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Optical Fiber Sensors
Raman based distributed optical fiber sensors

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ICTP Winter College on Optics: Fundamental of Photoncs
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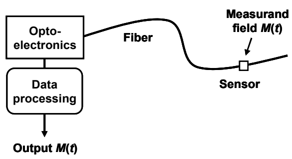
Outline

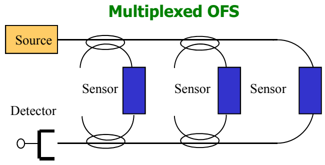
- OVERVIEW ON DISTRIBUTED OPTICAL FIBER SENSOR TECHNOLOGY
- RAMAN BASED DISTRIBUTED OPTICAL FIBER SENSORS
- RAMAN DISTRIBUTED TEMPERATURE SENSORS (DTS) ON MULTI-MODE FIBERS
- INDUSTRIAL APPLICATIONS OF RAMAN DTS SYSTEMS
- HIGH PERFORMANCE RAMAN DTS BASED ON SINGLE-MODE FIBERS USING PULSE CODING
- CONCLUSIONS

Overview on Optical Fiber Sensor (OFS) Technology

- **Optical fibers** offer attractive characteristics for **sensing**:
  - ✓ Immunity to EMI
  - ✓ Small and lightweight
  - ✓ Minimally invasive
  - ✓ No electrical power requirement at the sensing point
  - ✓ Easily multiplexable
  - ✓ In many cases low cost production
- **Discrete**, **Multiplexed** and **Distributed OFS**
- In OFS **environmental information** is impressed in:

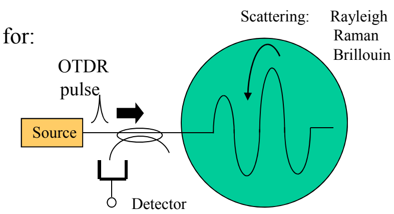
Intensity, frequency, phase, polarization and/or spectral content of the light





Distributed optical fiber sensors (DOFS)

- The fiber itself is used as sensing element, allowing for:
  - ✓ Several tens of km sensing distances
  - ✓ Meter and sub-meter spatial resolution
  - ✓ Tens of thousand sensing points
- Spatial information can be achieved through:
  - ✓ Optical time-domain reflectometry (OTDR)
  - ✓ Optical frequency-domain reflectometry (OFDR)



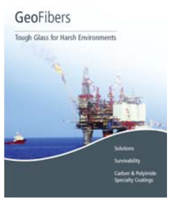
Distributed Optical Fiber Sensor Technology

- Distributed optical fiber sensors: **application fields:**

Fire detection, security, defence, energy sector *(oil&gas pipelines, power cables, geothermal plants)* ***environmental monitoring, structural health monitoring***

- **The market of *distributed optical fiber sensors* is expected to grow in next years**

Main Tecom Fiber Manufacturers are starting proposing specialty fiber cables for harsh environments !



- **Main advantages** over conventional sensors are well-known !

(Non-intrusive, Immune to electromagnetic interference, Low risk, Continuous and spatially resolved measurements,…)

- **Three main open issues** to be addressed in distributed sensing:
  - ✓ ***Long-range sensing with meter-scale spatial resolution***
  - ✓ ***Sub-meter scale spatial resolution***
  - ✓ ***Dynamic distributed measurement capability***

Pulse coding & Hybrid Sensors

Raman based Distributed Optical Fiber Sensors
Main Applications

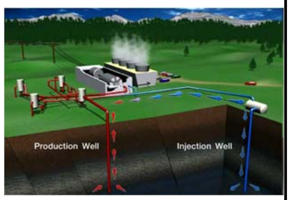
- Fire detection (tunnels, tanks)

- Leakage detection in oil & gas pipelines & tanks (gas, fuel, etc.)

- Leakage detection in platforms, tanks (gas, fuel etc.)

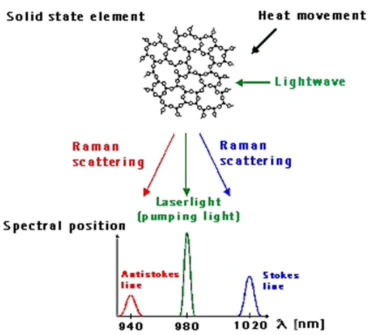
- Power cable monitoring

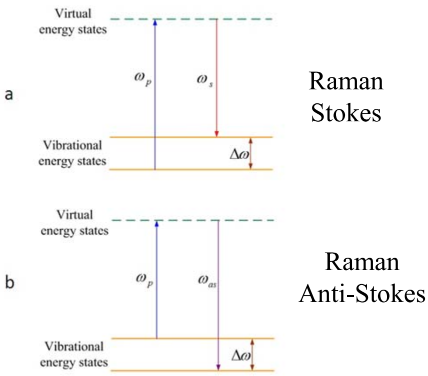
- Geothermal energy



Spontaneous Raman Scattering and Phonons

Raman scattering is generated by light interaction with resonant modes of the molecules in the medium (vibrational modes)





- **Phonons interact with photons in inelastic scattering**
- **Stokes line → photon energy is given to phonon**
- **Anti-Stokes line → phonon gives energy to photon**

Spontaneous Raman Scattering and Phonons

- The high energy of vibrational modes induce a large Raman frequency shift (~ 13 THz in silica fibers)
- For each molecular vibration two Raman components are observed:

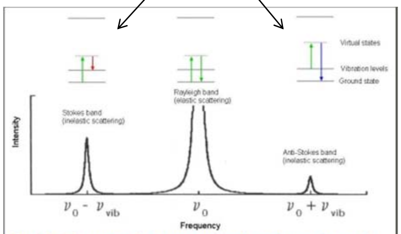
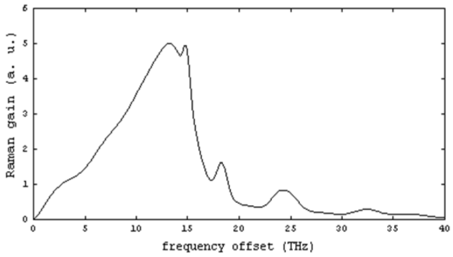


Fig. 4.1.2: Spectrum of photon transition from elemental ground level to virtual states.

© Mascarós et al., in: "Handbook on the Use of Lasers in Conservation and Conservation Science", 2008.



Spontaneous Raman Scattering and Phonons

- Transition rates and propagation equations due to thermal excitation:

$$W_S \propto N_0(1+N_\Omega) \quad \text{Stokes} \quad dP_S(z) = (1+N_\Omega)\Gamma_S P_o dz$$

$$W_{AS} \propto N_0 N_\Omega \quad \text{Anti-Stokes} \quad dP_{AS}(z) = N_\Omega \Gamma_{AS} P_o dz$$

N_0 is the incident photon number (proportional to pump intensity)

Γ_S and Γ_{AS} are the Raman Stokes and Anti-Stokes capture coefficients

N_Ω is the **Bose-Einstein thermal population factor**:

$$N_\Omega \propto \frac{1}{\exp\left(\frac{h\Delta\nu_R}{K_B T}\right)-1}$$

h: Plank constant
K_B: Boltzman constant
$\Delta\nu_R$: vibration frequency
T: absolute temperature

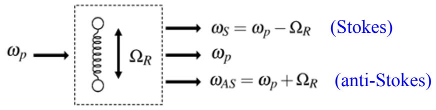
$$\frac{W_{AS}}{W_S} \propto \exp\left(-\frac{h\Delta\nu_R}{K_B T}\right)$$

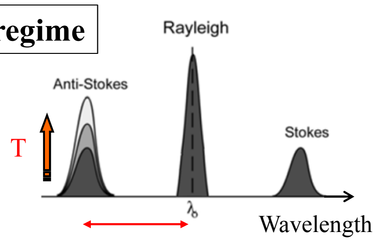
$W_{AS} \sim W_S$ at high T

$W_{AS}/W_S \longrightarrow 0$ for T $\longrightarrow$ 0 K

Spontaneous Raman Scattering

linear scattering regime

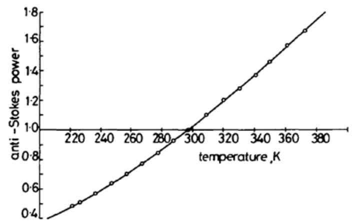




~ 13 THz
(100 nm @1550 nm)

$$\Delta\nu_R = \frac{\Omega_R}{2\pi}$$

Suitable for Temperature Sensing only !



Sensitivity: 0.8 % K^{-1}

Advantages	*Disadvantages*
Easy detection	Low backscattered power
High sensitivity	High input power required

Stimulated Raman Scattering

- When the incident light intensity is low the optical properties of the medium are not affected by the field (**linear scattering regime**)
- When high intensity fields are applied to the medium the **nonlinear** material response induces **stimulated scattering**
- Bidirectional Stimulated Raman Scattering can be initiated by :

✓ propagation of an additional probe signal at frequency $\omega_s=\omega_p- \Omega_R$

✓ propagating a single high intensity pump which generates spontaneous Raman scattering light acting as proble signal

(**beating between Stokes and pump lights coherently excites molecular vibration at $\omega_s=\omega_p- \Omega_R$ which in turns amplifies the Stokes wave at ω_s**)

⇩

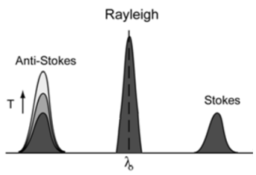
Raman amplification in optical communication systems

Raman based DTS
Basic Physical Principle

- Distributed Temperature Sensors (DTS) based on ***Spontaneous*** Raman Scattering & ***Optical Time Domain Reflectometry*** (OTDR)

- Rayleigh, Stokes (S) & Anti-Stokes (AS) Raman scattered light intensities are generated by an optical pulse propagating along the sensing fiber:

  Anti-Stokes (P_{AS}) : Strongly temperature dependent
  Rayleigh (P_{BS}) & Stokes (P_{AS}) : almost temperature independent



- The ratio R(T) between P_{AS} / P_{BS} or P_{AS} / P_S is used to get rid of losses !

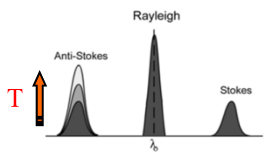
$$\frac{P_{AS}}{P_S} \propto \exp\left(-\frac{h\Delta\nu_R}{kT}\right)$$

$$\frac{P_{AS}}{P_{Rayleigh}} \propto \left[\exp\left(\frac{h\Delta\nu_R}{kT}\right) - 1\right]^{-1}$$

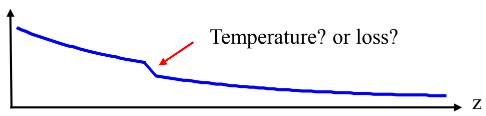
Sensitivity: 0.8 % K^{-1}

$\Delta\nu_R$=13.2 THz
for silica fibers

Raman based DTS
Basic Physical Principle



Anti-Stokes ROTDR trace

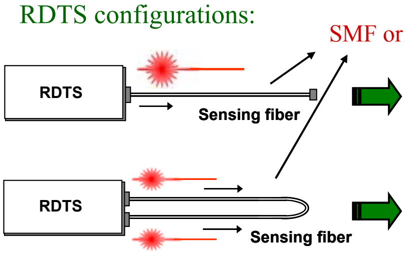


Usually the ratio R(T) between P_{AS}/P_{BS} or P_{AS}/P_S is used to get rid of losses

$$\frac{P_{AS}}{P_S} \propto \exp\left(-\frac{h\Delta\nu_R}{kT}\right)$$

$$\frac{P_{AS}}{P_{Rayleigh}} \propto \left[\exp\left(\frac{h\Delta\nu_R}{kT}\right) - 1\right]^{-1}$$

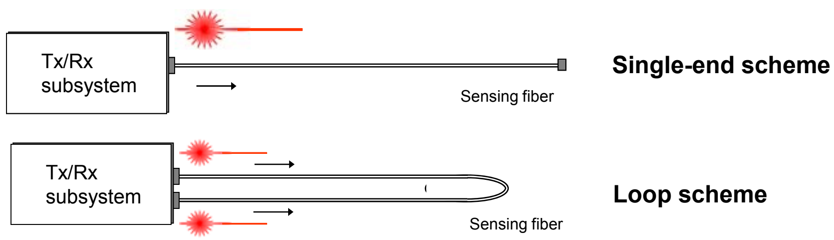
RDTS configurations:



Single-ended configuration
- Affected by wavelength-dependent losses (WDL)
- Long sensing range

Double-ended (loop) configuration
- Robust against wavelength-dependent losses (WDL)
- Limited sensing distance

Single end vs loop schemes



- In classical single-end scheme, only one fiber end is connected to Tx/Rx subsystem and optical pulses are repeatedly sent along the optical fiber

- In loop schemes, both fiber ends are connected to Tx/Rx subsystem, and pulses are alternatively sent into either fiber-end (forward and backward)

→ By taking the geometric mean of the two traces for the power ratios (P_S/P_{AS}) in forward and backward direction it is possible to cancel out WDL effects

Raman based DTS: Single-end Configuration Basic Theory

- Single-end configuration: $R(z)=\frac{P_{AS}}{P_S}=C_R(z)\exp[\frac{-h\Delta\nu}{K_B T(z)}]\exp\{\int_0^z -[\alpha_{AS}(\xi)-\alpha_s(\xi)]d\xi\}$

✓ $R(z)$ depends on the differential **Wavelength Dependent Loss** (**WDL**) of the fiber
✓ WDL can be corrected if they do not change with time

$$R(z)=\frac{P_{AS}}{P_S}=C_R(z)\exp[\frac{-h\Delta\nu}{K_B T(z)}]$$

- The temperature profile T(z) is obtained using a reference temperature:

$$T(z)=\{\frac{1}{T_{ref}(z)}-\frac{K_B}{h\Delta\nu}\ln[\frac{R(z,T)}{R_{ref}(z,T_{ref})}]\}^{-1}$$

- If WDL changes with time: $T(z)=\{\frac{1}{T_{ref}(z)}-\frac{K_B}{h\Delta\nu}\ln[\frac{R(z,T)}{R_{ref}(z,T_{ref})}]+\int_0^z \Delta\alpha(\xi)d\xi\}^{-1}$

$$\Delta\alpha(\xi)=[\alpha_{AS}(\xi)-\alpha_{AS\_ref}(\xi)]-[\alpha_S(\xi)-\alpha_{S\_ref}(\xi)]$$

Temperature TILT

Raman based DTS: Loop Configuration Basic Theory

- Loop configuration:

$$\begin{cases} R^{For}(z) = \frac{P_{AS}^{For}}{P_S^{For}} = C_R^{For}(z)\exp\{-\int_0^z[\alpha_{AS}(\xi)-\alpha_s(\xi)]d\xi\}\exp[\frac{-h\Delta\nu}{K_B T(z)}] \\ R^{Back}(z) = \frac{P_{AS}^{Back}}{P_S^{Back}} = C_R^{Back}(z)\exp\{-\int_z^L[\alpha_{AS}(\xi)-\alpha_s(\xi)]d\xi\}\exp[\frac{-h\Delta\nu}{K_B T(z)}] \end{cases}$$

$$R^{Loop}(z) = \sqrt{R^{For}(z)R^{Back}(z)} = [C_R^{For}(z)C_R^{Back}(z)]^{1/2}\exp[-(\alpha_{AS}-\alpha_S)\frac{L}{2}]\exp[\frac{-h\Delta\nu}{K_B T(z)}]$$

✓ All loss factors dependent on the fiber position are cancelled out ! No WDL !

- The temperature profile T(z) is obtained using a **reference temperature**:

$$T(z) = \{\frac{1}{T_{ref}(z)} - \frac{K_B}{h\Delta\nu}\ln[\frac{R^{Loop}(z,T)}{R_{ref}^{Loop}(z,T_{ref})}]\}^{-1}$$

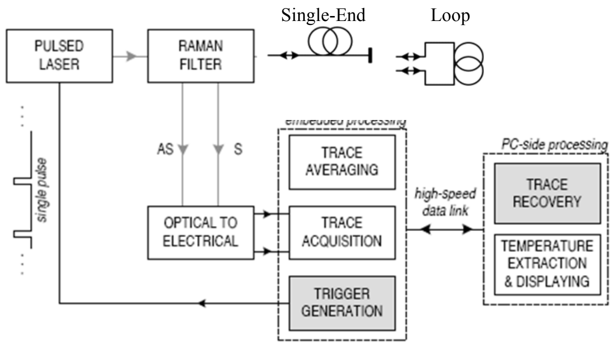
- If WDL changes with time: $T(z) = \{\frac{1}{T_{ref}(z)} - \frac{K_B}{h\Delta\nu}\ln[\frac{R^{Loop}(z,T)}{R_{ref}^{Loop}(z,T_{ref})\Delta loss}]\}^{-1}$

$\Delta loss = \exp\{-\frac{1}{2}\int_0^L \Delta\alpha(\xi)d\xi\} \longrightarrow$ z-independent offset that can be easily corrected !

Loop configuration to avoid WDL

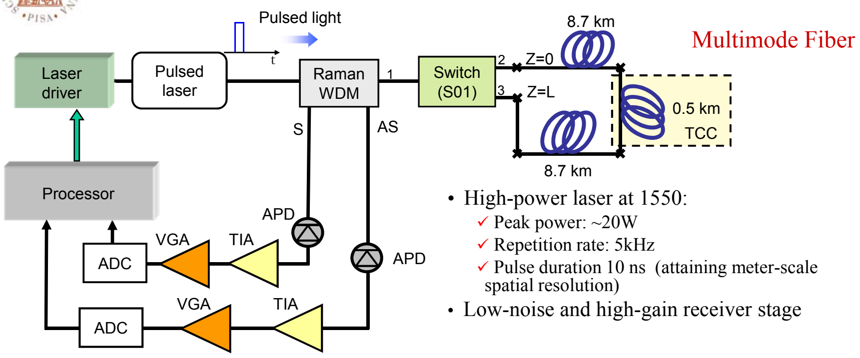
- WDL is currently the limiting factor in terms of measurement inaccuracy for Raman-based sensors
- Ways of reducing it, e.g. initial WDL calibration at sensor deployment and use of optimal wavelengths offer benefits but do not completely avoid the issue
- Possible solution: using ***loop schemes*** instead of single-end configuration
- A geometrical mean value of the Stokes/Anti-Stokes ratios measured from both fiber ends can be conveniently used to avoid the WDL issue, but has impact on SNR
- Worst-case SNR is always better in loop configuration
- Best-case SNR is better with loop scheme only for fiber lengths with loss < 3 dB

Scheme of Long Range Raman DTS system on MM fibers

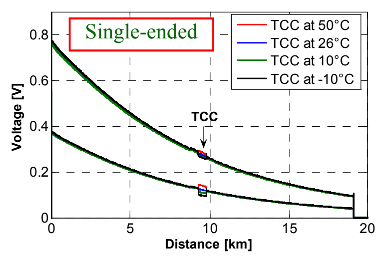


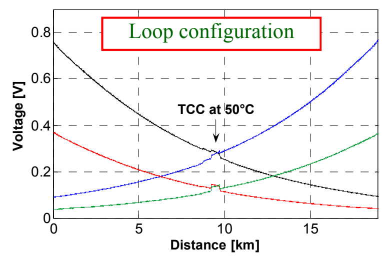
- Pulsed laser at 1550 nm (single pulse), large bandwidth, high peak power
- 10 ns : 1-2 meter spatial resolution
- 10 – 30 km of graded index MM fiber (50/125)
- TIA + VGA + ADC
- BPF selecting Anti-Stokes and Stokes backscattered lights

Long-Range High-Performance RDTS

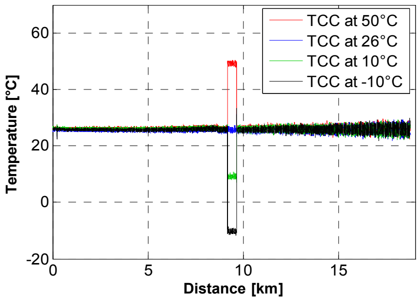


- High-power laser at 1550:
  - ✓ Peak power: ~20W
  - ✓ Repetition rate: 5kHz
  - ✓ Pulse duration 10 ns (attaining meter-scale spatial resolution)
- Low-noise and high-gain receiver stage





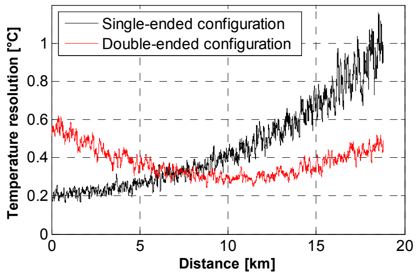
Long-Range High-Performance RDTS



Temperature profiles
with
different TCC temperatures

- Multimode fiber
  - ✓ Long sensing distance
  - ✓ ~2-m spatial resolution (modal dispersion)

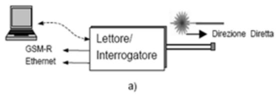
- Temperature resolution (computed as standard deviation)
  - ✓ Single-ended configuration: ~1°C
  - ✓ Loop configuration: : 0.6°C
  - ✓ Measurement time: 20 s and 40 s



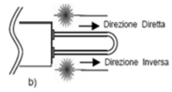
Industrial Applications of Raman DTS Systems

Fire Detection
Field trial with Italian Railways

- PC-based system architecture:



single-end



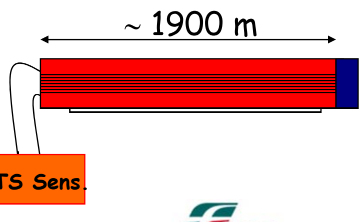
loop

preferred by the user

- Field trial inside long tunnel

✓Multi-fiber cable 50/125 (8 fibers)

✓System capabilities:
- dynamic range two-way: up to 25 km
- spatial resolution between 1 and 5 meters
- temp.res: 10 sec – 2.5 °C (2 meters)
  10 sec – 1.9 °C (5 meters)
  60 sec - 1 °C (2 meters)
  60 sec - 0.8 °C (5 meters)



✓Software specs:
- multi-zone alarm system
- compliant with internal communication infrastructure

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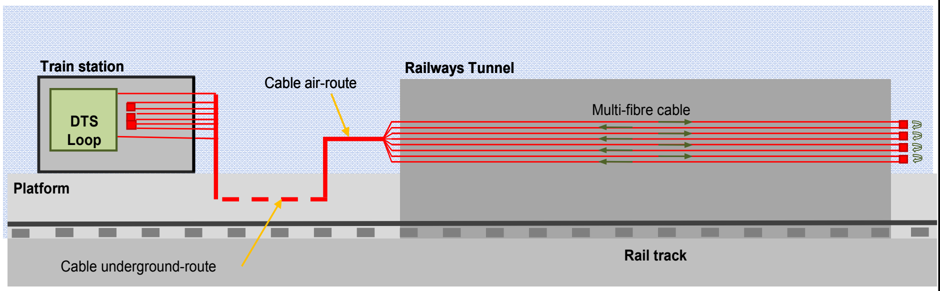
Railways Tunnel Field Trial

Field-trial architecture:



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Railways Tunnel Field Trial

Tunnel and cable deployment

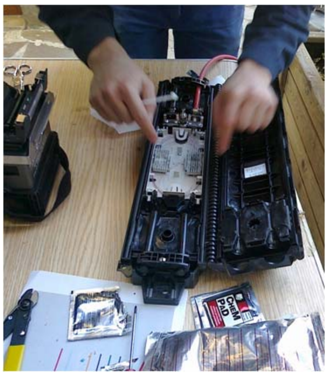
Fiber cable

Cable termination

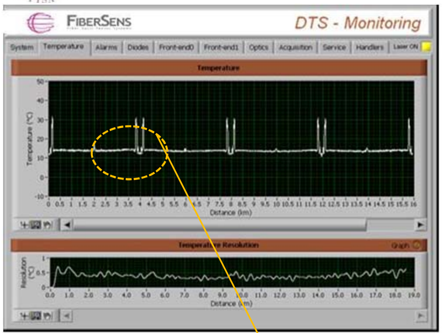
Railways Tunnel Field Trial

Detail of FO cable outside of tunnel
(cable air-route)

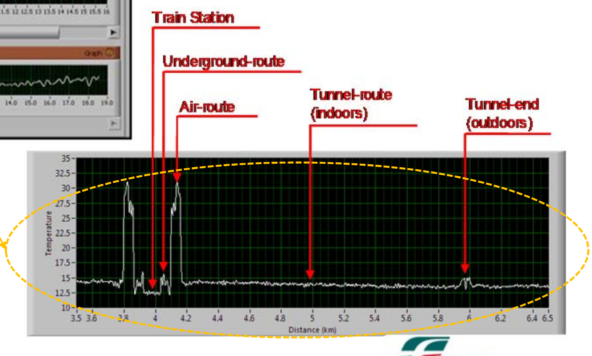
Fusion splicing for cable-end



Railways Tunnel Field Trial



- Measured temperature: before and along tunnel



- 20 sec measurement time

✓min: 1 m resolution
✓max: 2 m resolution

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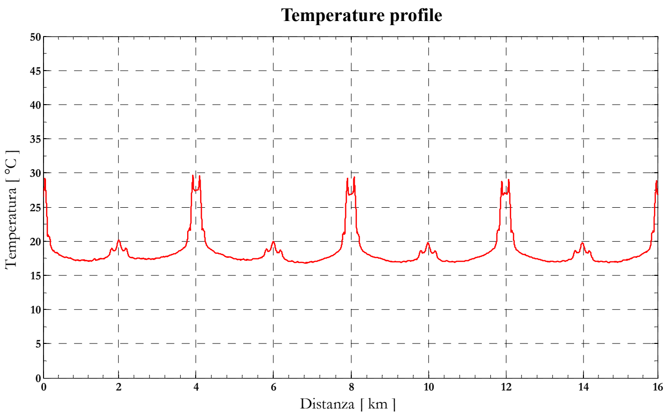
Railways Tunnel Field Trial



- Periodic temperature behaviour (8 fiber MM cable: 4 round trip along the tunnel)
- Average temperature in DTS room ≈ 27 °C.
- Tunnel temperature: almost constant at 17 °C.

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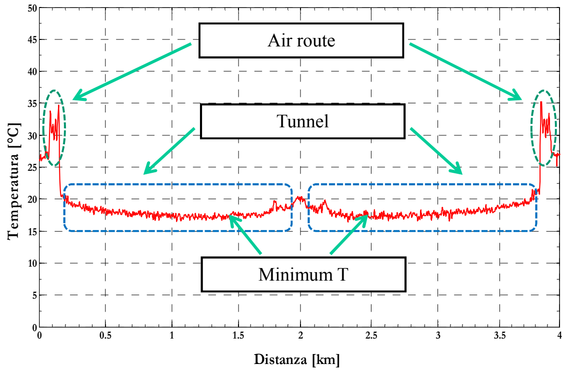
Measured Temperature

Round trip temperature profile (06/05/2011, 12:00am)



- Air route ≈ 34 °C, tunnel indoors ≈ 17 °C
- Almost constant temperature profile along central tunnel part
- Slightly asymmetric temperature profile near tunnel entrances:
  - ✓ North entrance: 3 rails
  - ✓ South entrance: 1 rail

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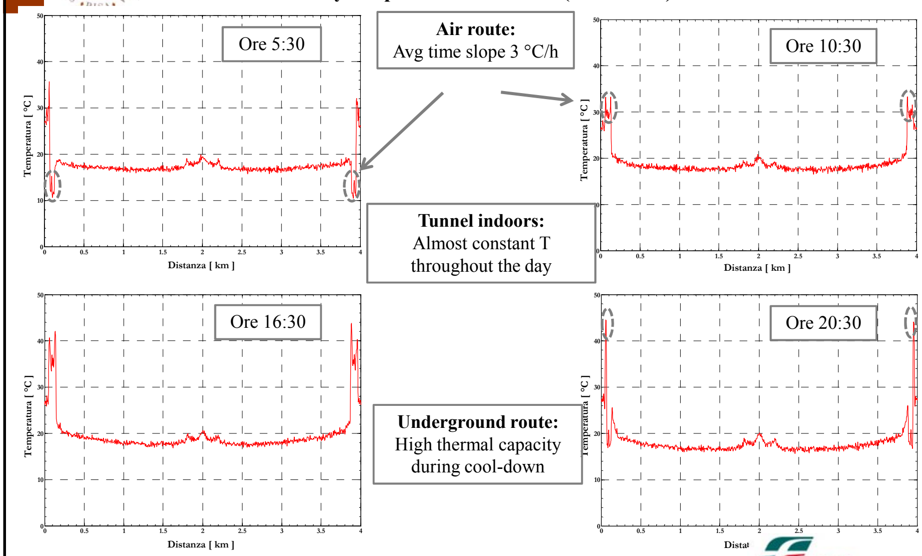
Measured Temperature

Daily temperature excursion (06/05/2011)



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GRUPPO FERROVIE DELLO STATO

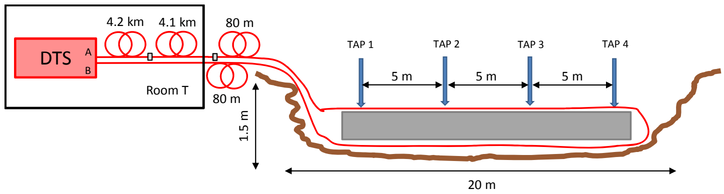
Pipeline intrusion & leakage detection: Field Trial Test-bed

Measure Parameters

Sensing Distance:	~ 9 km
Measurement Time :	4 min 30 s
Maximum Temperature Resolution:	< 0.1 °C
Spatial Resolution:	< 2 m

Leakage Simulation

Water Temperature:	30 °C
Localization:	Tap 2
Flow Rate:	18 l/min
Total Volume:	45 l




Excavation


Cable Position


Tap Position


Boiler

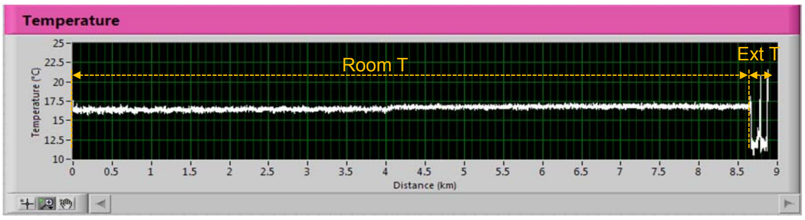

Tap detail


Water-meter

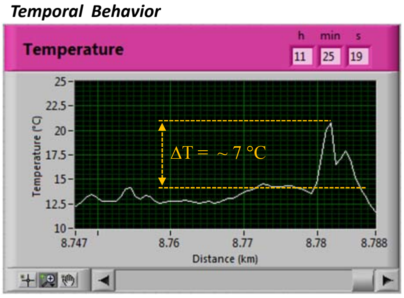
DTS2000 Leakage & Intrusion Detection - Field Trial Case Study

Leakage Detection: Temp. vs Time

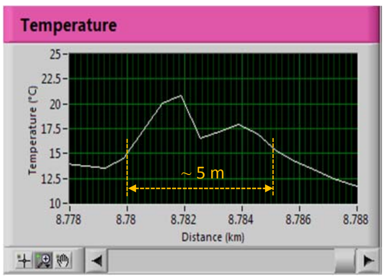
Full Profile



Temporal Behavior

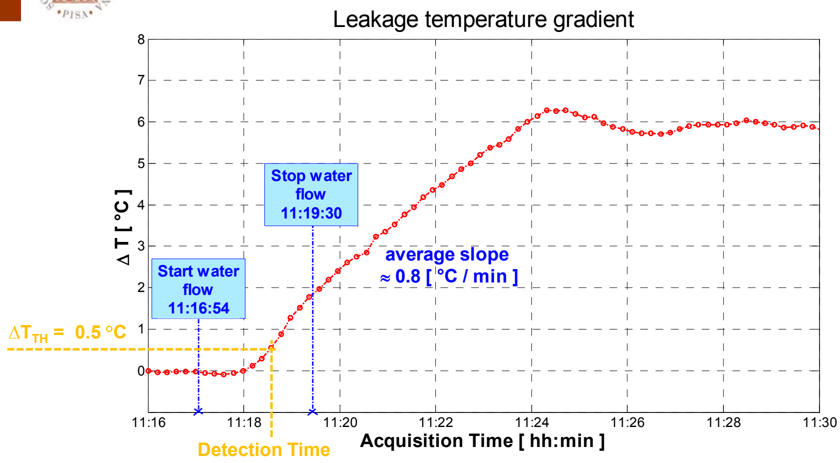


Event Spatial Resolution



DTS2000 Leakage & Intrusion Detection - Field Trial Case Study

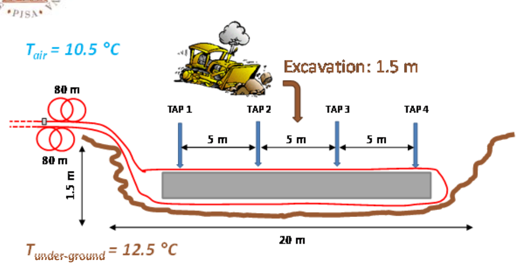
Leakage Detection: ΔT



- *Flow rate of 18 l/min*
- *Measurement time of 4 min 30 s*
- *Detection threshold $\Delta T = 0.5$ °C*

Detection Time:	*100 s*
Detection Leakage:	*32 l*

Intrusion Detection: ΔT

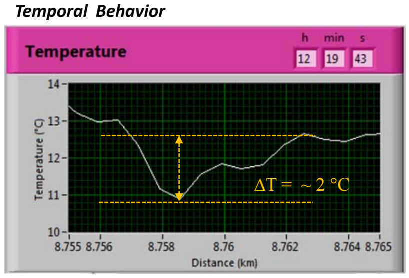


Field Trial History

11:45	*Excavation Start*
12:00	*Excavation End*
12:04	*Intrusion Detection: $\Delta T = 0.5$ °C*
12:25	*ΔT_{max} Obtnaible: $\Delta T_{max} = 2$ °C*

Excavation *Excavations 1.5 m length*

Temporal Behavior



Event Spatial Resolution