Distributed Temperature Sensing (DTS)

DTS Principles

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IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

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Ministero dell'Università e della Ricerca
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OVERVIEW

- DTS Basics
- System Performance

What is Distributed Fibre Sensing?

- Light based measurement system
- Fibre-optic cable and an interrogator
- Simultaneous measurements at all points along optical fibre
  - (up to 40,000 measurement points)
- Measure temperature (DTS), strain-rate (DAS) or strain (DSS)

ULTIMA-DTS

XT-DTS

Silixa's Distributed Temperature Sensors (DTS)

- Measurement range up to 35 km
- High-density spatial sampling (0.25 m capability)
- Low power consumption
- Field ruggedized XT-DTS (-40 to +65°C operating temp range)

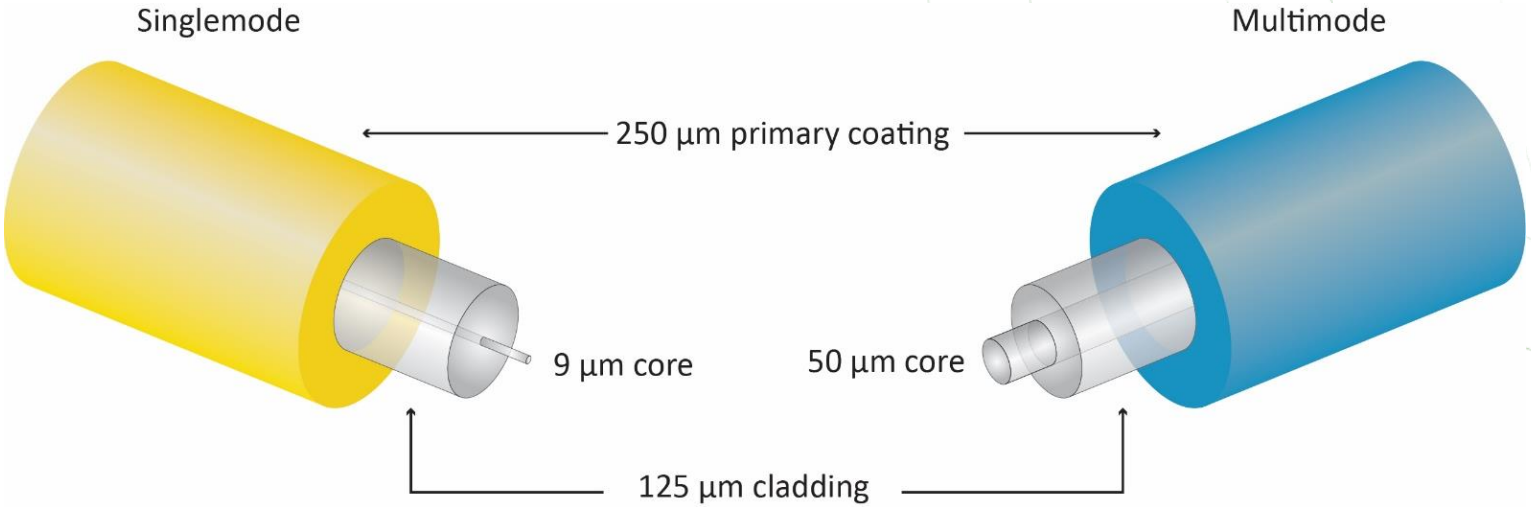
Key advantages of distributed fiber optic sensing

- Full coverage up to 35 km (DTS) or 50 km (DAS)
- Spatial resolution from >0.25 m
- On-demand or continuous recording
- Autonomous
- Low power
- No electronic or mechanical parts
- Minimum maintenance
- Suitable for harsh environments and high temperature
- Flexible deployments

Key components of a DTS

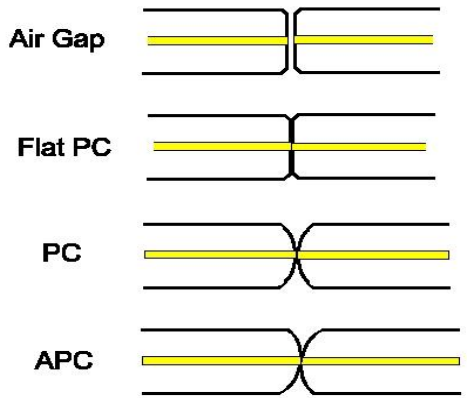
- A pulsed laser
- Optoelectronic detectors
  - Gain and bandwidth optimized for target SNR and spatial resolution
- DAQ card
  - Capability to spatially distribute measured backscatter signal by accounting for time of flight; sampling frequency set by target spatial resolution
- Optical fiber

Optical fiber: SMF vs MMF

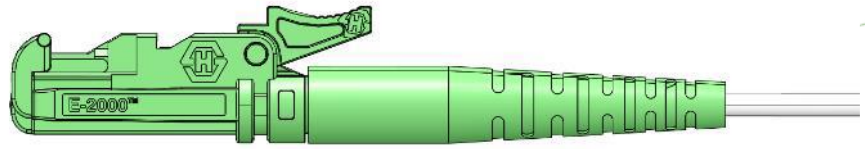


- There are two basic optical fiber types: singlemode and multimode.
- Multimode used for DTS, though singlemode can be used with specific instrument.
- In general, multimode fiber gives a better system signal-to-noise ratio, so better temperature resolution.
- Multimode fiber connector losses are typically smaller compared to singlemode fiber connectors.

System hardware: Optical fiber connector ferrule shapes & polishes



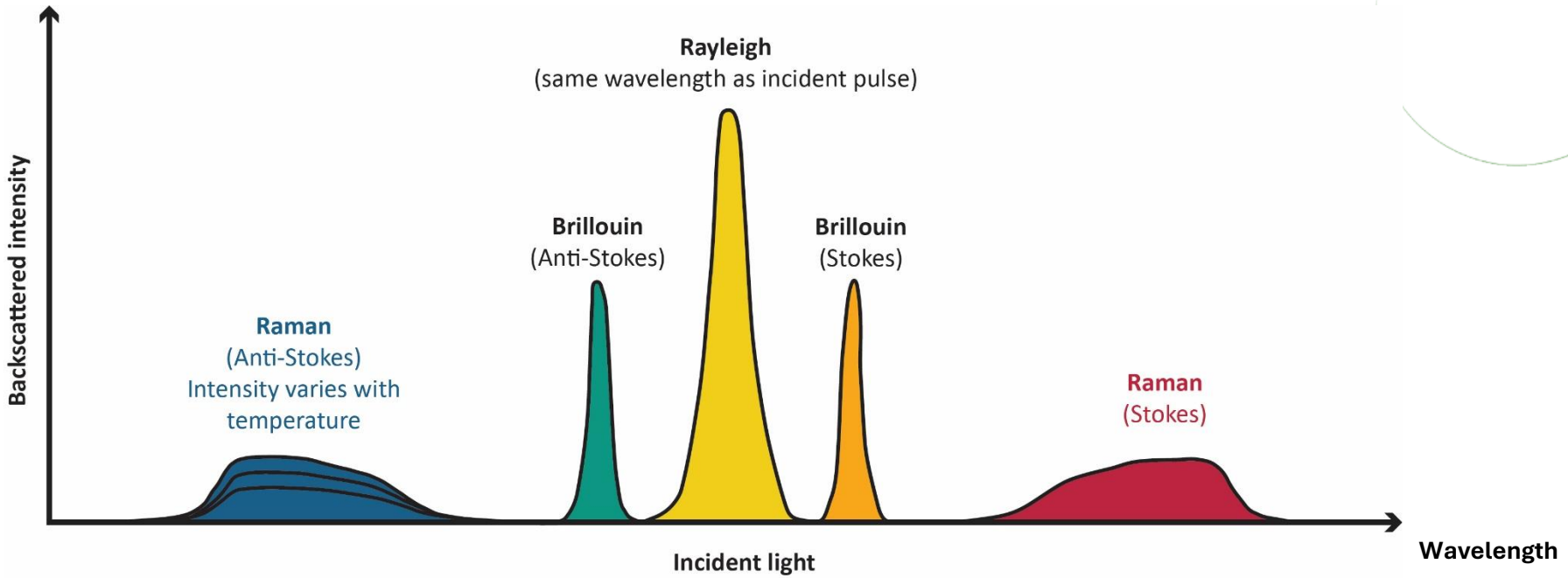
E2000 APC



DTS utilizes the Raman scattering signal

Loss mechanisms are useful.

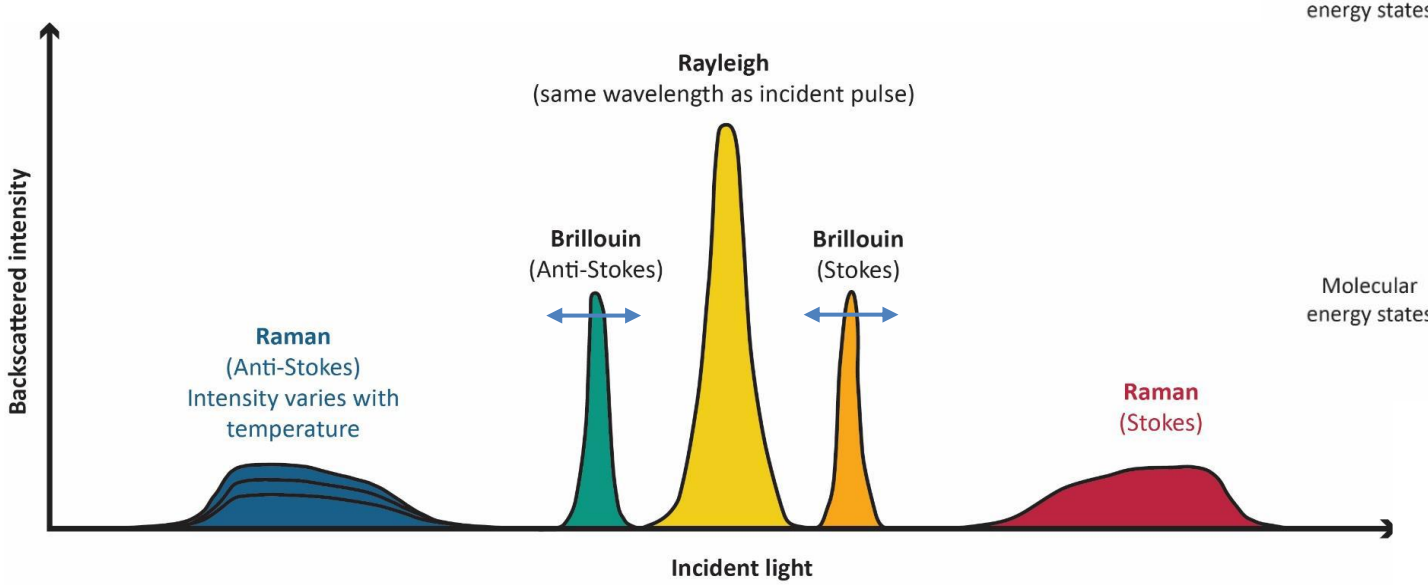
- **Rayleigh scattering:** Scattering caused by microscopic density and refractive index variations
- **Brillouin scattering:** The interaction of light photons and acoustic waves in the glass
- **Raman scattering:** The interaction of light photons at molecular energy levels

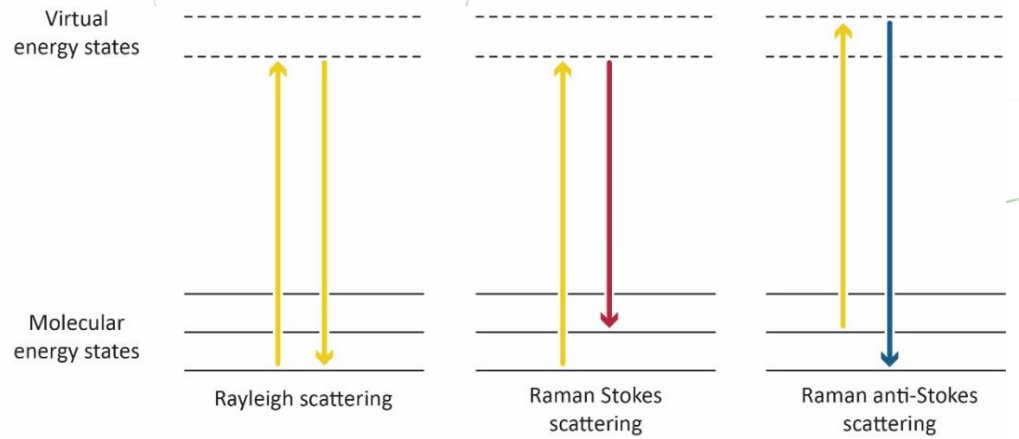


Backscatter

- Light enters optical fiber, scatters in the glass and returns. The further away the source of scatter, the less light comes back to the detector.

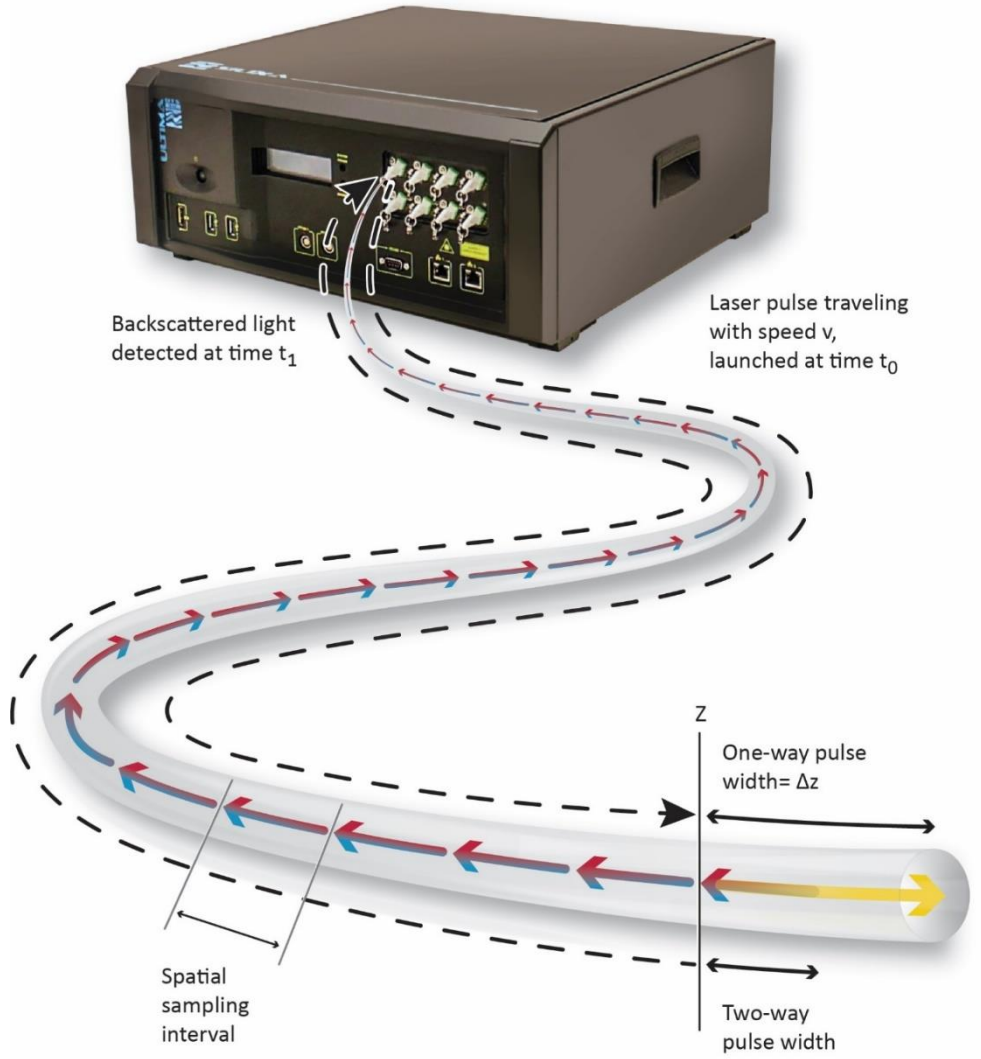
- **Raman Scattering** (inelastic process)
  - Molecules gain or lose energy in photon/fiber molecule collisions.
  - Generates backscatter at two new wavelengths: **Stokes** and **Anti-Stokes** (highly temperature dependent).
  - Temperature determined from the ratio of the Stokes and anti-Stokes signal intensities.





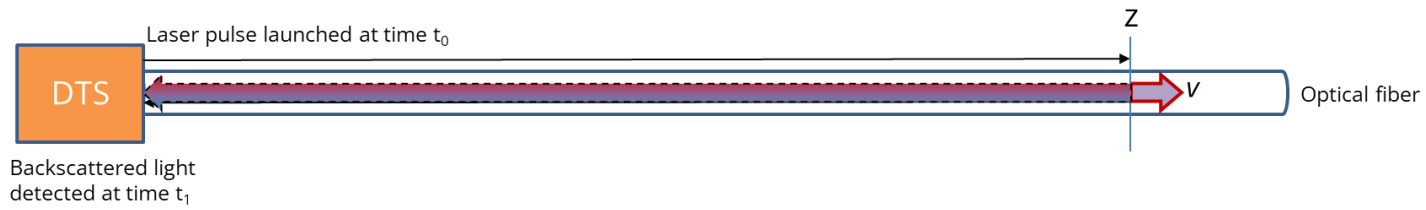
Laser pulse

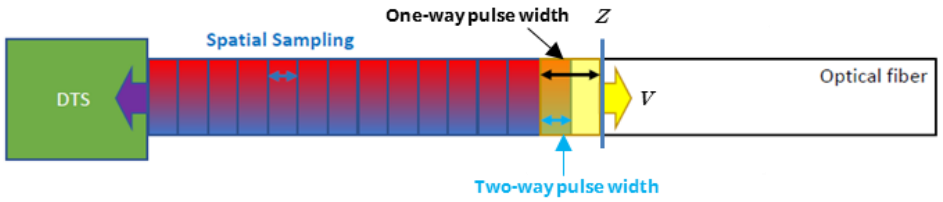
- Backscattered light signal is sampled in time.
- The measured signal is spatially distributed using optical time domain reflectometry (OTDR).
- Signal measured over a time sample corresponds to a spatial sampling interval (equivalent to the two-way pulse width).



Basic Principle of OTDR

The incident pulse width has a direct impact on the spatial resolution.





$$v = \frac{c}{n}$$

$$z = \frac{v * t}{2}$$

Speed of light in fiber	v
Speed of light in vacuum	c
Effective refractive index	n
Distance to signal source	z
Measured time of flight	$t=t_1-t_0$

Example

Pulse duration (Δt) 10 ns traveling at $2x10^8$ m/s has a distance extent of (Δz) 2 m

- The backscatter light signal is the average backscatter over half the distance extent of the pulse (Δz/2).
- Resulting temperature information at sample location z is the average over Δz/2 distance = 1 m.

Incident pulse duration Δt [ns]	Incident pulse distance extent Δz [m]	Backscatter distance extent Δz/2 [m]
1.25	0.25	0.125
2.5	0.5	0.25
5	1	0.5
10	2	1

Light propagation in optical fibres

Light loss occurs because a small portion of the forward propagating light is scattered.

- some of which is guided back and used for sensing
- determines the maximum distance that can be sensed

Material attenuation

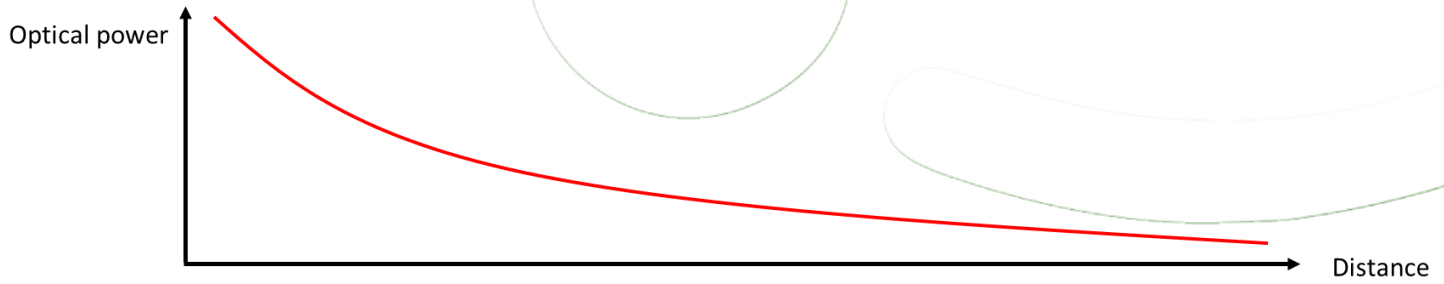
- Absorption by atoms
- Scattering: Rayleigh, Raman, Brillouin, etc.

Waveguide attenuation

- Bends and kinks in the fiber

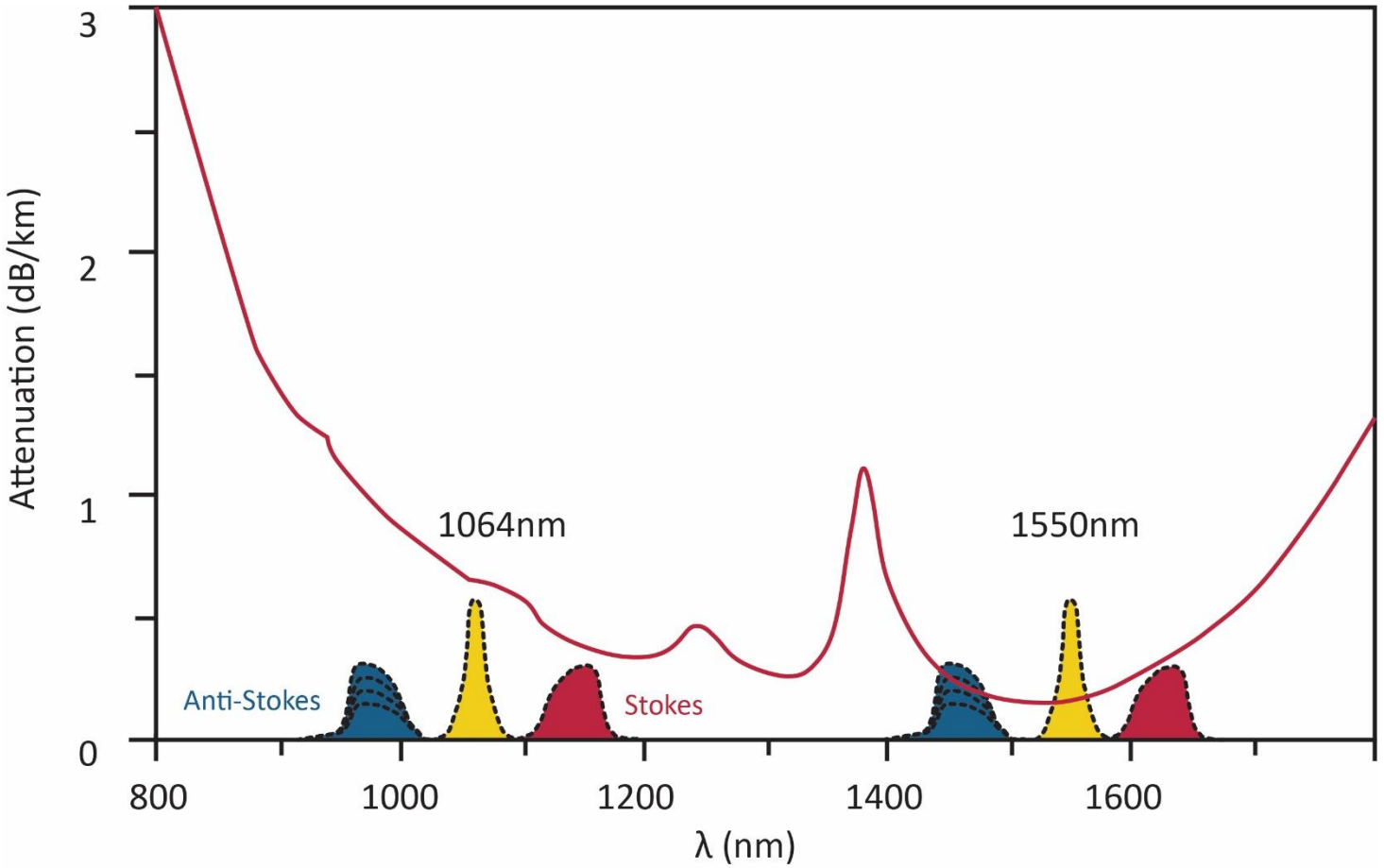
Fiber coupling losses

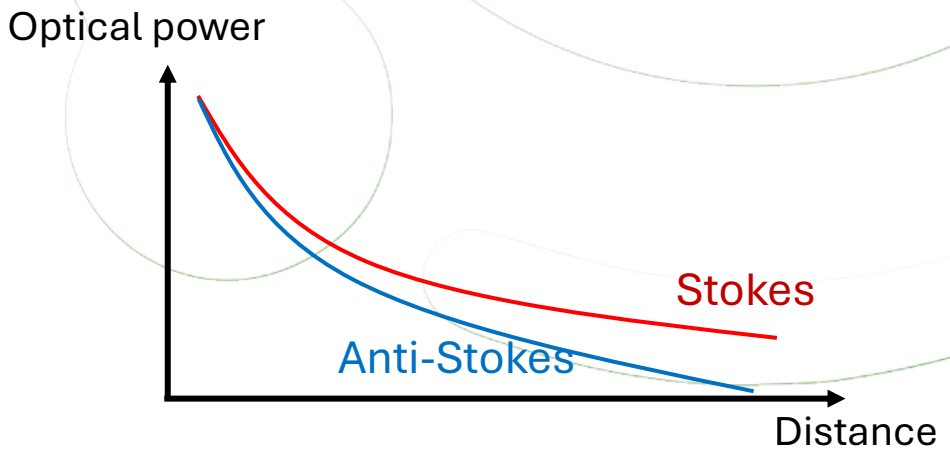
- Splices and connectors
- Physical connector losses can be significant!



Differential Loss

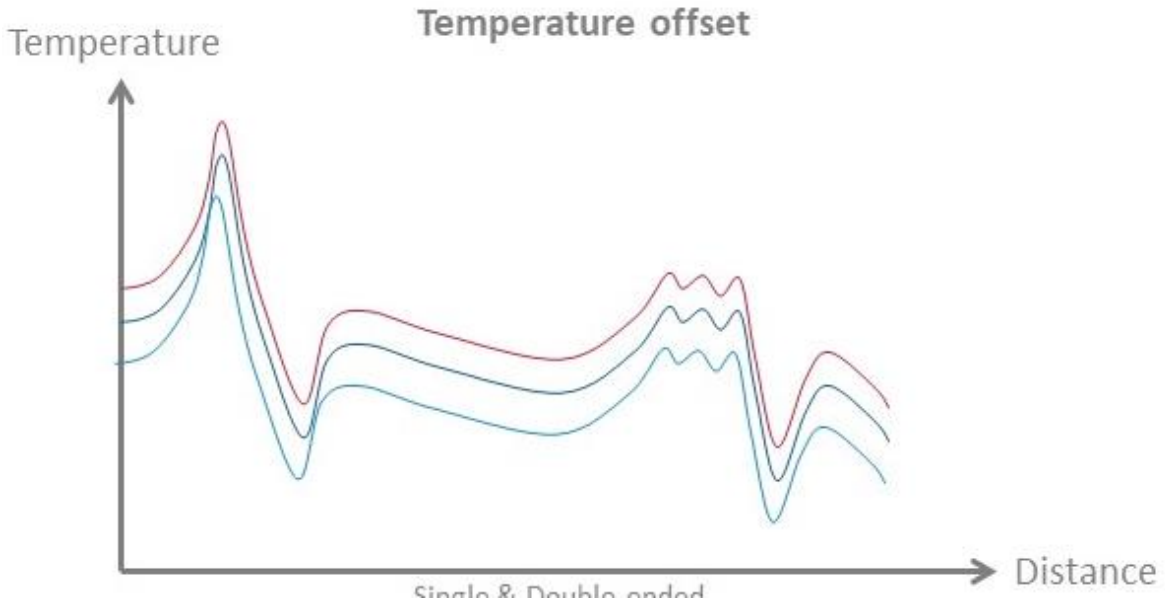
- Stokes and anti-Stokes signals experience different losses. Differential loss calibration parameter Δα accounts for this.

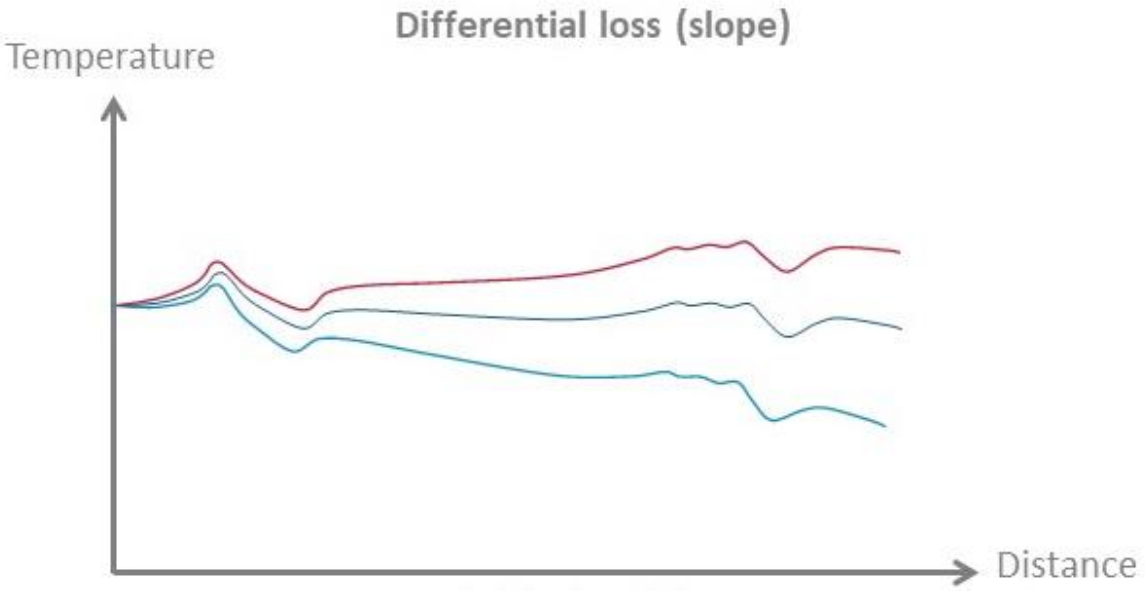




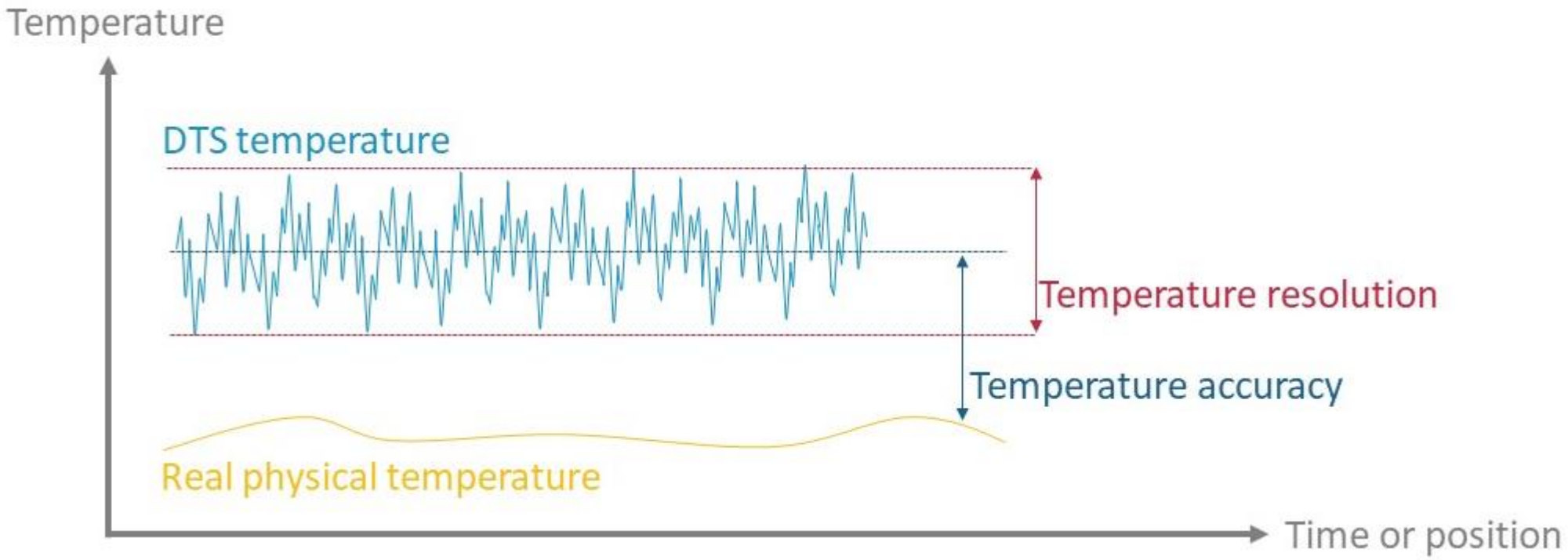
Note: Stokes and anti-Stokes signal wavelengths are ±40 nm around the Rayleigh peak wavelength; do not correspond to OTDR wavelengths

Temperature Offset and Differential loss





Temperature resolution



If absolute temperature is needed, it is important to determine the temperature offset using external probes, calibration baths, or other methods.

DTS Temperature equation

Temperature retrieval equation:

$$T(z) = \frac{\gamma}{K - \Delta\alpha \cdot z - \ln\left(\frac{I(z)_{st}}{I(z)_{ast}}\right)}$$

Symbol	Unit	Function
γ	[K]	a system constant fixed during the manufacturing process ($\gamma=\hbar\Omega/k$)
K		a dimensionless calibration parameter related to the temperature offset that accounts for efficiency of DTS system components (e.g. laser optical power, efficiency of photodiodes)
$\Delta\alpha$	[km^{-1}]	differential loss
z	[km]	fiber distance (z=0 at the connector by default)
$I(z)_{st}$		Stokes signal amplitude over distance
$I(z)_{ast}$		anti-Stokes signal amplitude over distance

SYSTEM PERFORMANCE FACTORS

DTS performance factors

Temperature, temporal and spatial resolutions are the key performance factors of a DTS system.

DTS provides spatially distributed temperature in time.

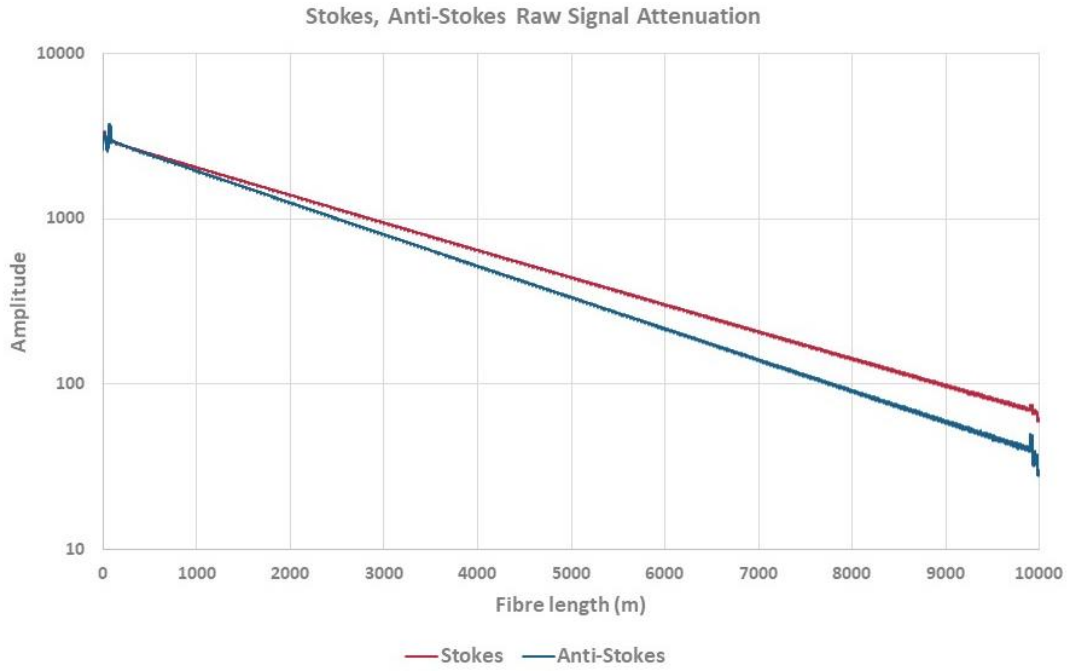
Parameter	
Temperature Resolution	From 0.01 °C
Sensing range	2/5/10 km variable
Laser repitition rate	≤ 36 kHz
Sampling Resolution	25 cm and 50 cm
Spatial Resolution	65 cm
Measurement time	From 5 sec

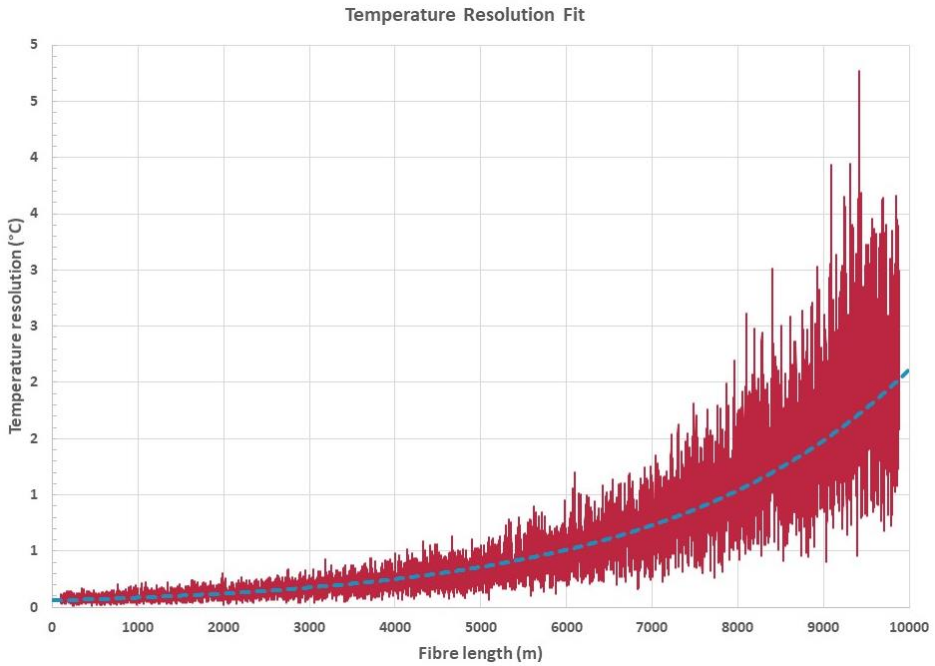
These factors are inextricably linked, and depend on:

1. Range (length of fiber)
2. Sampling resolution
3. Laser pulse width and repetition rate

Temperature Resolution

The temperature resolution of a DTS system is the smallest temperature variation a system can detect or resolve.



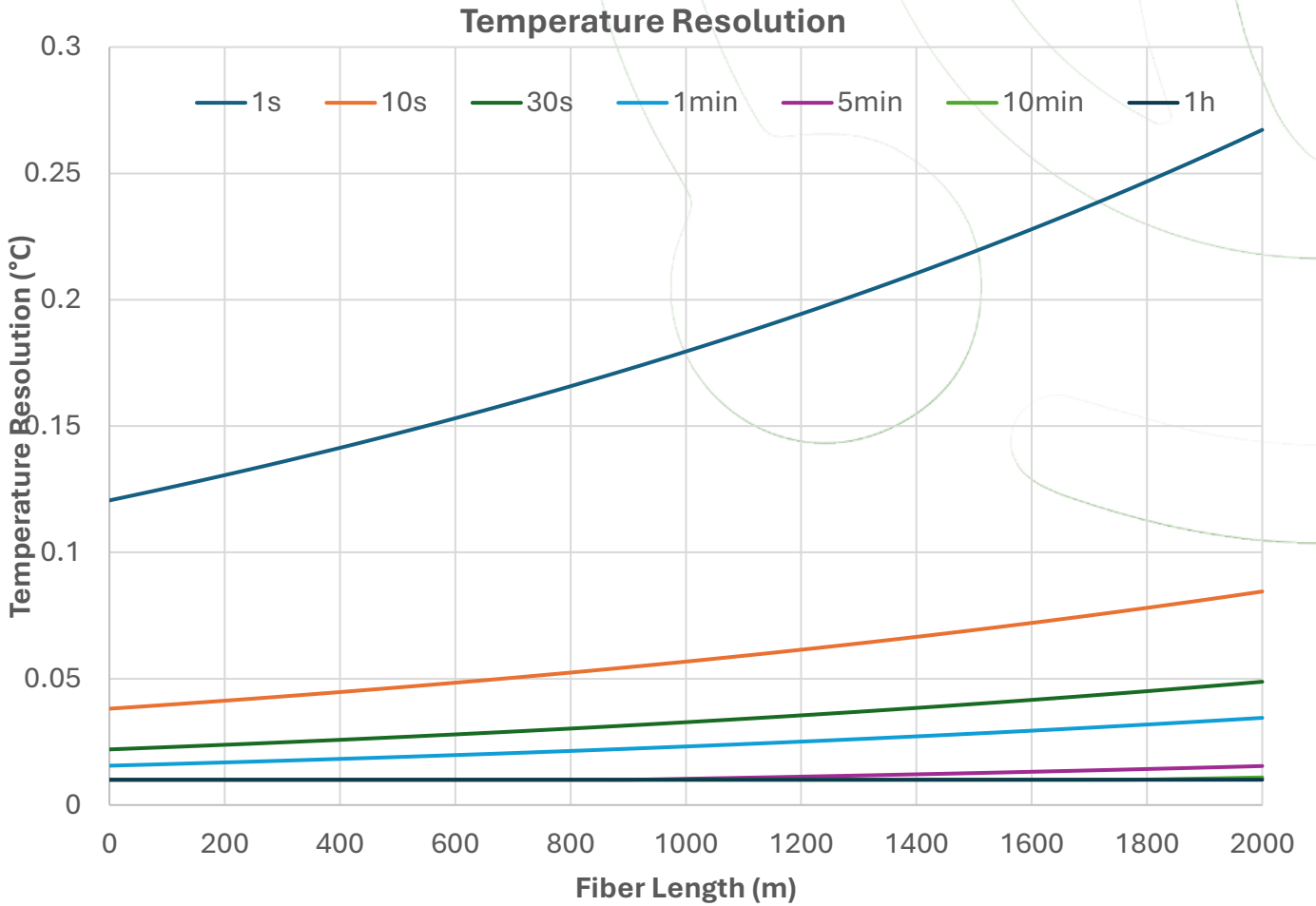


Temperature Resolution: time-domain averaging

The resolution improves when the integration time increases.

The improvement factor is:

$$\sqrt{\frac{\Delta t_{new}}{\Delta t_{old}}}$$



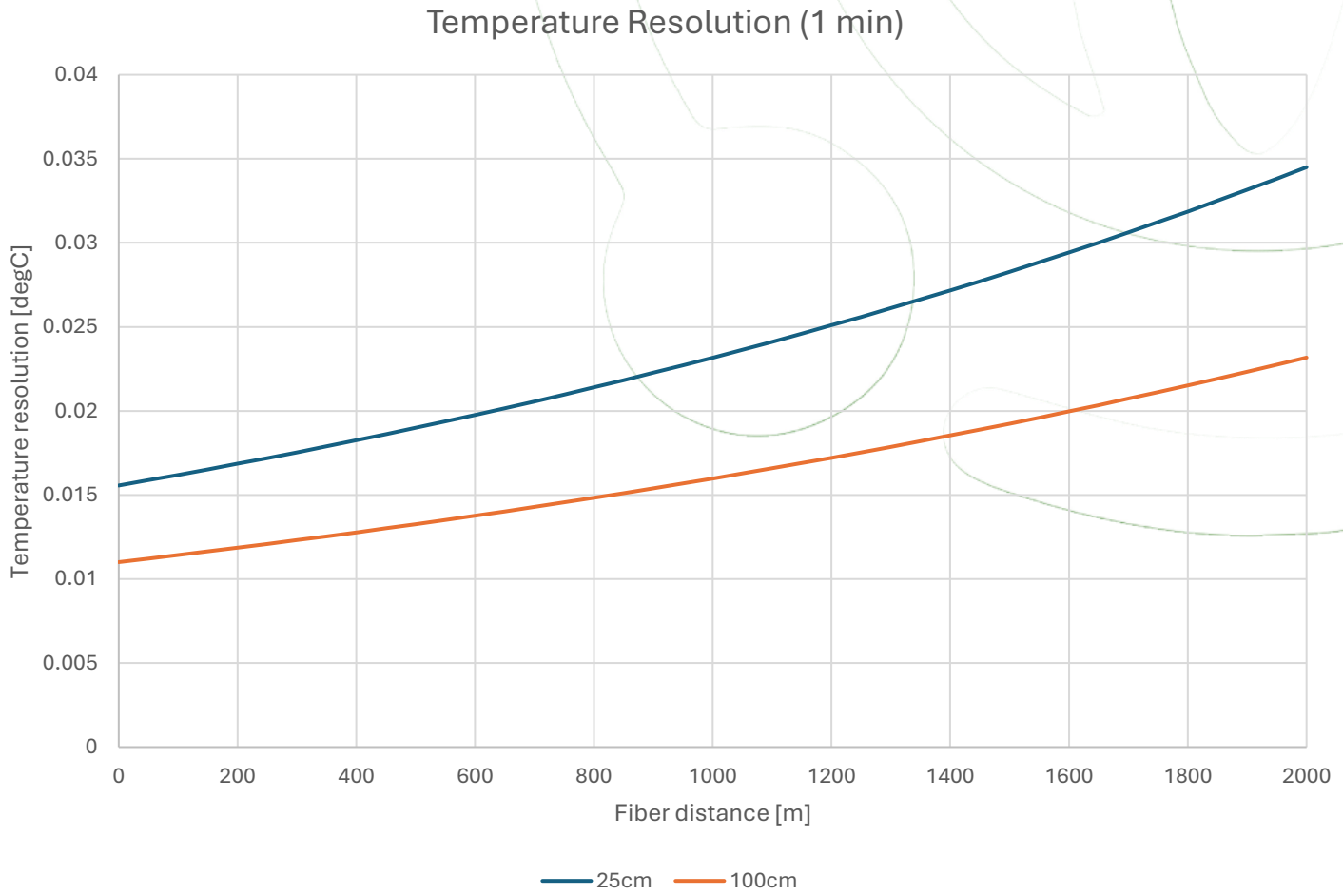
Temperature Resolution: space-domain averaging

The temperature resolution improves when the spatial integration increases.

The improvement factor is:

$$\sqrt{\frac{\Delta z_{new}}{\Delta z_{old}}}$$

assuming z_{new} and z_{old} are
≥ spatial resolution of the unit



Sensing Range

DTS system provides one averaged temperature measurement per sample.

Maximum pulse repetition rate determined by range

- Pulse rate is set by DTS acquisition software based on measurement length; cannot be set independently

Laser pulsed as fast as possible to improve temperature resolution

- Higher rep rate means more samples obtained to be averaged per second

Range (km)	Max. pulse rep. rate (kHz)
5	20
10	10
15	6.7
20	5
25	4
30	3.3
35	2.9

n = 1.5

Laser Repetition Rate

Only one light pulse can be in the fibre at a time, so maximum pulse repetition rate depends on length of fiber.

$$R = \frac{1}{\Delta t} = \frac{c}{2 \cdot L \cdot n} \propto \frac{1}{L}$$

R = launch repetition rate

Δt = minimum time between pulses

v = c/n is the speed of light in the fiber

(where c *is the speed of light in vacuum and* n *is the refractive index)*

L = total length of the fiber

As the repetition rate increases, so does the number of samples that can be averaged per second

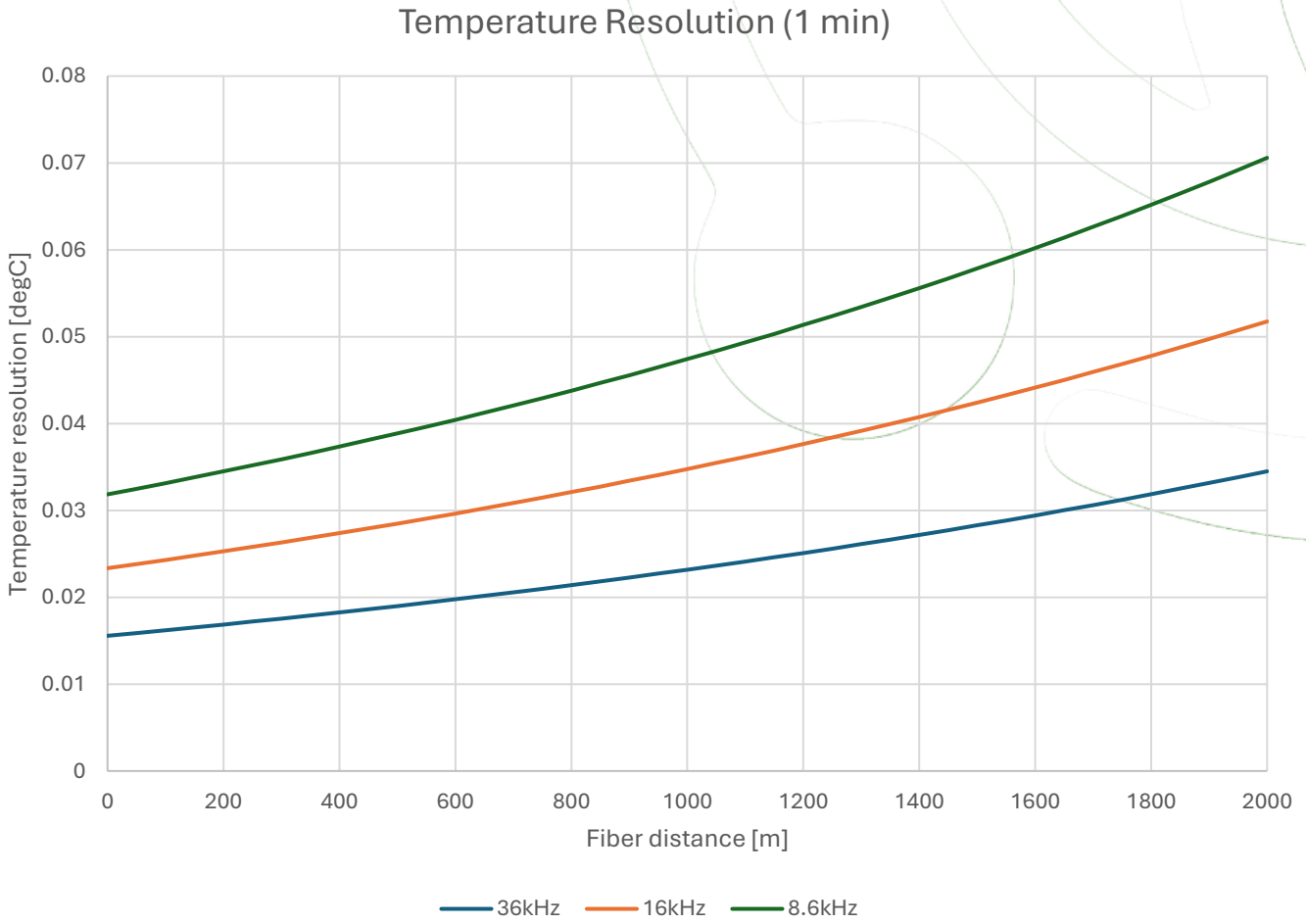
- **improves temperature resolution**

Laser repetition rate: temperature resolution

The resolution improves with increased laser repetition rate.

The improvement factor is:

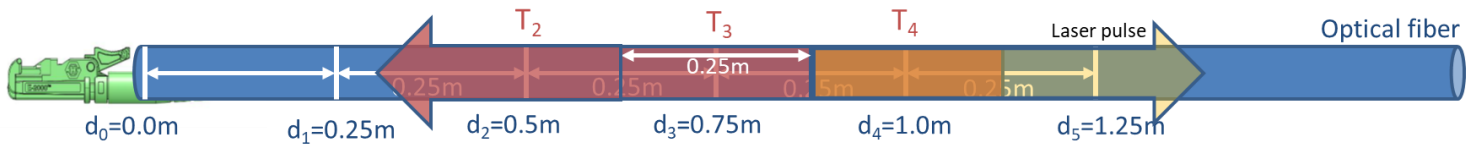
$$\sqrt{\frac{rep_{new}}{rep_{old}}}$$



Sampling Resolution

Sampling resolution = the smallest length increment a DTS system can sense/sample

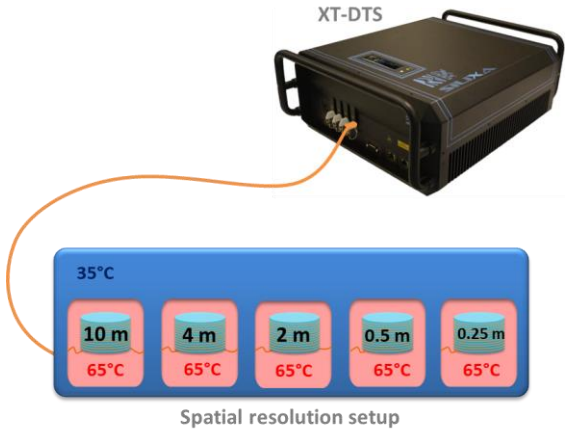
- 25 cm for XT-DTS
- The temperature at each sampling location is determined from the total signal measured over a length equal to the sampling interval, centered on the sampling location.



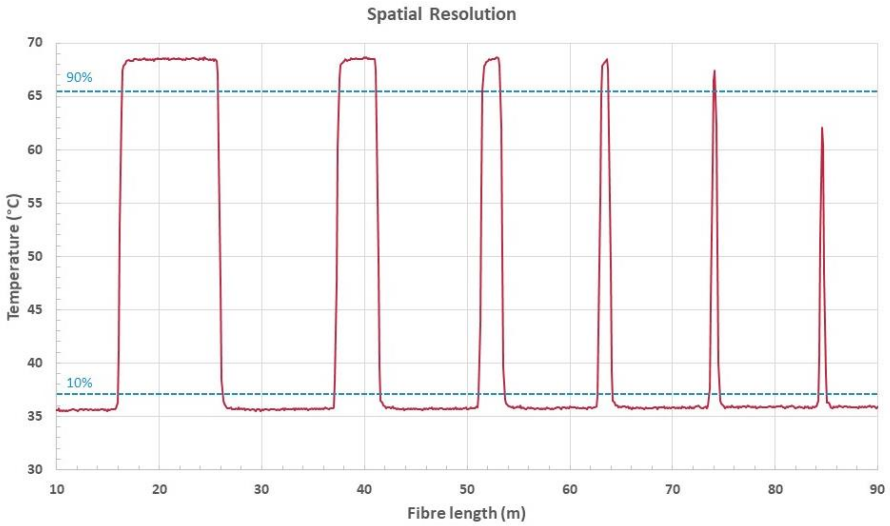
Distance	Temperature
d_0	T_0
d_1	T_1
d_2	T_2
d_3	T_3
d_4	T_4

Spatial Resolution

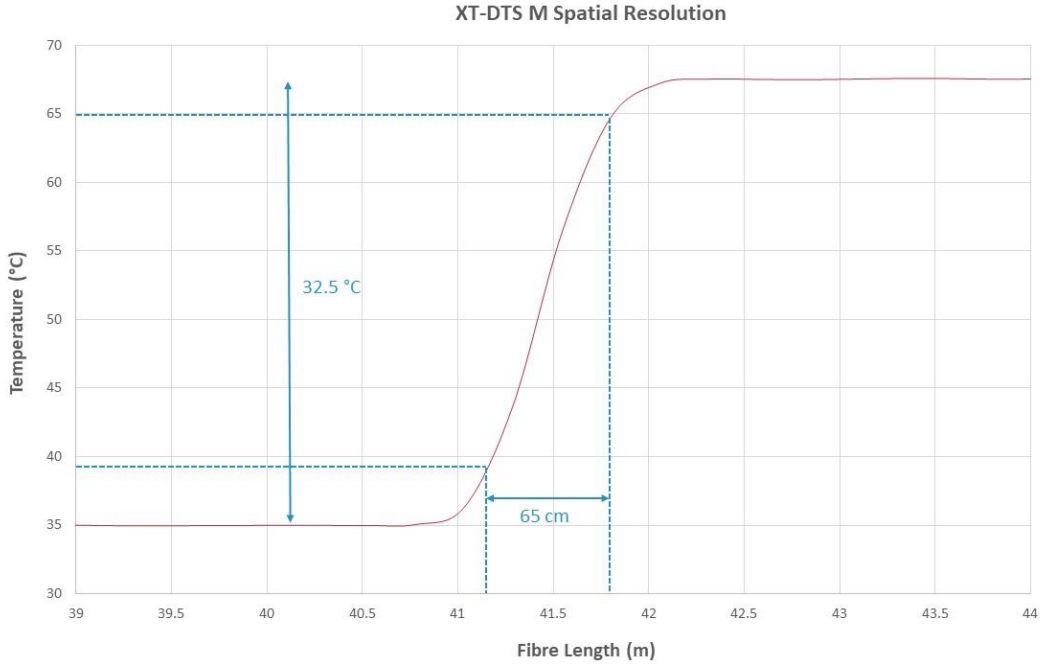
The spatial resolution is the effective distance required to detect a 30°C step change in fibre temperature.



Spatial resolution setup



The distance is worked out from 10% to 90% of the step height.



Spatial sampling = 25 cm
Spatial resolution = 65 cm

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