Distributes sensing using optical fibres

Lars Grüner-Nielsen and
Mads Holmark Vandborg
Technical University of Denmark

DEIC Conference November 7

Introduction

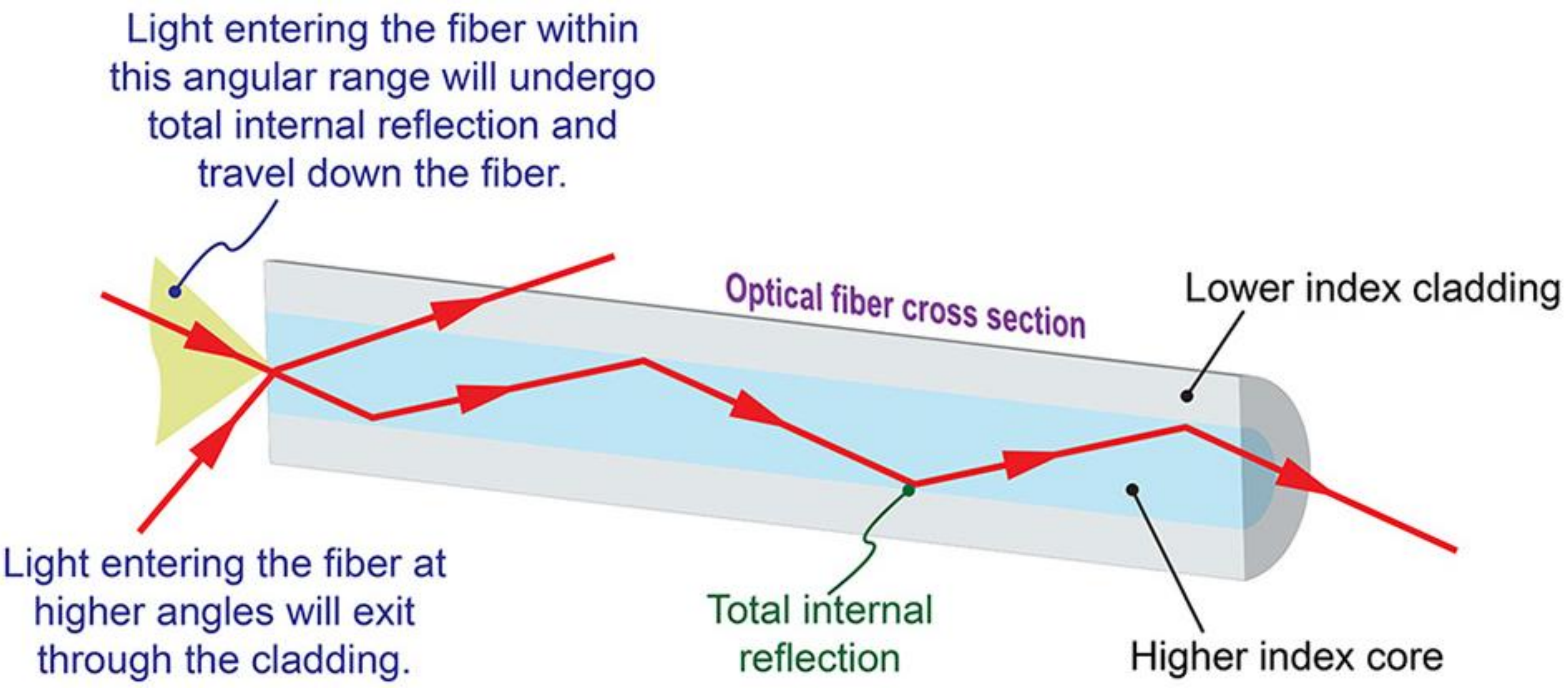
- Optical fibers are today together with wireless the preferred media for communication and is the backbone of the internet
- Several billion km of optical fiber installed

- Optical fiber also have application outside communication
  – One is for distributed sensing

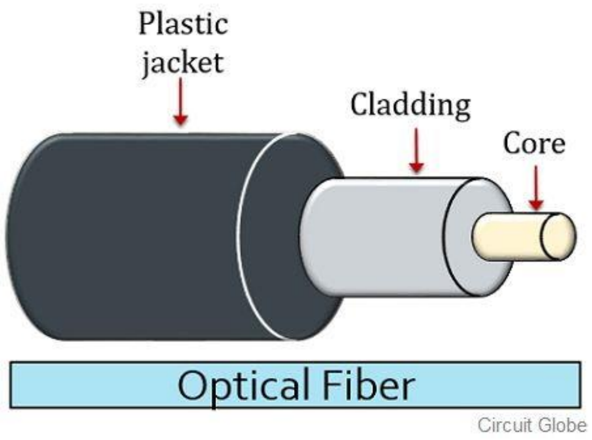
Outline

- Optical fibers and optical cables
- Basic principle distributed sensing
- Types of distributed sensing
  - Acoustic sensing
  - Temperature sensing
  - Strain sensing
- Application examples
- Future trends
- Conclusions

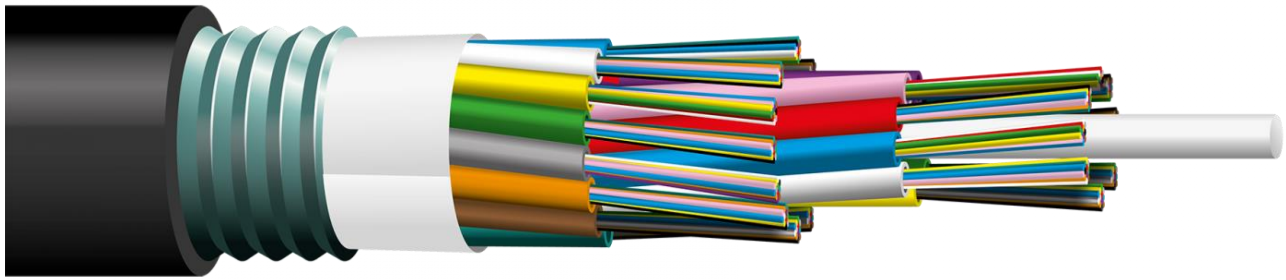
Basic Operation of an Optical Fiber



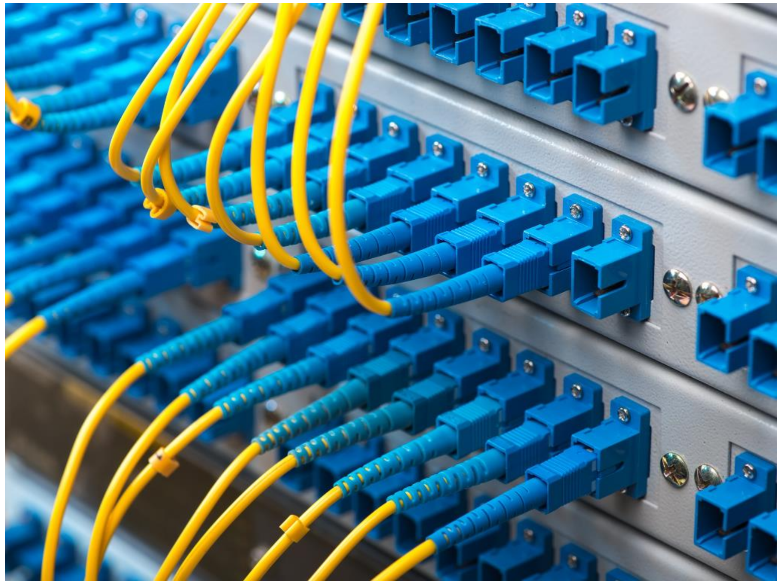
Optical fibers and cables



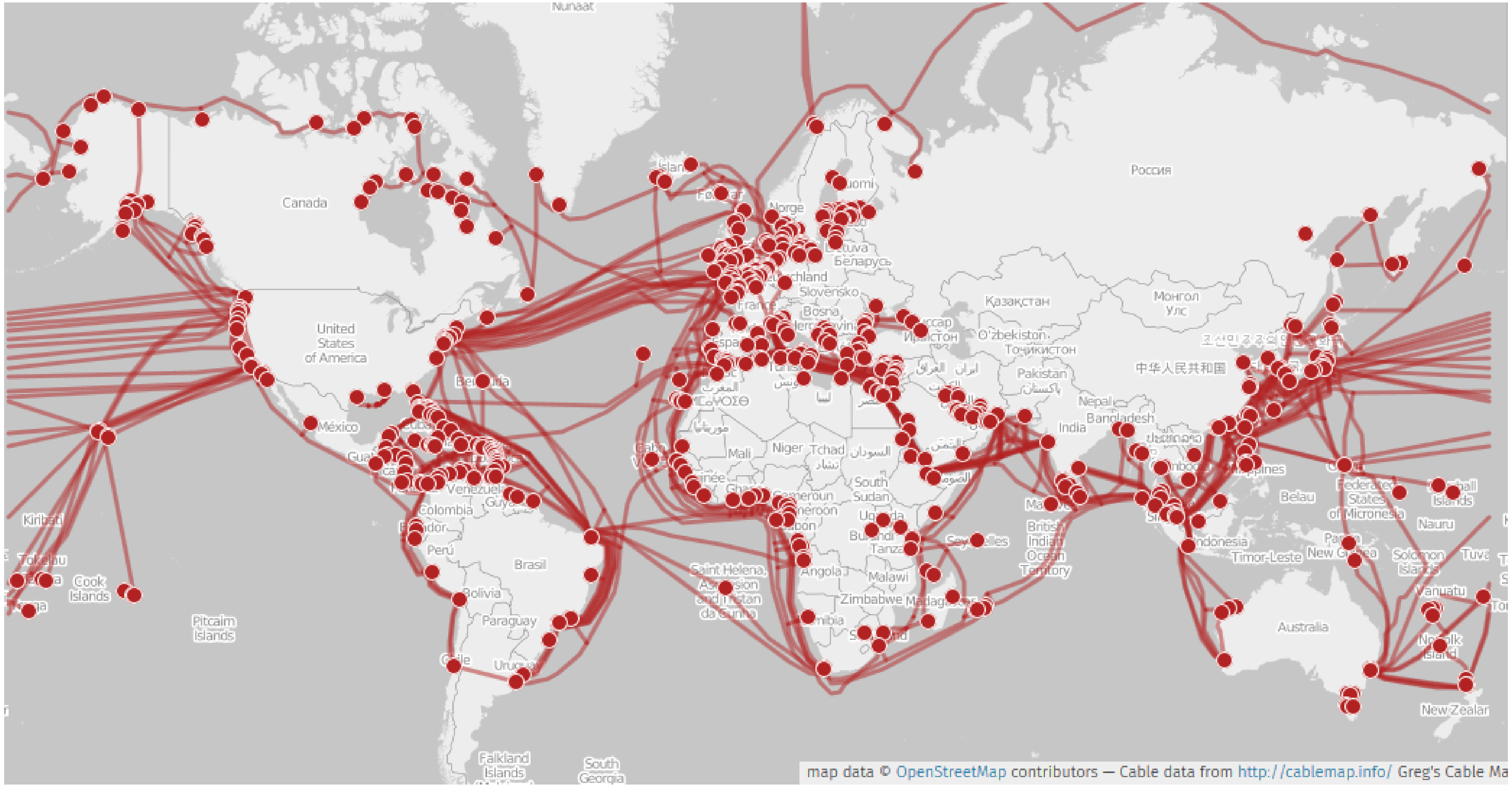
Single fiber indoor cable with connectors

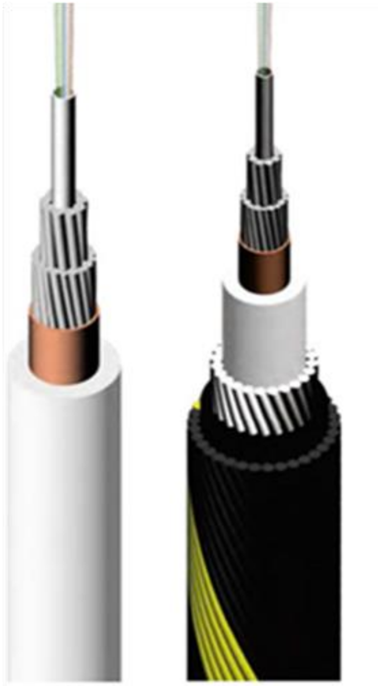


Terrestrial outdoor cable



Submarine cable network





Attenuation

- Typical attenuation of an optical fiber 0.2 dB/km
  – Corresponds to 50 % of the input optical power is left after 15 km
  – After 100 km only 1 % of the power is left
- Modern communication systems therefore have amplifiers every 80 – 100 km

- Within distributed sensing use of amplification is still a research topic
  – Commercial distributed sensing systems therefore have a typical maximum range of ~100 km

Optical Fiber Sensors

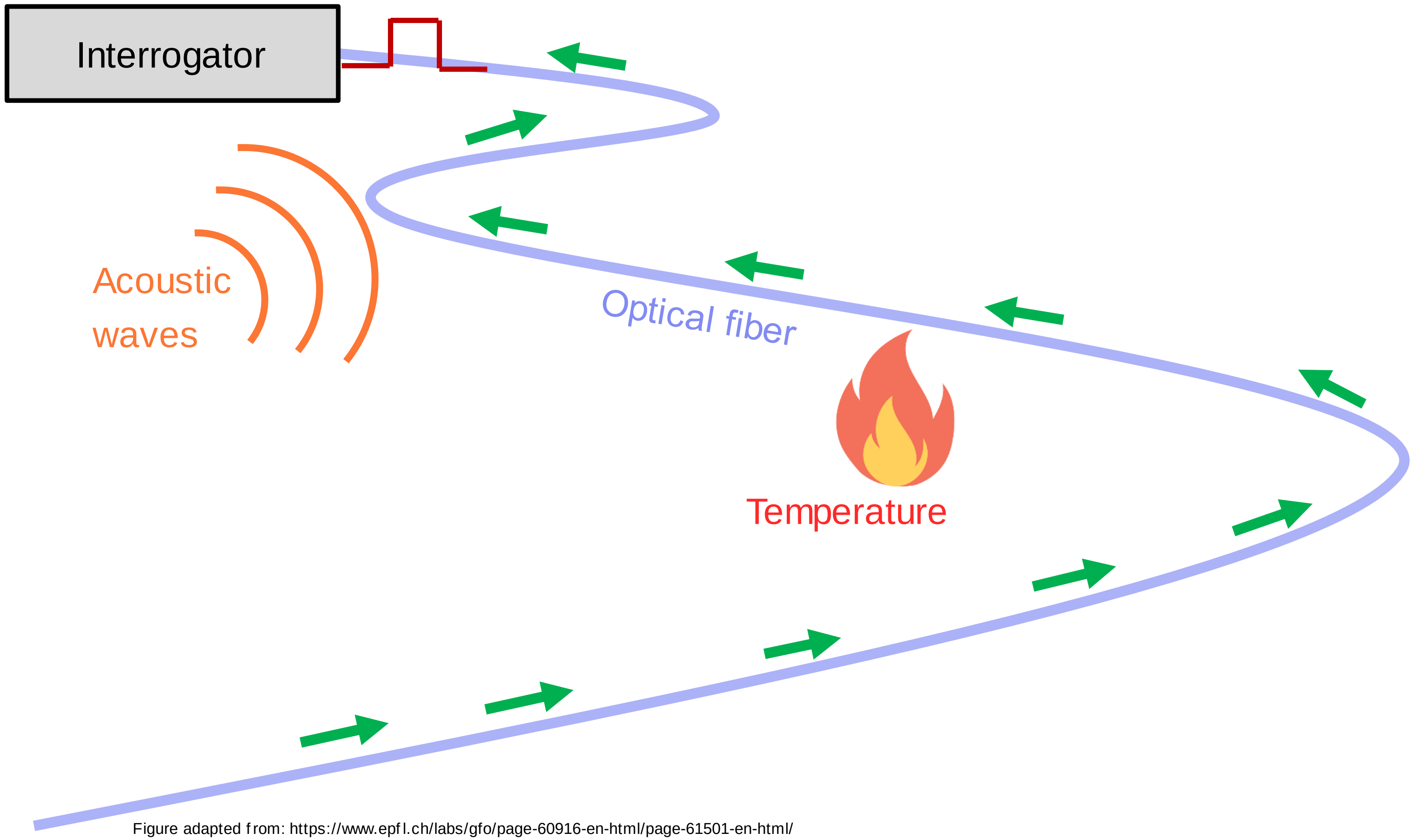
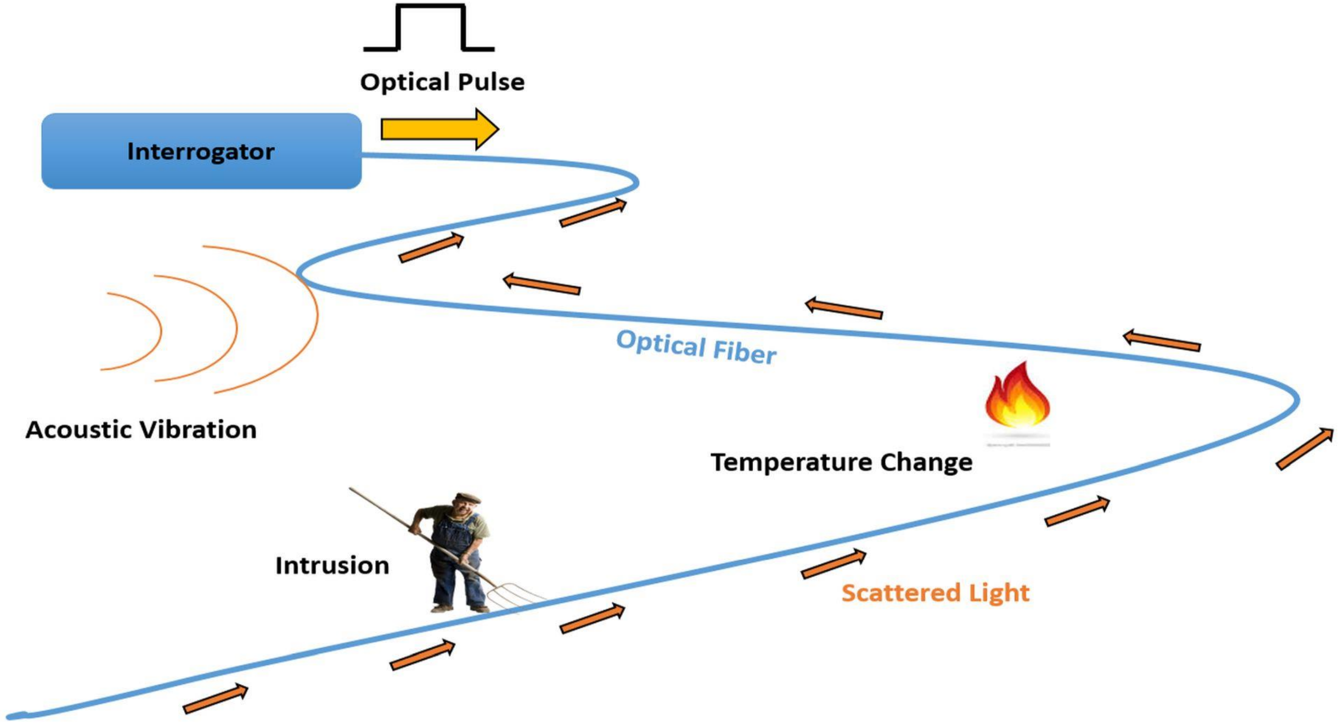
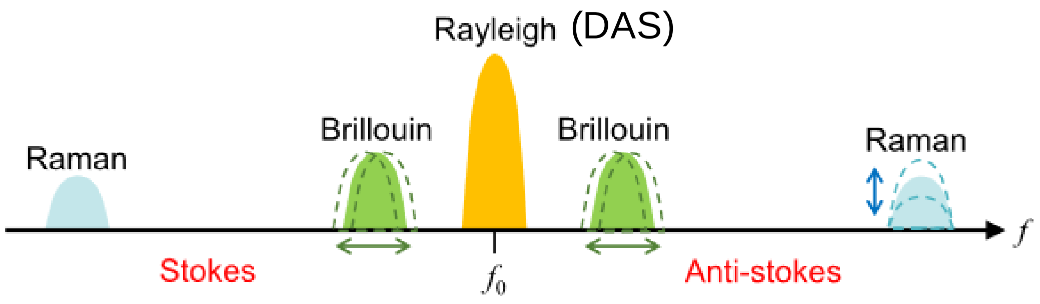


Figure adapted from: https://www.epfl.ch/labs/gfo/page-60916-en-html/page-61501-en-html/

Optical Time Domain Reflectometry (OTDR)





f_0: Input pulse frequency.

f: Scattered light frequency.

Range:	<100 km
Spatial resolution:	~10 m
Maturity:	Commercial product

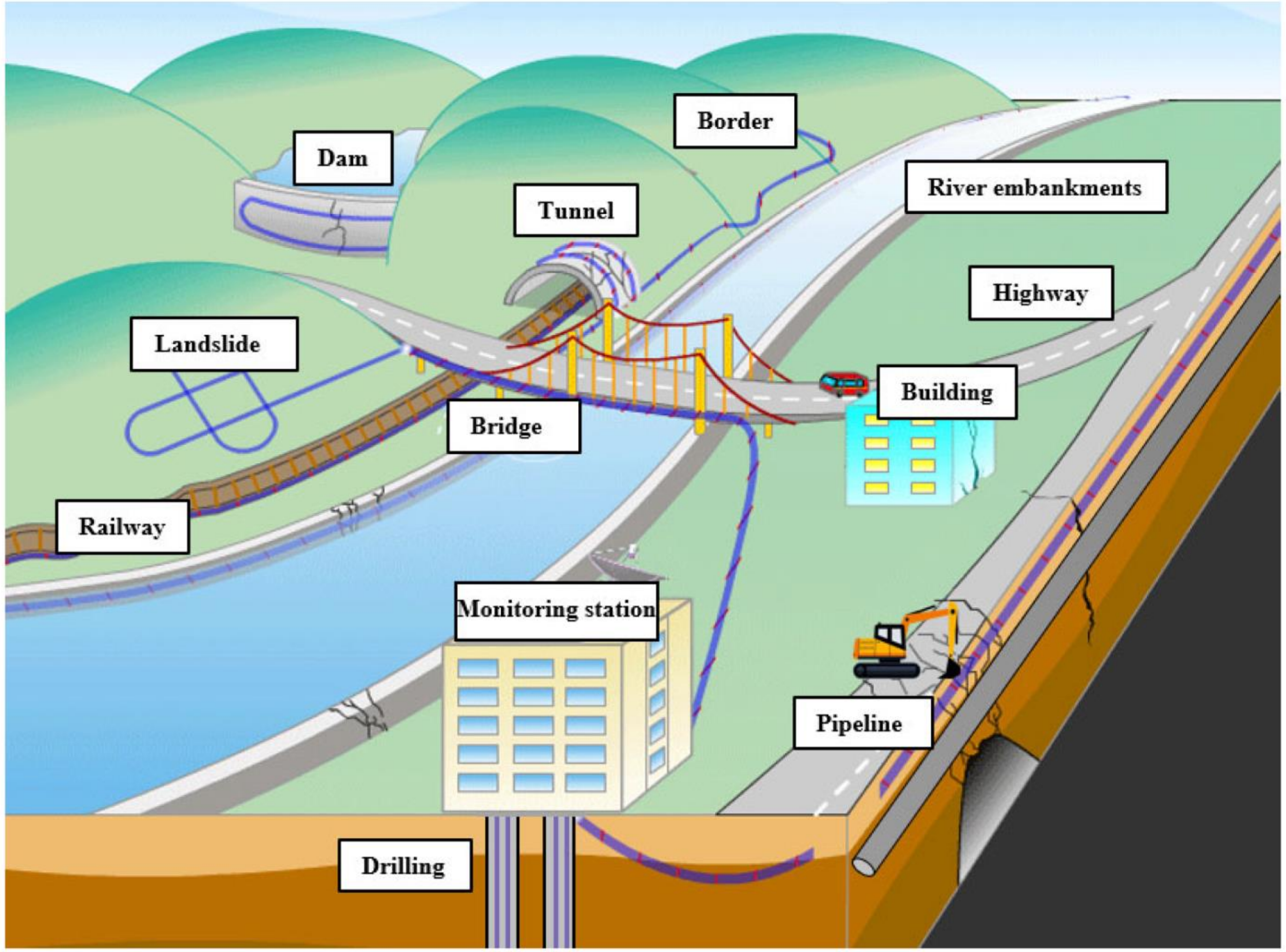
Comparison distributed sensing principles

<table>
<tr><th></th><th>Raman</th><th>Brillouin</th><th>Acoustic</th></tr>
<tr><td>Acoustic measurement?</td><td colspan="2">No</td><td>Yes, up to a kHz</td></tr>
<tr><td>Temperature measurement?</td><td colspan="2">Yes</td><td>Only relative changes</td></tr>
<tr><td>Strain measurement?</td><td>No</td><td>Yes</td><td>Only relative changes</td></tr>
<tr><td>Range</td><td><30 km</td><td><100 km</td><td><100 km</td></tr>
<tr><td>Spatial resolution</td><td colspan="3">~10 m</td></tr>
<tr><td>Hardware requirements</td><td colspan="3">Dark fiber + interrogator unit</td></tr>
<tr><td>Sensor maturity</td><td colspan="3">Commercially available</td></tr>
<tr><td>Applications</td><td colspan="2">• Slowly varying temp. or strain.</td><td>• Sea vessels detection.
• Earthquake/seismic detection.
• Storm detection.
• Swell detection.
• Whale sound detection.</td></tr>
</table>

Application examples of distributed sensing

- Temperature and vibration sensing of power cables and pipelines
- Temperature and vibration sensing in oil wells
- Temperature sensing in tunnels
  - Fire detection
- Structural health monitoring
  - Bridges
  - Land slides
- Intrusion monitoring
  - E.g., airports and military installations
  - Acoustic sensing along the fence

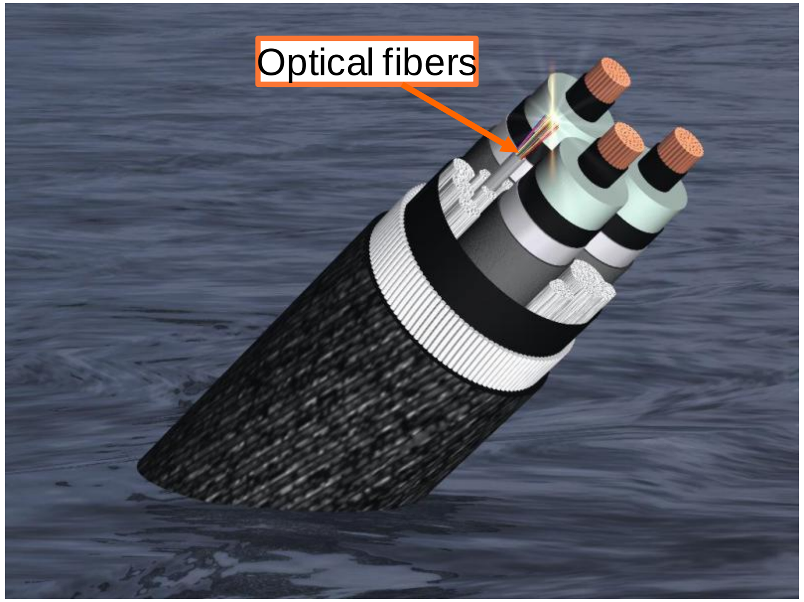
Applications I

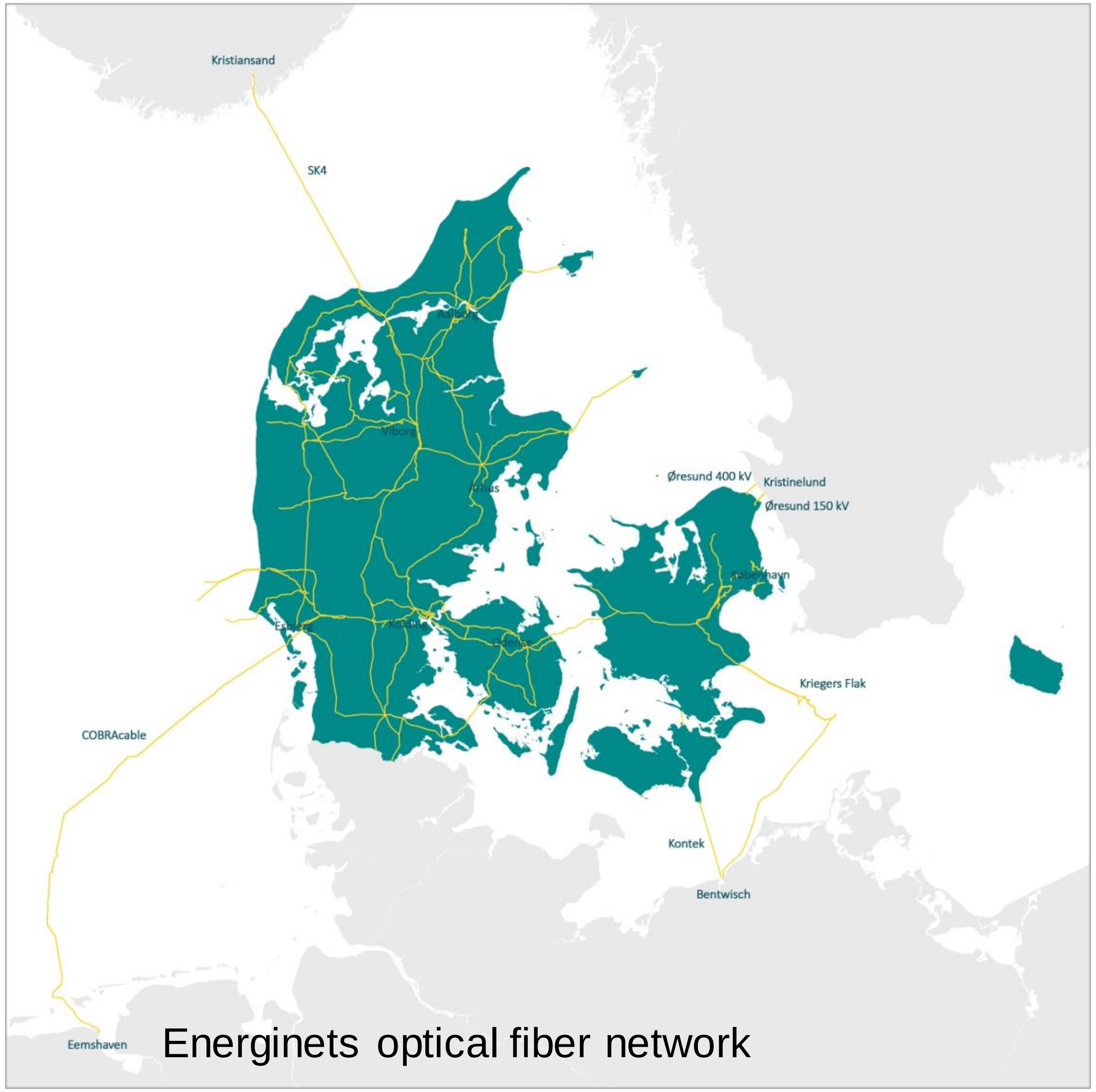


Applications II

High voltage cables monitoring

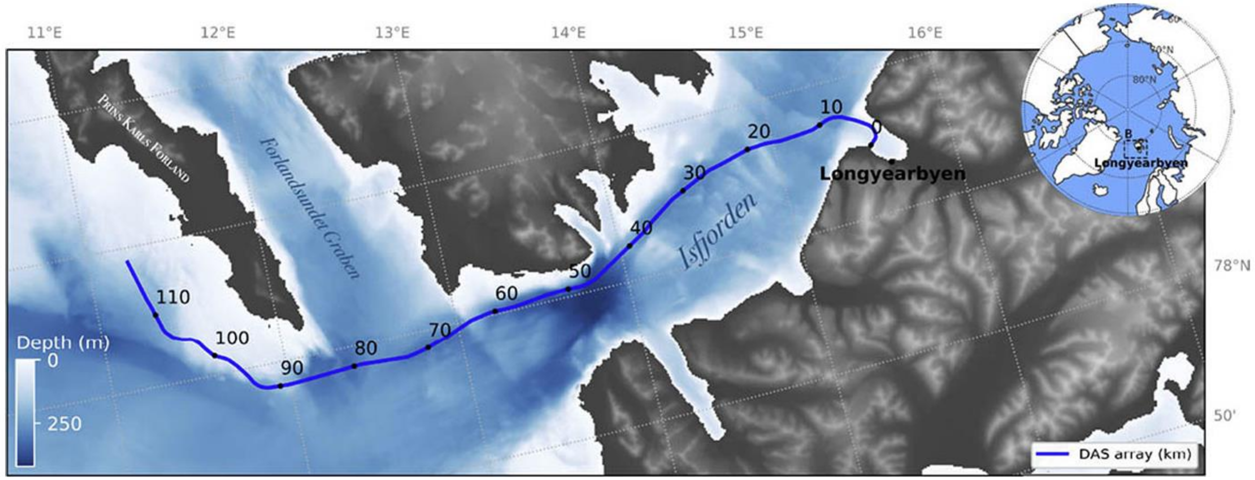
- Sense temperatures on high voltage cables
  - Raman or Brillouin sensing
- Vibration
  - Acoustic sensing

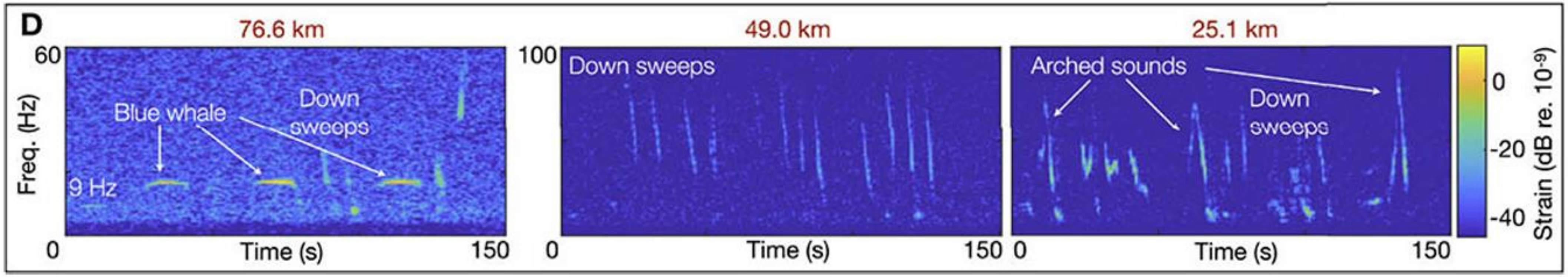




Applications III

- Rayleigh OTDR (DAS)
- Whale sound detection.
- Sea vessel detection.
- Earthquake detection.





M. Landrø et al: "Sensing whales, storms, ships and earthquakes using an Arctic fibre optic cable", Scientific Reports ***12****(1) (2022)*

L. Bouffaut et al.: "Eavesdropping at the Speed of Light: Distributed Acoustic Sensing of Baleen Whales in the Arctic", Frontiers in Marine Science ***9*** *(2022)*

Research topics in distributed sensing

What new possibilities can be expected in the future?

Research topics in distributed sensing

- GO-SENS project
  - Use of amplification for increased reach
  - Temperature strain discrimination
- New sensing technologies
- Sensing using existing infrastructure

GO-SENS project

In short

- The next generation of distributed optical fiber sensing
  - The aim of the GO-SENS project is to develop the next generation of distributed optical fiber sensors (DOFS) for real-time monitoring of the well-being of high-voltage power cables.
- August 2021 to July 2024
- Funded by the Innovation Fund Denmark
- Web site: https://go-sens.dk/

Goal 1, Increased range

- Long distance optical fiber distributed Brillouin sensing of high-voltage submarine cables
  – Commercial optical fiber sensors range 70-100 km.
  – Increase the range to > 200 km.

Viking link HVDC link between Denmark and UK 765 km. https://viking-link.dk/

Goal 1, Increased range

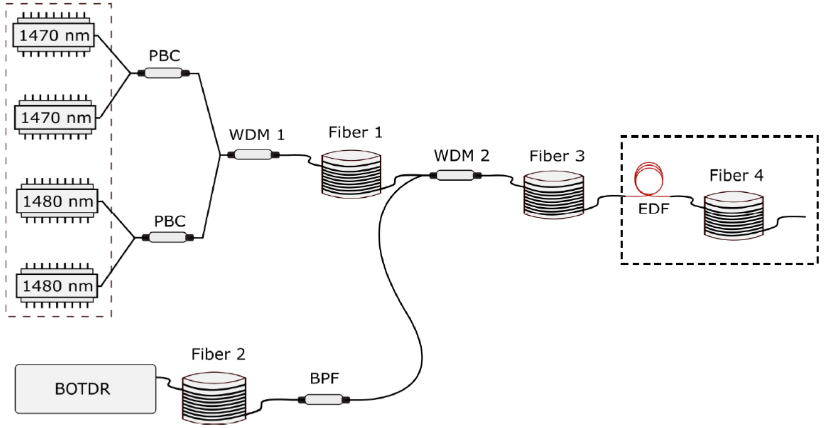


Fig. 1. Schematic presentation of the entire setup. EDF and Fiber 4 (in dashed box) are only used for experiments on combined Raman and ROPA amplification. Optical spectrum analyzer, power meter and oscilloscope can be connected to the outer end of fiber for analyzing transmitted pump and signal light. (1470 / 1480 nm – pump lasers, PBC - polarization beam combiner, WDM – wavelength division multiplexer, EDF – erbium doped fiber, BPF – band pass filter, BOTDR – interrogator).

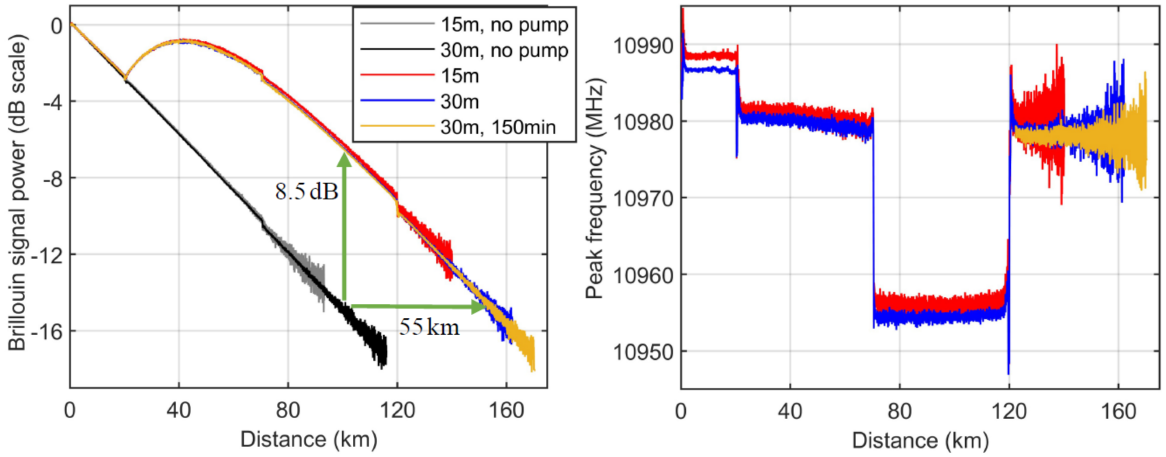


Fig. 2. Power (left) and peak frequency (right) of Brillouin backscattered signals from 170 km fiber, where the first 20 km have 150 µm² MFA, followed by 150 km with 112 µm². Unless otherwise noted, the measurement time is 40 min. Power profiles taken without pump light are shown for comparison. Green arrows depict the impact of Raman amplification on signal power at 100 km range and on distance range at 15 dB loss. The 150 min frequencies are only shown from 125 km onwards, for clarity.

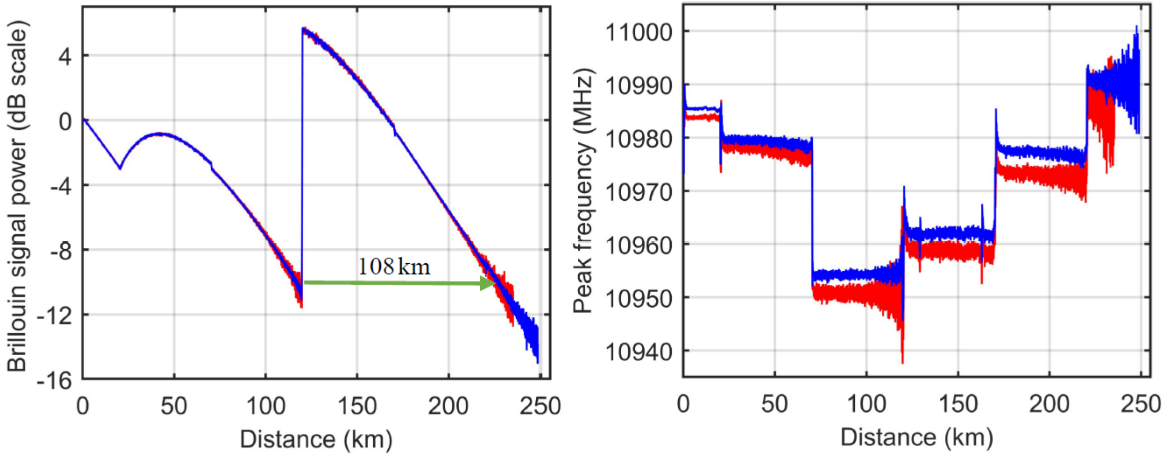


Fig. 3. Power (left) and peak frequency (right) of Brillouin backscattered signals over a distance of 250 km, where the first 20 km and the 50 km starting at 120 km have 150 µm² MFA, the last 30 km have 80 µm², and the remaining fiber has 112 µm². The measurements have 15 m and 30 m spatial resolution with 92 min and 115 min measurement time, shown in red and blue color, respectively. Raman amplification starts at 20 km distance and 12 m of EDF is placed at 120 km. The green arrow depicts the effect of the ROPA on distance range at 10 dB loss.

T. Joy et al, “Increasing the Distance Range of Repeaterless Brillouin-OTDR to 250 km by Optical Amplification”, 27th International Conference on Optical Fiber Sensors (2022)

Goal 2, Temperature and strain discrimination

In Brillouin sensing is the measured frequency shift sensitive to both temperature and strain

$$\Delta f_B = C_T \Delta T + C_S \varepsilon$$

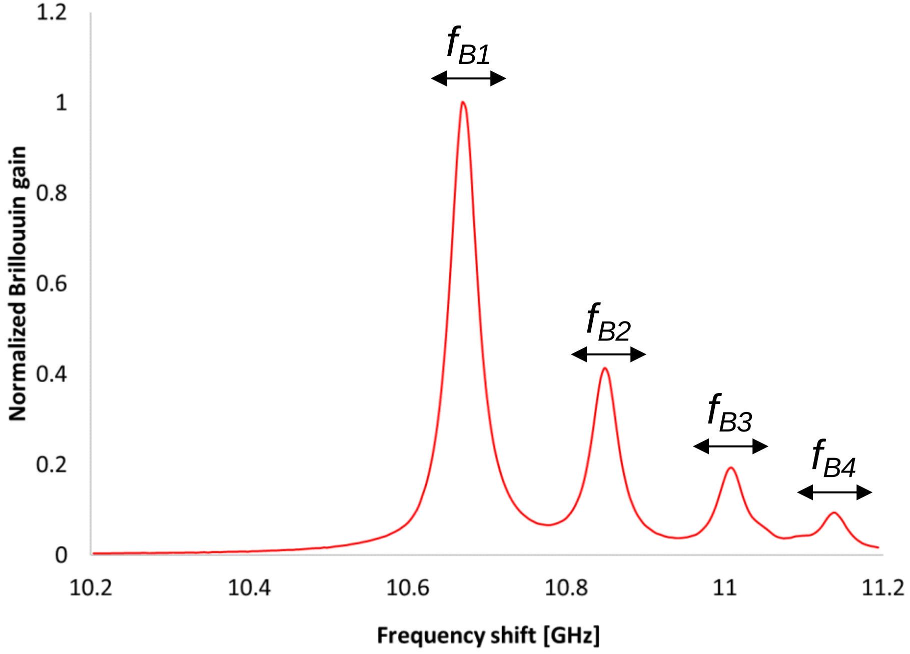
Investigate solution using special fibers with more peaks in the Brillouin spectrum to get more independent equations

$$\Delta f_{B1} = C_{T1} \Delta T + C_{S1} \varepsilon$$

$$\Delta f_{B2} = C_{T2} \Delta T + C_{S2} \varepsilon$$

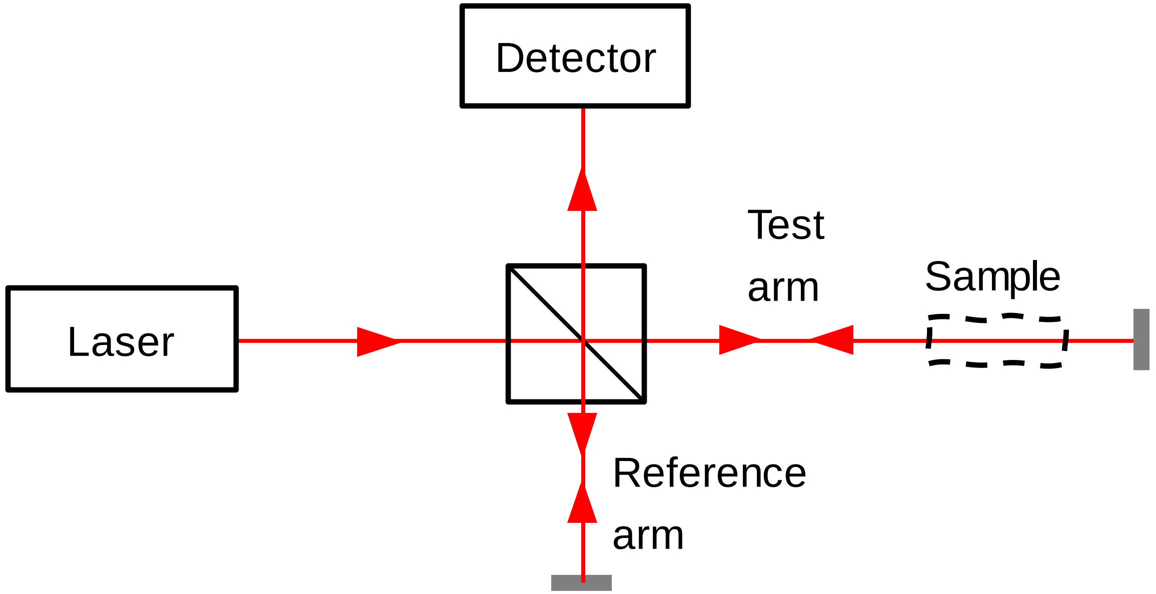
$$\Delta f_{B3} = C_{T3} \Delta T + C_{S3} \varepsilon$$

$$\Delta f_{B4} = C_{T4} \Delta T + C_{S4} \varepsilon$$



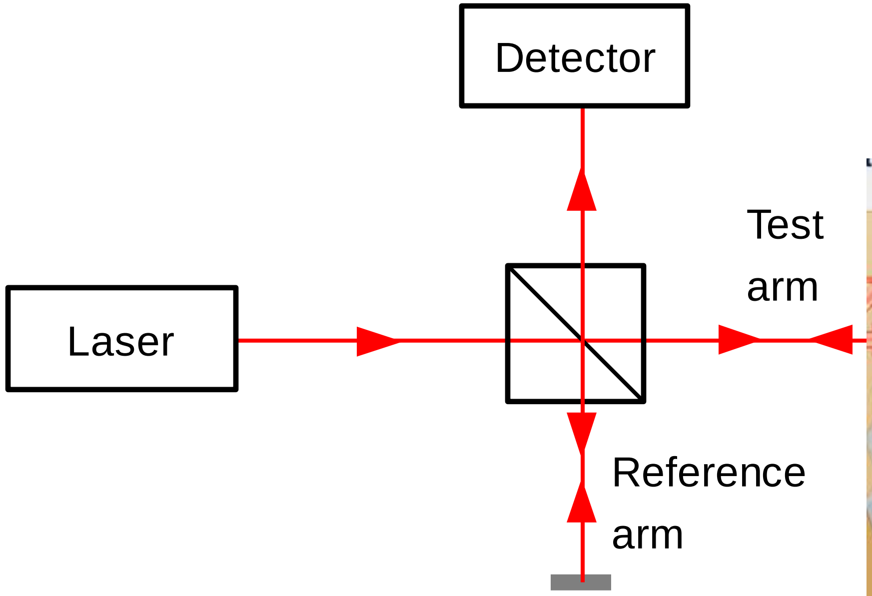
New sensing techniques using already installed cables

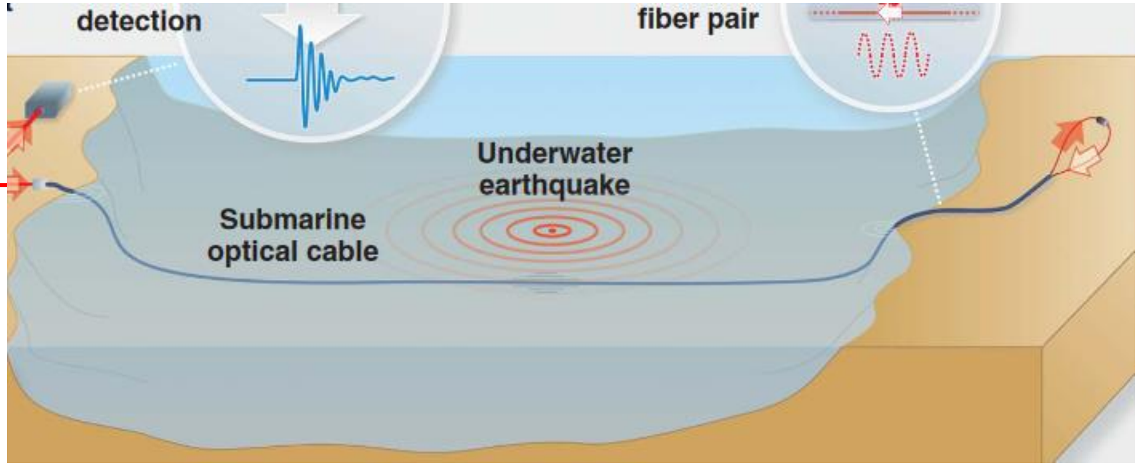
Transmission sensing (interferometric)



Transmission sensing (interferometric)

Range:	>10,000 km
Spatial resolution:	None or 50-100 km
Maturity:	Early research stage

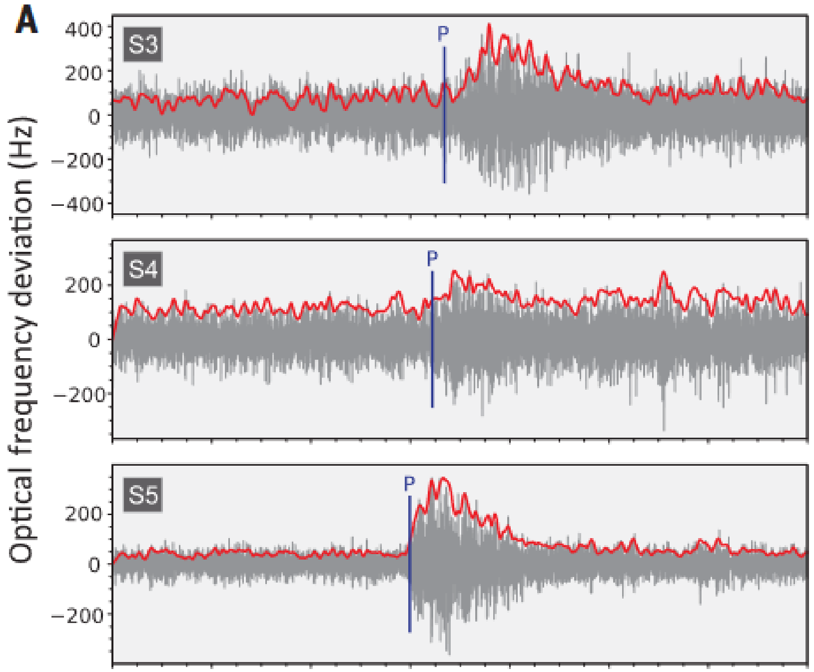


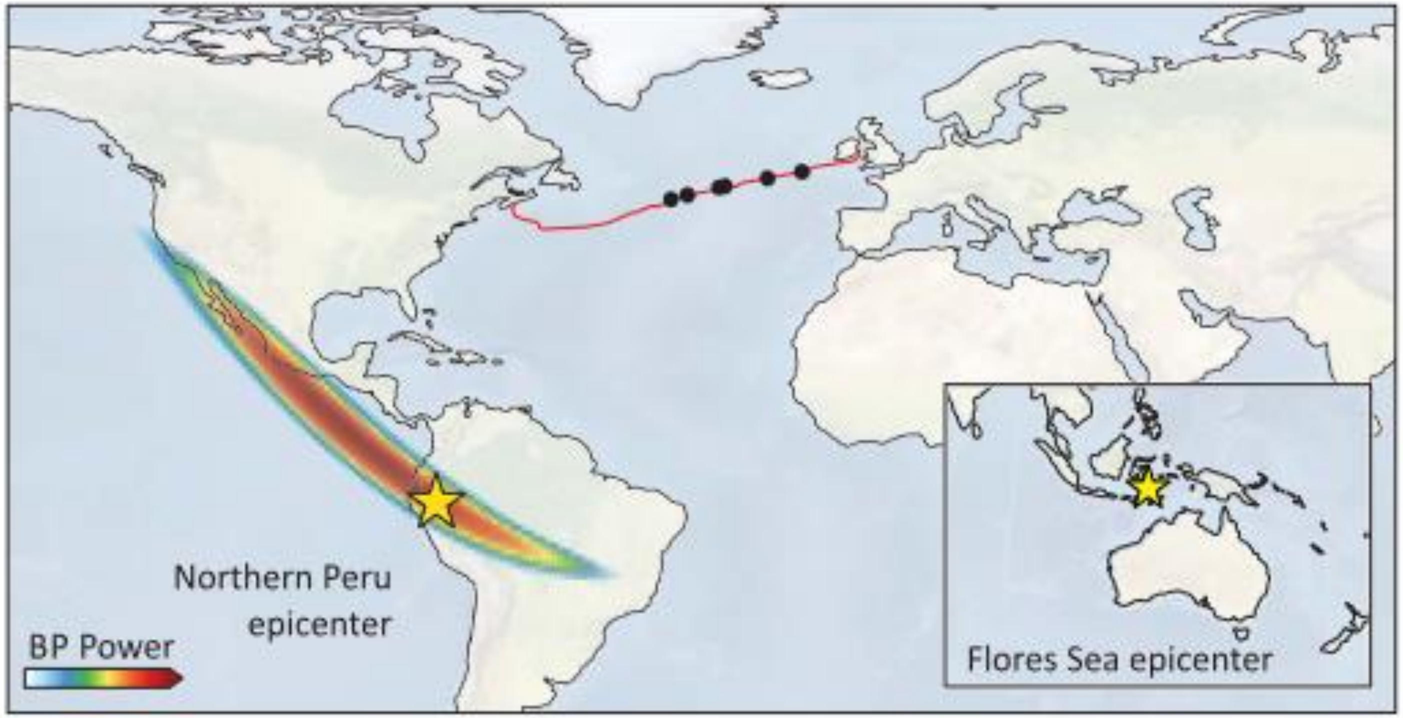


Reference:
G. Marra et. al.: “*Optical interferometry–based array of seafloor environmental sensors using a transoceanic submarine cable*”, Science **376**, 874-879 (2022)

Transmission sensing applications

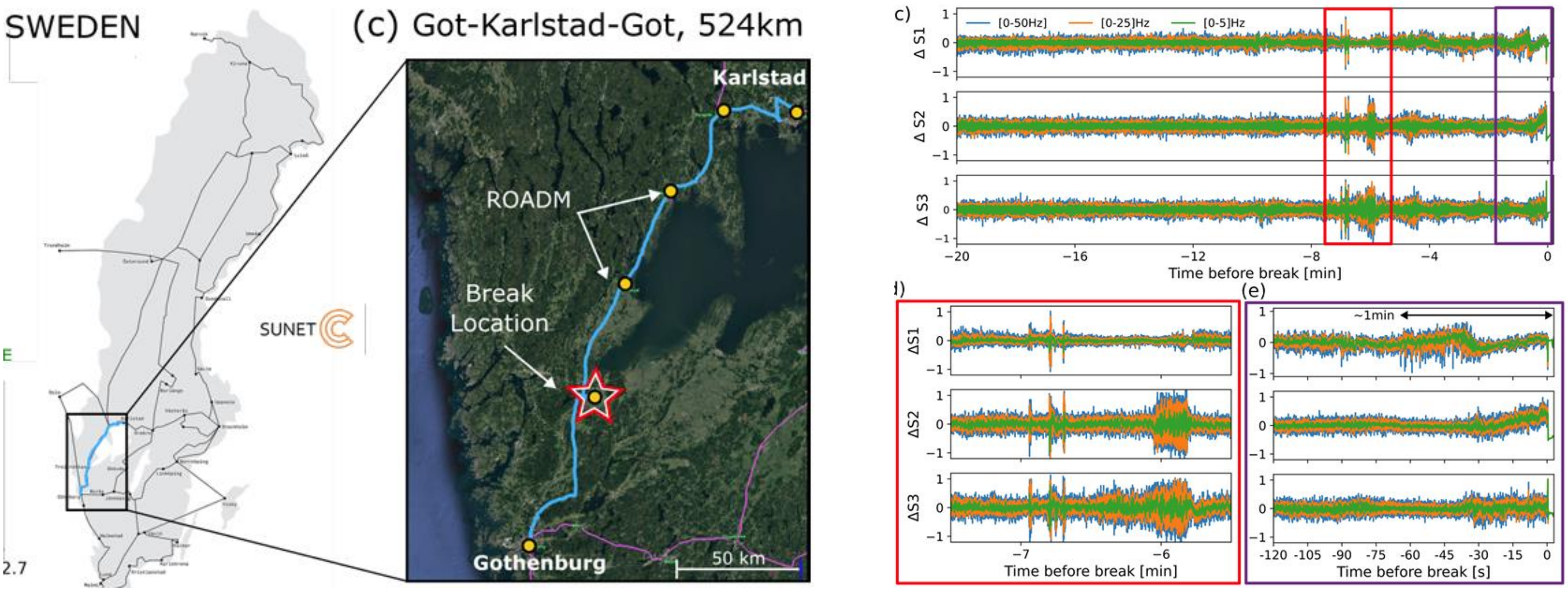
- Earthquake sensing





Reference:
G. Marra et. al.: "*Optical interferometry–based array of seafloor environmental sensors using a transoceanic submarine cable*", Science **376**, 874-879 (2022)

Using custom coherent receiver



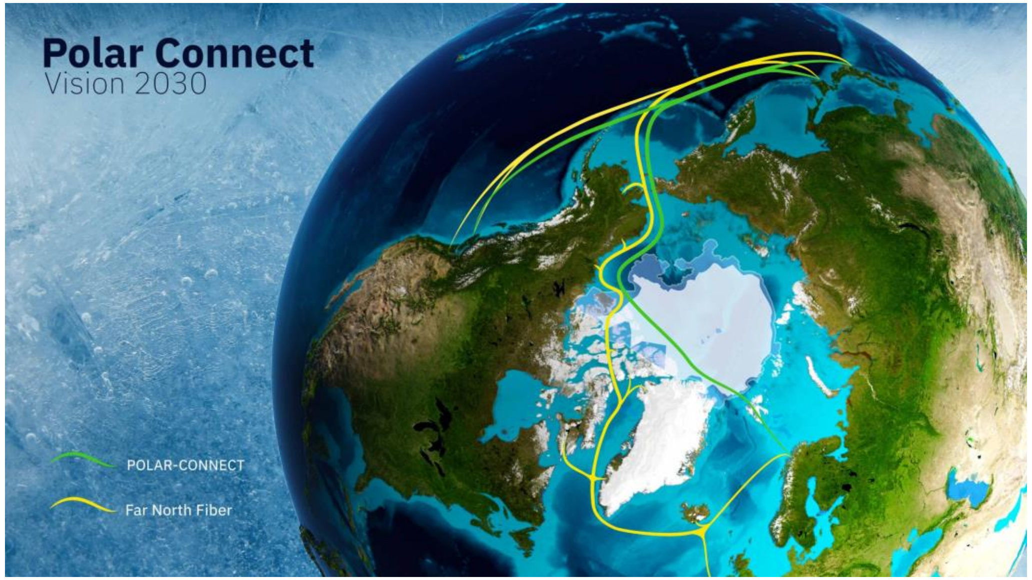
M. Mazure et al., "Real-Time Monitoring of Cable Break in a Live Fiber Network using a Coherent Transceiver Prototype", arXiv:2307.01291 (2023)

Conclusion

- Optical fibers can be used as efficient distributed sensor
  - Sensing properties such as temperature, strain and vibrations
- Is a mature technology already today used for various application
- Ongoing research topics
  - Increased range using optical amplification
  - Temperature/strain discrimination
  - Use of already installed cables

Acknowledgements

- Polar Connect: https://nordu.net/polar-connect/



- The GO-SENS project supported by the Innovation Fund Denmark under Projects
  - GO-SENS 0224-00074B

GO-SENS https://go-sens.dk/