - Better temperature resolution
- Single mode fibre advantages
  - None really except most communications cables are all single mode

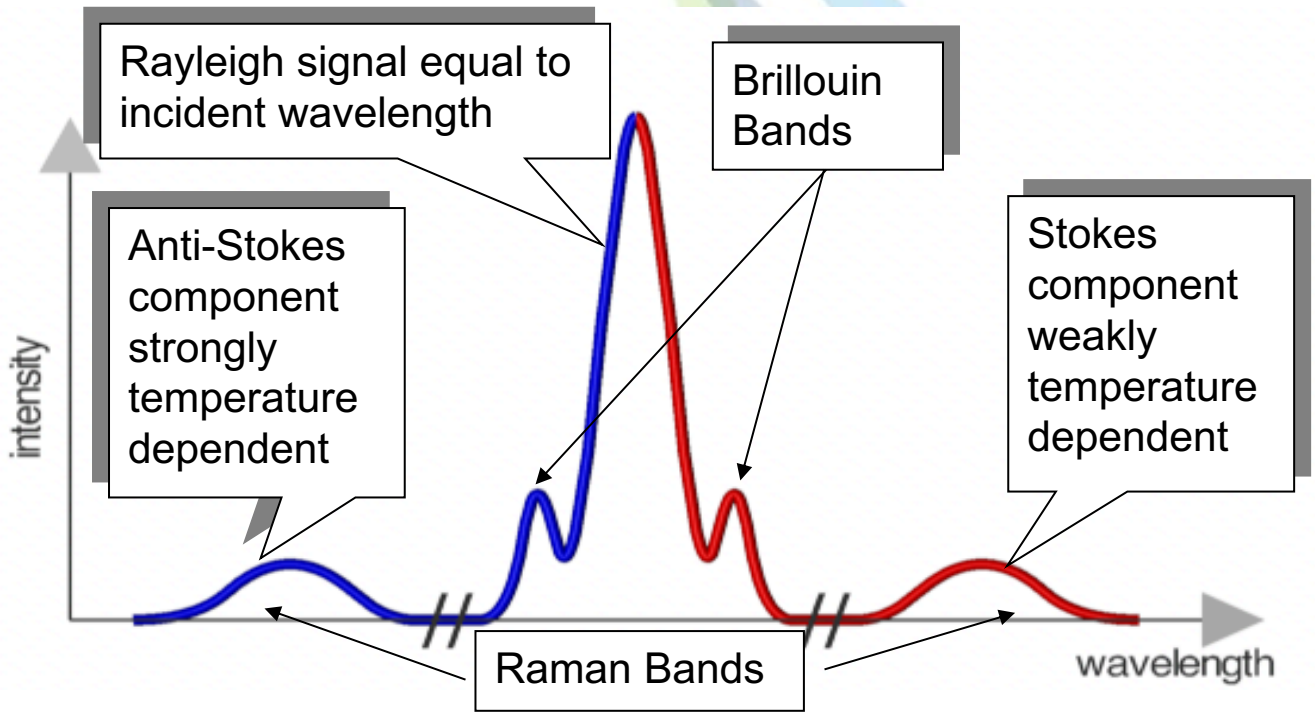
# Differential Loss Example

- Wavelength dependent loss is different between Stokes and Anti-Stokes wavelengths in fibre
- Important parameter for temperature calculations



# Backscatter signals - review

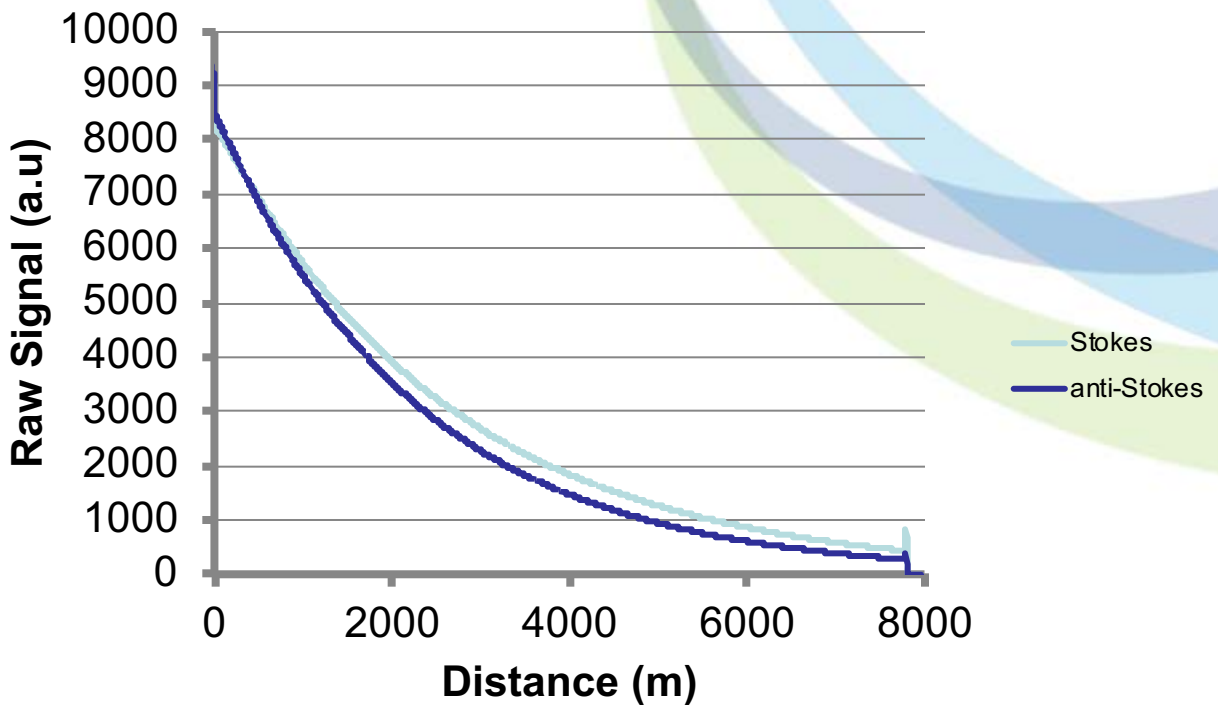
- Raman signals are about ±40nm (at 1064nm)



# Differential Loss

- Difference in loss between Stokes and Anti-Stokes signal (e.g. $\Delta\alpha$=0.2dB/km)
- Single ended system it is always assumed to be constant
  - If it is not constant a temperature deviation can occur i.e. a slope in the temperature
  - Double ended measurements account for a non-constant differential loss (explained later)

# Raw Data – review



# Temperature from Light

- Raman signal is used to calculate the temperature
  - (Power Ratio / differential loss) $\alpha$ temperature
    - Ratio is referenced to a known temperature (reference oven)
  - Time of flight gives distance
    - Remember: we know the when we started the laser pulse and its speed

# Things to remember about the fibre

- It is flexible but does not like sharp bends or many twists
- Connectors add optical loss – reduces measurement length

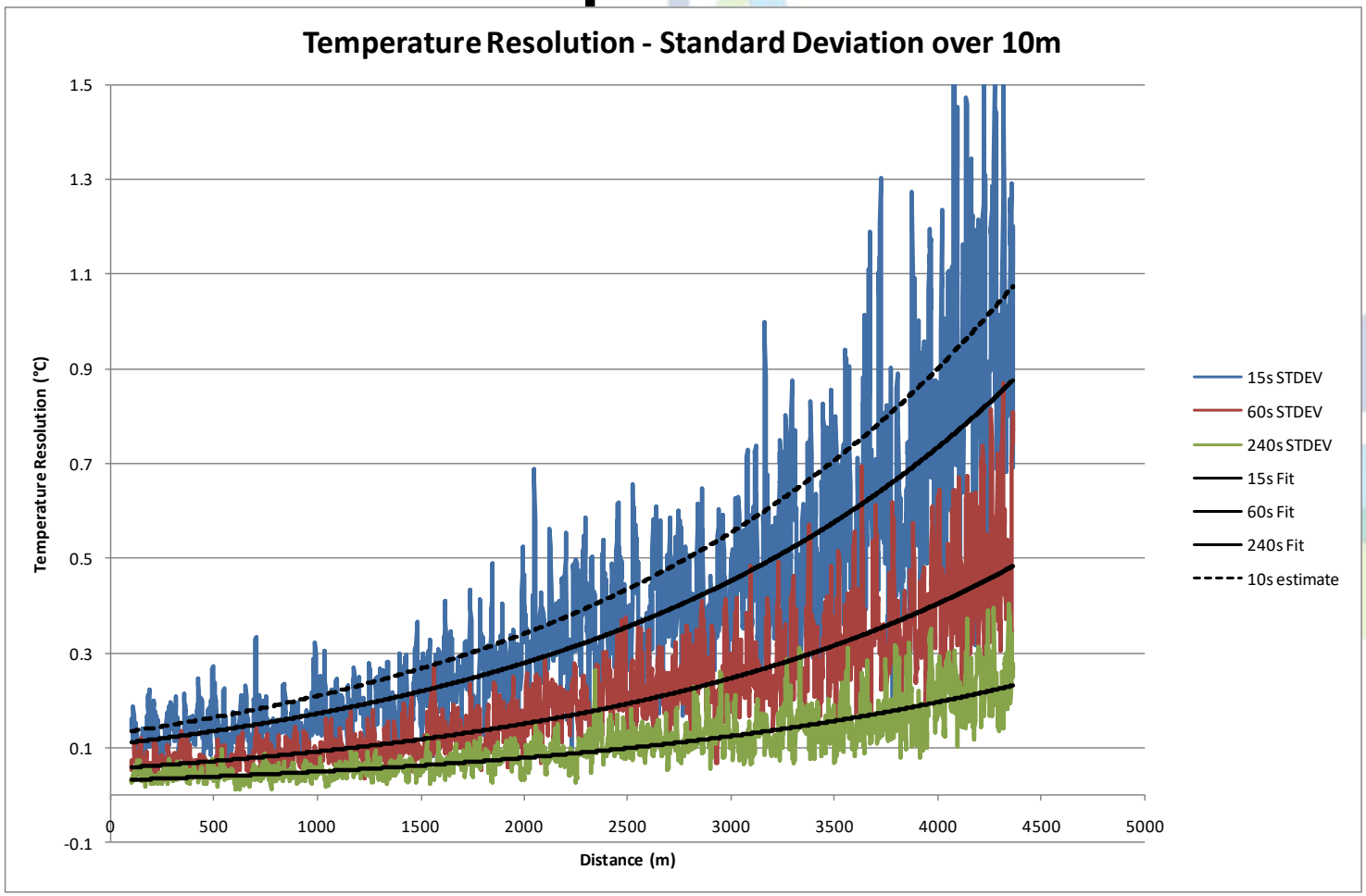
# Temperature resolution

- Typical DTS data sheet gives DTS performance from a Temperature Resolution Graph
- Temperature measurement from a fibre at constant temperature
- Standard deviation taken over 10m and 10m window is incremented to the next point
- Best fit exponential line on the deviation trend

# Background

- Moving average with a window of N samples
  - Sum of N samples and then divide that number by N
  - Move to next point and repeat
  - Used for smoothing data
- Moving standard deviation with a window of N samples
  - At one location calculate the standard deviation of N samples
  - Move to next point and repeat

# Typical Temperature resolution plot



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# Temperature resolution curves

- Standard deviation over 10 points
- Incremented every point
- Plot on graph
- Take exponential best fit curve

# Temperature resolution

- Given a Distance and Measurement Time what temperature changes can be resolved
- Temperature resolution becomes worse with increasing distance…
- …but improves with measurement time

# Measurement trade offs

- Increasing acquisition time
  - Longer measurement time gives better temperature resolution
  - $\Delta T \alpha 1/\sqrt{t}$
- Increasing spatial averaging
  - Larger spatial averaging give better temperature resolution
  - $\Delta T \alpha 1/\sqrt{L}$
- Temperature resolution decrease with distance
  - Due to attenuation of signal in fibre

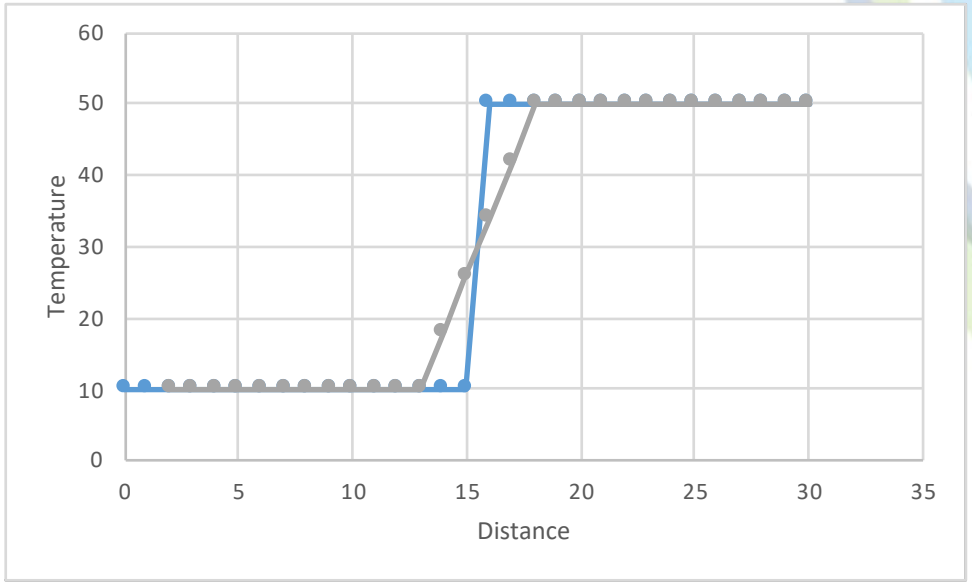
# Sample Resolution

- The DAQ card runs acquires data at 100 Million samples per second or f=100MHz or $10x10^{-9}$s or 10ns
- The speed of light is c=299,792,458m/s
- The refractive index of the optical fibre is about n=1.4760 and varies from fibre to fibre
- The simple distance, time and speed relationship is:
  - $d = v\,.\,t$
- The pulse of light travels twice the distance so d=2z (forward pulse, and backscatter)
- The speed of light is slower in glass, divide by the refractive index v=c/n
- Using ADC frequency instead of time, t=1/f
  - $2z = \frac{c}{n} \times t$ or $z = \frac{c}{2nf}$
- $\frac{299792458}{2*1.476*100e6} \approx 1.016m$

# Spatial Resolution

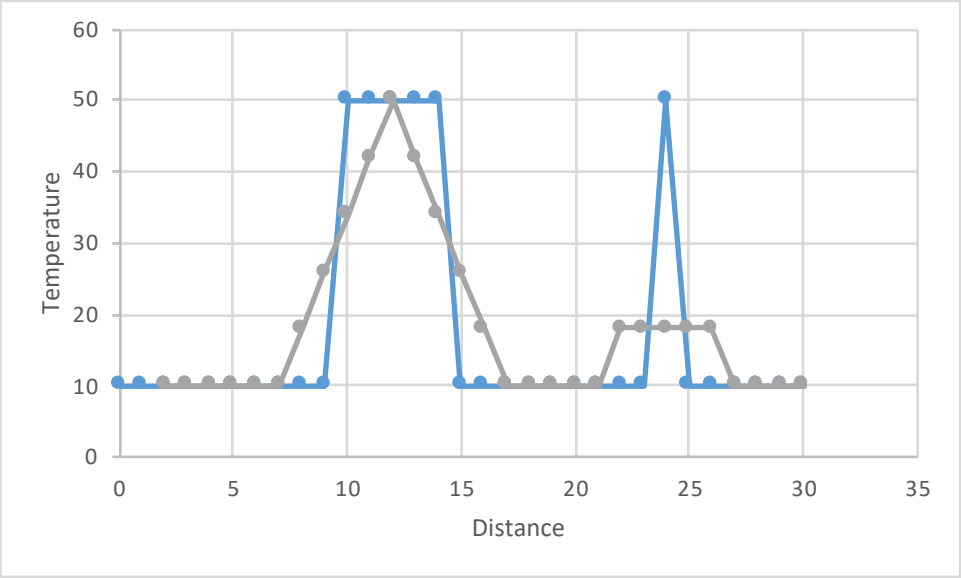
- How many measurement points do I need to determine a temperature step change?
- Spatial resolution depends on laser pulse width, detector bandwidth and ADC sample rate
- Several methods of determining Spatial resolution but:
  - Spatial resolution > sample resolution * 1.6
    - Minimum Nyquist requirement (twice sample rate)
    - 10% to 90% of a temperature step change

# Importance of spatial resolution




- Step temperature change
- 5 point window
- New trace has a larger spatial resolution

# Importance of spatial resolution




- Averaging window
- 5 point window
- Short fast changing temperatures can appear to have lower temperatures if spatial resolution is large

# Maximum measurement length

- Maximum memory on data acquisition system
- Repetition rate of laser

# END OF 2ND LESSON

# Lesson Three

- DTS Software Training - FireLaser DTCM Software
  - DTS Safety
  - Explanation of connections
    - Cable types
    - Connector types
  - Software configuration
  - Manipulating graphs
  - Data review
  - Errors

# Understanding the temperature trace

- <0m internal reference fibre
  - Fibre inside the DTS used for calibration
- >0m attached optical cable
- What are the large temperature variations, at the beginning and at the very end
  - No optical signal => no fibre => undetermined temperature

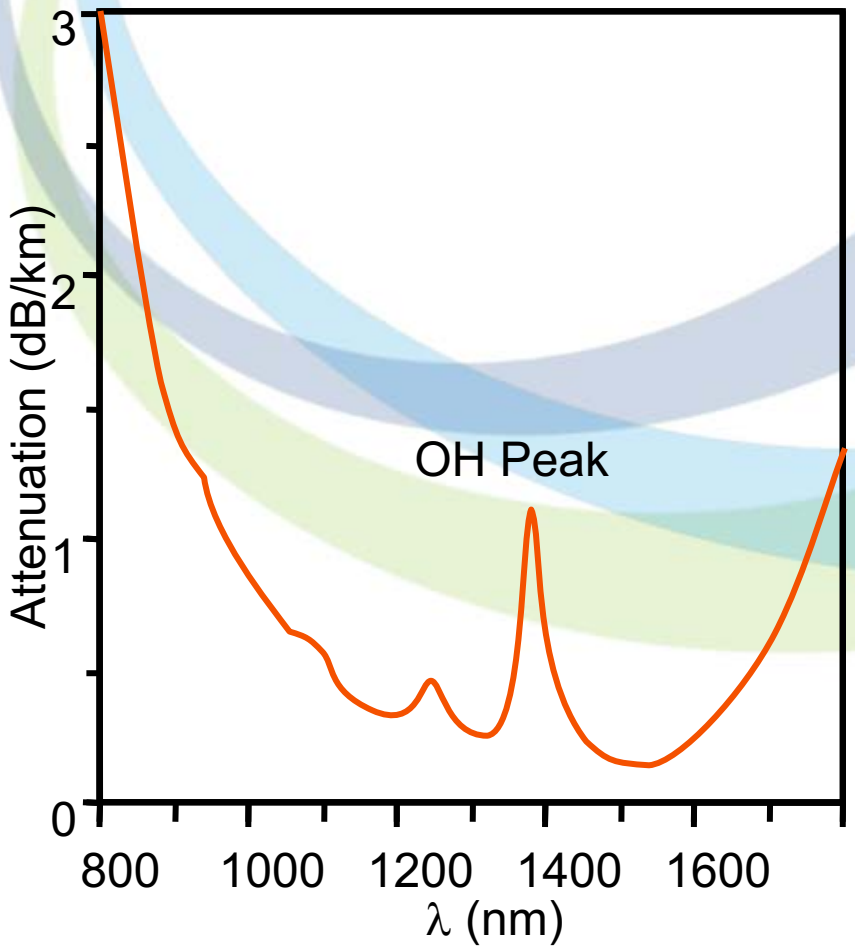
# END OF 3RD LESSON

# Lesson Four

- DTS platforms
- Main markets
  - Fire detection
  - Power
  - Oil and Gas
  - Hydro (Dam monitoring)
  - Process monitoring
  - Emerging markets ← new markets to concentrate on

# Some Problems in the Oil and Gas Industry

- Hydrogen darkening
  - Hydrogen reacts with the optical fibre absorbing light at around 1400nm
- 1400nm is called the OH peak
- $OH^-$ – Oxygen and Hydrogen usually in the form of $Ge(OH)_2$



# DTS Platforms

- Bandweaver
  - FireLaser – specific for the Fire Market
  - TLaser < 30km

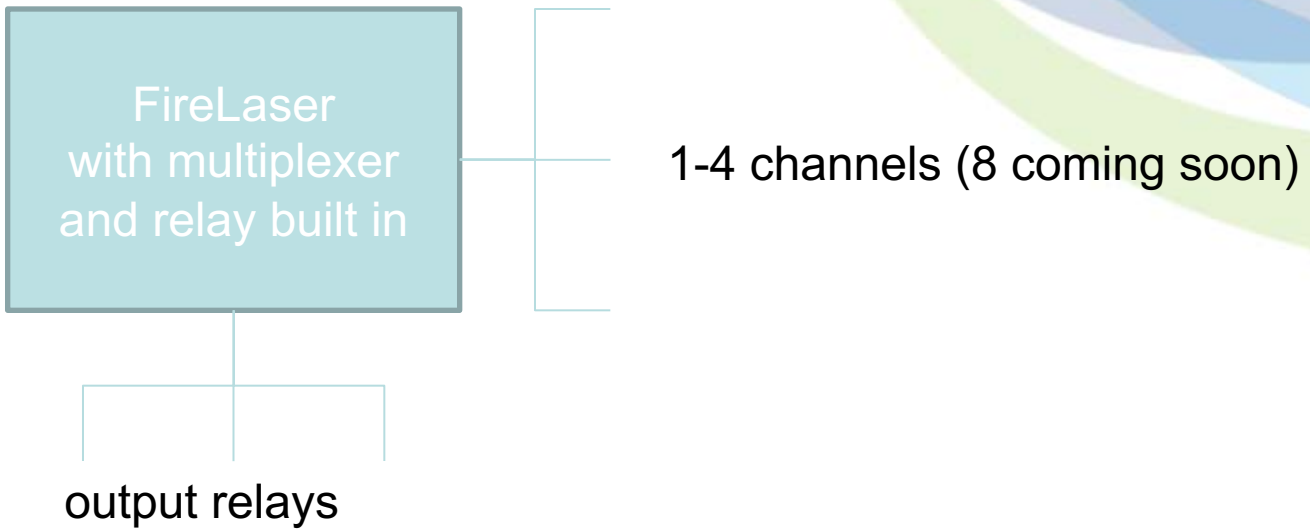
  - Access < 500m @ 1m
  - Access <1.5km @ 2m

# Bandweaver FireLaser

- 3U 19inch Unit
- Embedded process (ARM and TI processors)
- Built in optical multiplexer, relay unit and modbus
- Standard DTS with the fire market in mind

# Bandweaver FireLaser

- All components combined into one unit
- Embedded processor (no MS Windows)



# Fire Detection

- Direct temperature measurements
- Alarms software to trigger when temperature is out of range
- Which DTS to use
  - Cost, measurement length and temperature resolution
  - FireLaser designed to conform to China's new Fire Regulation

# Fire Detection cont.

- Cable
  - Multimode fibre in steel tube
- Software
  - Alarms software
  - If a zone becomes too hot need to trigger an alarm
- Hardware
  - Relays to connect to fire panel

# Fire Market cont.

- Alarms relay connected to Fire Panel via relays
- Modbus to SCADA system
- Applications
  - Tunnels
  - Emerging markets
    - Buildings
    - Car parks (Germany)

# Power Industry

- Temperature of cable is critical to its overall life time
- DCR uses DTS data to determine cable temperature and maximum permissible loads
- DTS
  - Measurement length and channels
  - Sentinel

# Power Industry cont.

- DTS is used to measure temperature along a power cable
- DCR translates surface temperature to cable core temperature
- Cable
  - Multimode cable
- Software
  - CSM, DCR and DTS software
- Hardware
  - DCR 100/DCR 200
  - DTS Sentinel with Multiplexer

# Power Industry cont.

- DTS can also be used for fire monitoring in cable tunnel
- Software needs customisation for each customer
  - All power networks are different
  - Cable designs are different
- Multiplexer allows for multiple cable to be monitored, each power phase
- Intelligent Power network management

# Oil Gas Industry

- DTS measuring temperature
  - Flow
    - Measuring oil temperature gives an indication of oil flow
  - Water ingress
  - Steam break through for ‘heavy’ oil (SAGD)
- Main aim (oil) well management
- Complex installation
  - Requires special fibre and cable protection

# Oil Gas Industry cont.

- Cable
  - Needs to be very rugged
  - Mutlimode with special coatings – could be high temperature
  - Prevent hydrogen getting into the fibre (prevent hydrogen darkening which causes non linear differential loss)
  - Stainless tube or hydrogen getter to absorb hydrogen

# Oil Gas

- $H_2S$ hydrogen sulfide in oil wells causes hydrogen darkening in optical fibre
  - Special coatings on fibre are required to stop hydrogen ingress
  - Specialty fibres that are immune to hydrogen
- Complicated installation
- Oil wells may be close together requiring a multiplexer

# Hydro

- Leak detection in dams
- Earth dams made of sand and gravel as opposed to concrete dams
  - Earth dams are generally leaky
  - Monitoring leak temperature compared with seasonal temperatures cycles can predict leaks

# Emerging Markets

- Take advantage of China's lower costs to make cheaper DTS
  - More commercial areas rather than industrial application
  - Higher volumes
- Building/warehouse monitoring
- Environmental monitoring
- Alternative energy/Green industries

# END OF 4TH LESSON

# Bandweaver

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