Incab

FIBER OPTIC SENSING
For Electric Utilities

Mike Riddle
Executive Vice President, Incab America LLC

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Registered Continuing Education Program

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PURPOSE STATEMENT/COURSE DESCRIPTION

Fiber Optic Sensing for Electric Utilities webinar will teach attendees about:

- Reasons why fiber optic sensing is becoming so popular
- Basic principles behind fiber optic sensing, specifically backscattering
- The three types of backscatter, what changes in the fiber each will respond to, and how each can effectively be used for sensing
- The three basic types of fiber optic sensors: discreet, quasi-distributed, and distributed
- The fiber types of distributed sensing used today: DTS, DAS, DSS, DTSS, and DPS
- Utility applications for fiber optic sensing, both how they are already being used and how they could be used in the future
- How to put together an optimal fiber optic sensing system

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LEARNING OBJECTIVES

After this class you will be able to:

1. Explain the advantages of fiber optic sensing and why it has become so popular
2. Name the three **types of optical backscatter** and describe their sensitivity to changes in the fiber
3. State the three **basic types of fiber optic sensors**
4. State the five **types of distributed sensing** in use to today by electric utilities, plus what each is used for and how each is used
5. State the **conditions and failures** that can be detected and monitored with fiber-optic sensors
6. Explain how to go about putting together an optimal fiberoptic sensing system

Incab University "School of Excellence in Fiber Optics"

Learning Hub

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Webinar Rules

- Introduction and sound check
- Presentation: 90 min
- Use chat for questions during presentation
- Q&A (NB! Technical questions only)
- Let's start!

Fiber optic sensing advantages

Why use fiber optic sensors?

— Intrinsically safe – “No moving parts” (so to speak)

— High sensitivity

— Wide bandwidth

— Passive – no need for electrical power

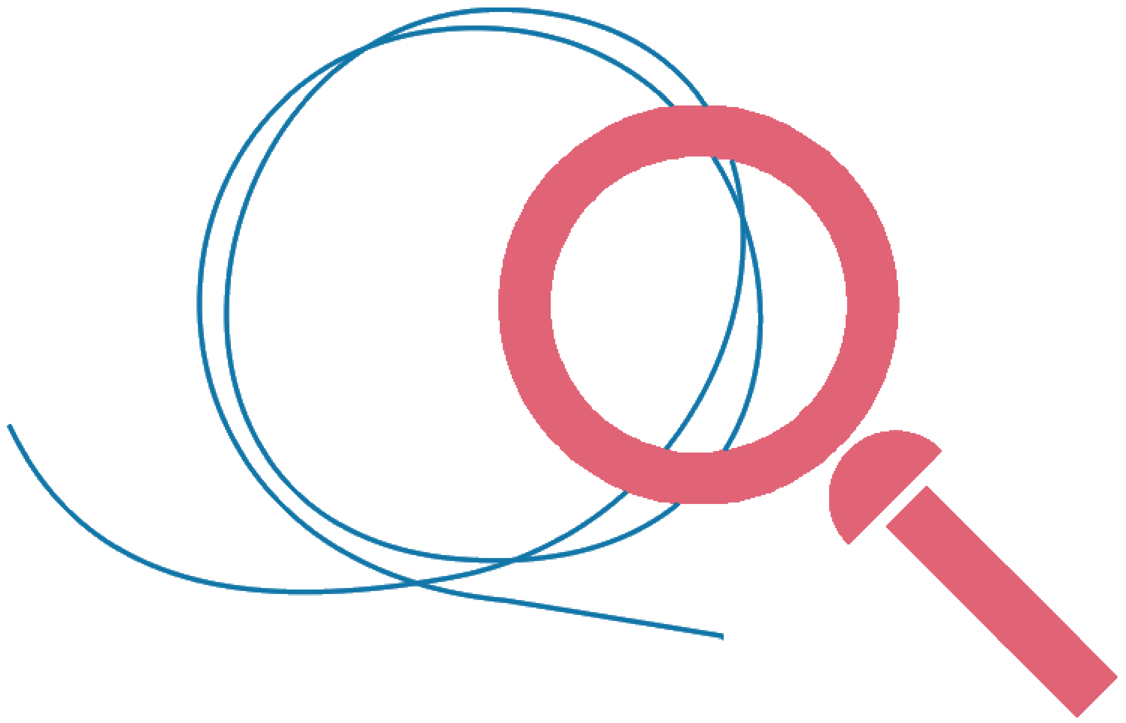
— Integrated communication: the fiber itself is its data link

*May be able to use fiber in cables already installed or to be installed

— Immune to electromagnetic interference (EMI)

— Small and lightweight

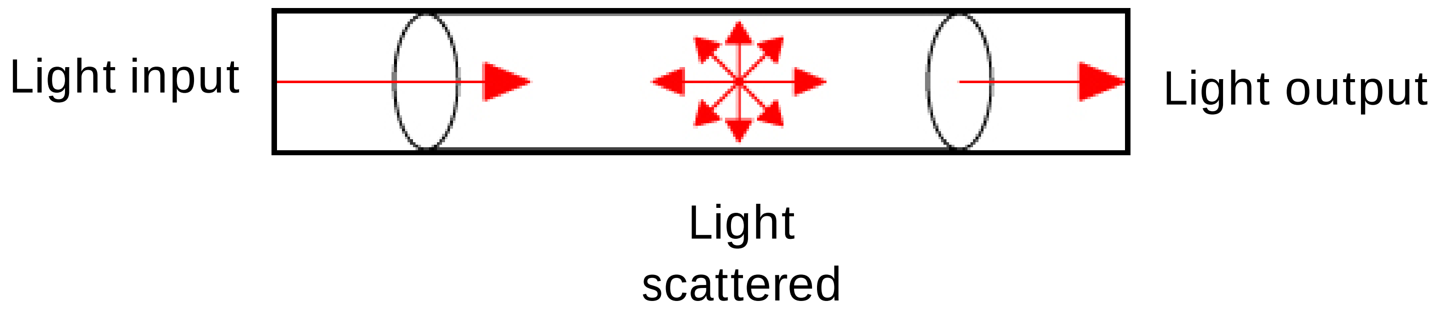
— Non-metallic, so no galvanic issues



Fiber optic sensing principles

Backscatter

- The reflection of light as it travels down a fiber
- Two sources (causes) of the reflection are:
  1. The photons hitting the particles (molecules) that make up the fiber ("Rayleigh" and "Raman"), or



  2. The interaction of the electromagnetic field of the light with the material waves in the fiber ("Brillouin")

Drawing courtesy of the Fiber Optic Association

Fiber optic sensing principles

Backscatter characteristics

Two characteristics of backscatter are:

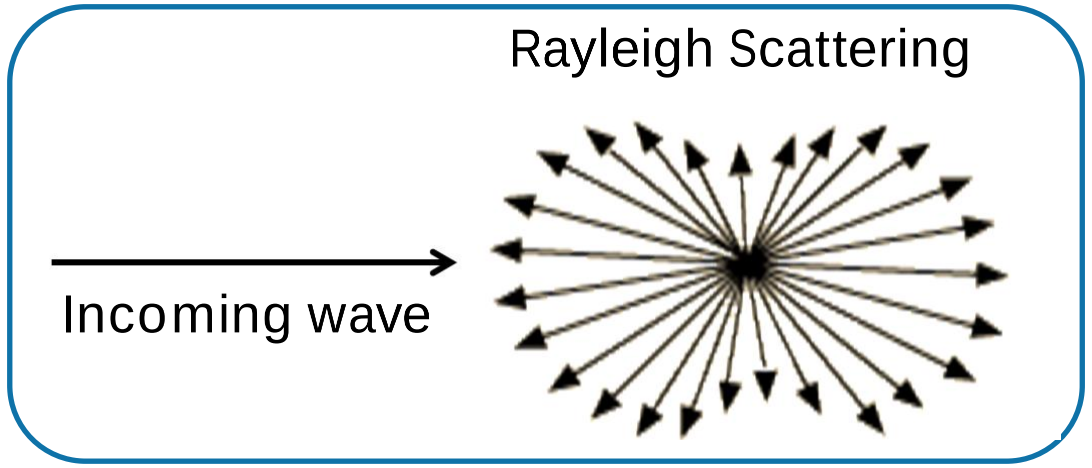
1 **Elastic**
= The total kinetic energy remains the same after the collision (Rayleigh)

2 **Inelastic**
= Some kinetic energy appears to be lost, but actually it is transformed in some way (heat, wavelength or frequency shift) (Raman, Brillouin)

Fiber optic sensing principles

Backscatter – the three types

Rayleigh Scattering = Elastic scattering of the light by particles much smaller than the wavelength



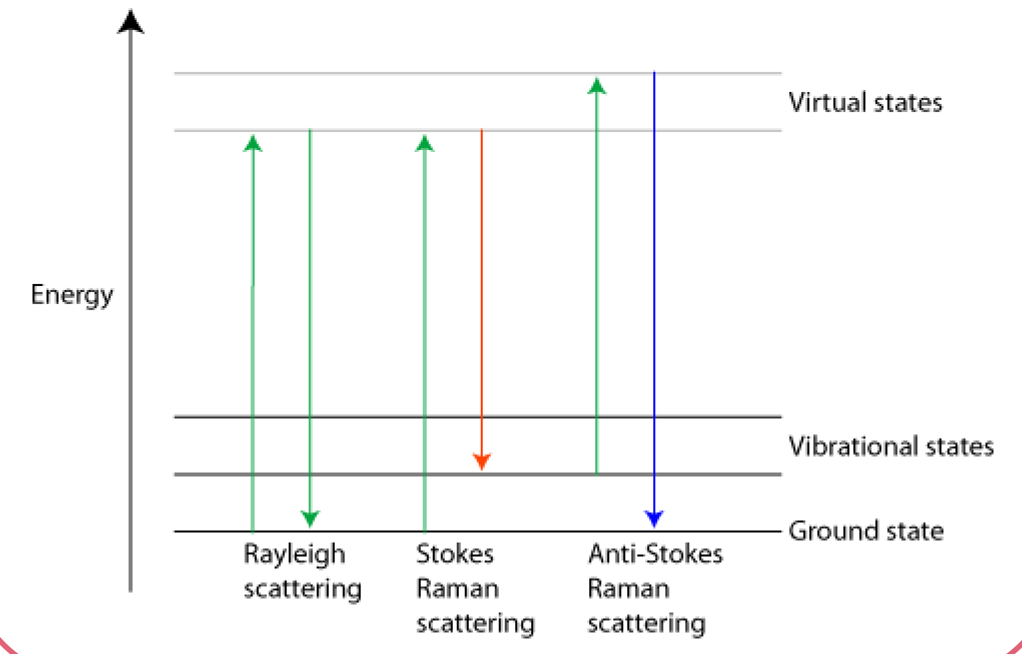
- The scattered photons have the same energy (frequency and wavelength), but their direction may change
  - Some continue forward
  - Some reflected backward
- Consequently, Rayleigh Scattering is the cause of attenuation (loss of optical power) because energy "going forward" (transmitted) is reduced
- But, because the energy reflected backward can be detected, it is the reason that optical time domain reflectometers (OTDR's) work
- Rayleigh Scattering is not sensitive to temperature or fiber strain

Fiber optic sensing principles

Backscatter – the three types

Raman Scattering (a.k.a the "Raman Effect") = Inelastic scattering of the light by the particles comprising the fiber (molecules), meaning there is both an exchange of energy *and* a change in the light's direction

- The scattered photons likely will lose energy (a "Stokes Shift"), but they could gain energy (an "Anti-Stokes Shift") too
  - A corresponding change in frequency occurs too
  - Because frequency and wavelength are inversely related, the wavelength changes too
- The molecule of the fiber is affected in the opposite way: It will either gain energy (with a "Stokes Shift") or lose energy (with an "Anti-Stokes Shift)
- The Raman Effect varies with changes in temperature of the fiber
  - ➔ We can use it for detecting changes in temperature



Fiber optic sensing principles

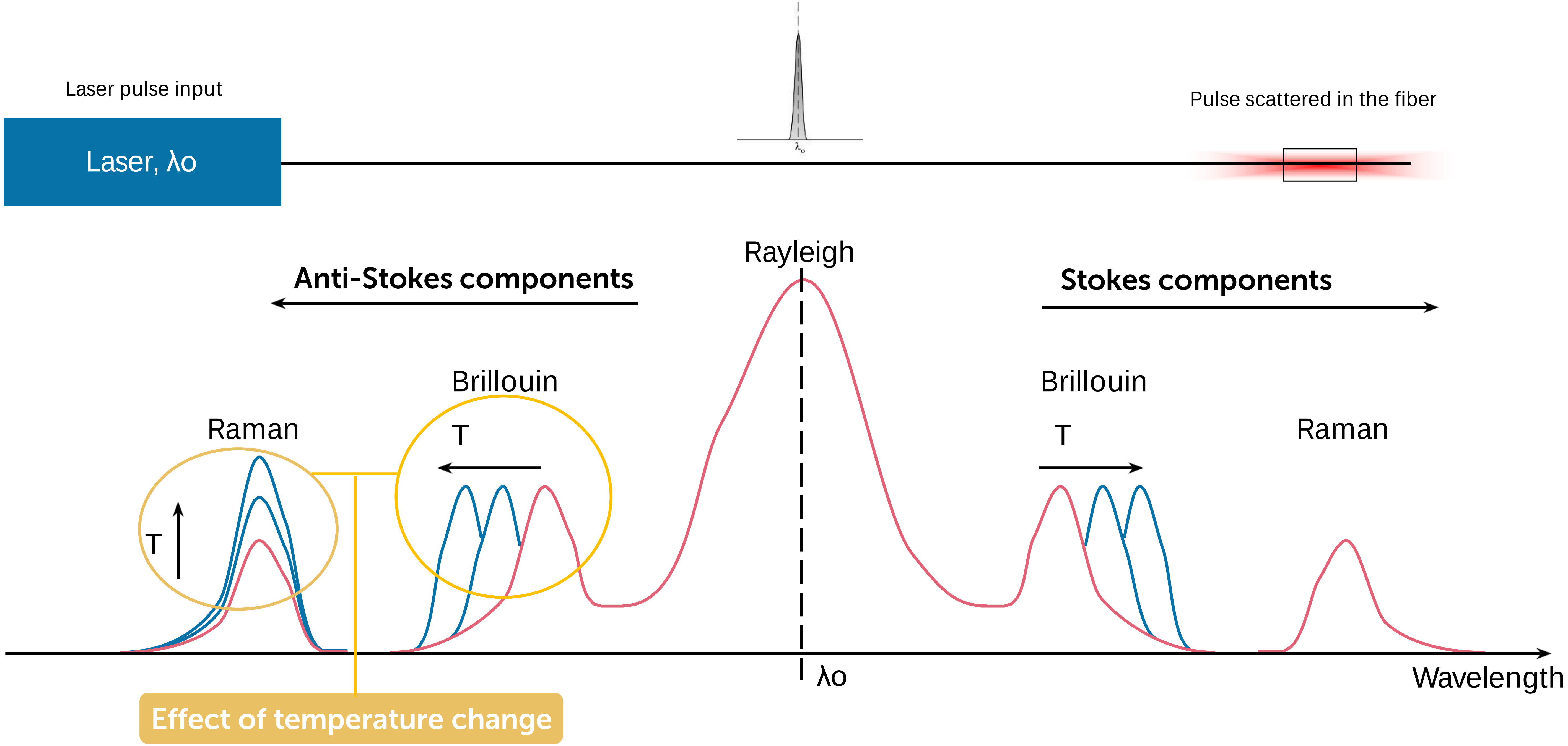
Backscatter – the three types

Brillouin Scattering = Inelastic scattering of the light caused by the interaction of the electromagnetic wave of the light with the "structure" of the particles (molecules) comprising the glass (cannot say "lattice" because of the amorphous nature of glass)

- Like Raman scattering, there is both an exchange of energy plus there is a change in the electromagnetic field of the light
- Like Raman scattering, the change of energy can be a loss ("Stokes Shift") or a gain ("Anti-Stokes Shift")
- Brillouin scattering varies with changes in the structure of the glass, and such changes can be caused by:
  - ➔ Temperature changes. So, we can use it for temperature sensing
  - ➔ Strain. So, we can use it for strain sensing
  - ➔ Pressure. So, we can use it for pressure or acoustic sensing (because sound waves act to create pressure on the fiber)

Fiber optic sensing principles

Backscatter – visualizing the three types



Fiber optic sensing principles

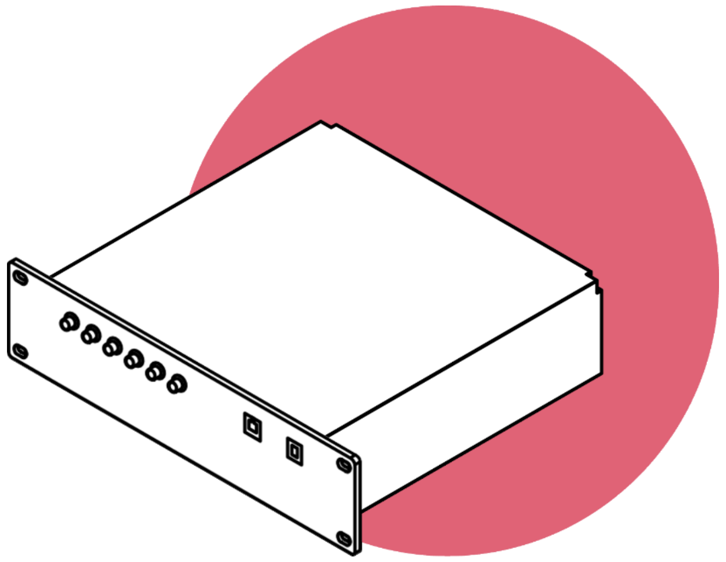
Backscatter – theoretically how best to use each type for sensing

Type of scattering	Temperature sensitivity	Strain sensitivity	Best for
Rayleigh	Weak	Weak	OTDR (at first glance), but using interferometry, can use for Acoustic
Raman	Strong Anti-Stokes – Intensity	Weak	Temperature
Brillouin	Strong – Wavelength	Strong – Wavelength	Temperature or Strain (+ Pressure or Acoustic)

Fiber optic sensing application overview

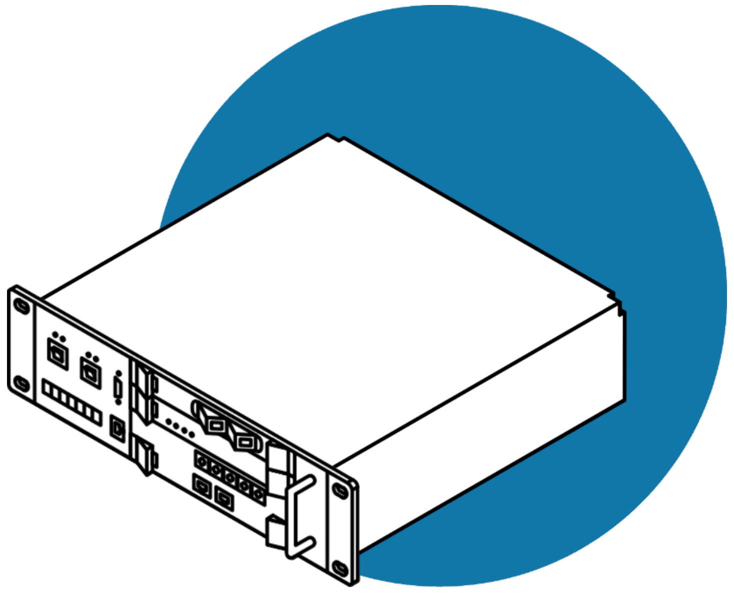
Three ways to apply backscatter for sensing

- **Discreet sensors**
  — Use one FO sensor to sense backscatter at one point of a fiber



- **Quasi-distributed fiber optic sensors**
  — Use an array of discrete sensors along a fiber

- **Fully distributed sensors** ← Especially interesting!
  — Use the fiber itself as a linear, continuous sensing element



Fiber optic sensing applied

The discreet sensing option

FBG—Fiber Bragg Gratings

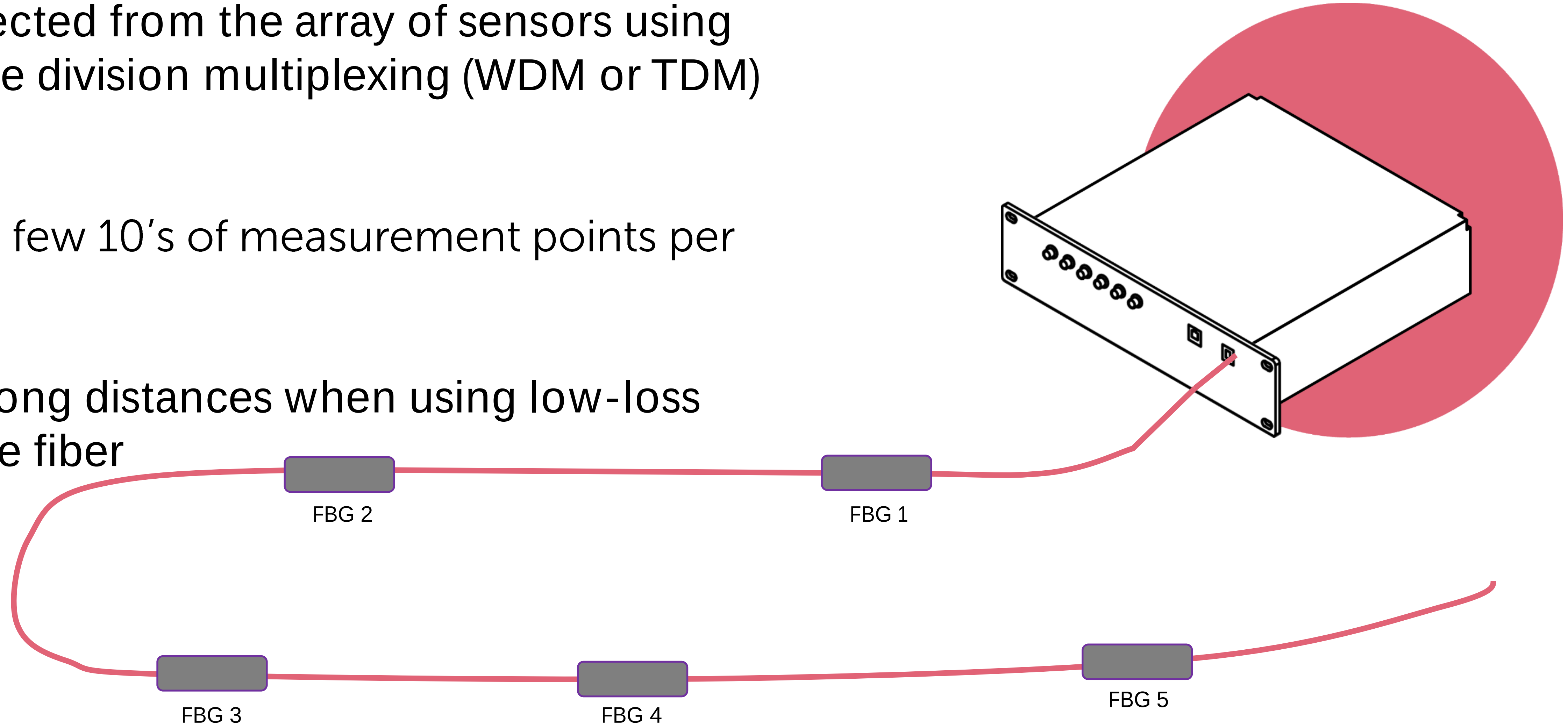
- FGB's are a well-established technology for sensing at a single point
  - They work on Fresnel Reflection – How light both reflects and refracts at the interface between two materials with different indices of refraction.
    - * In fiber, the interface is between the core and the cladding
    - * So, a little different that the types of backscatter that we have discussed
  - Lots of different types and structures
  - Many applications besides sensing. Most notably: FO multiplexers and de-multiplexers, and optical filters
- Discrete temperature, pressure, and strain FBG sensors are available and can provide data for a single point
- Permanent or fixed installations

Fiber optic sensing applied

The quasi-distributed sensing option

An array of Fiber Bragg Gratings (FBG's) installed at discrete points along a single optical fiber

- Data is collected from the array of sensors using wave or time division multiplexing (WDM or TDM) techniques
- Limited to a few 10's of measurement points per fiber
- Can cover long distances when using low-loss single-mode fiber



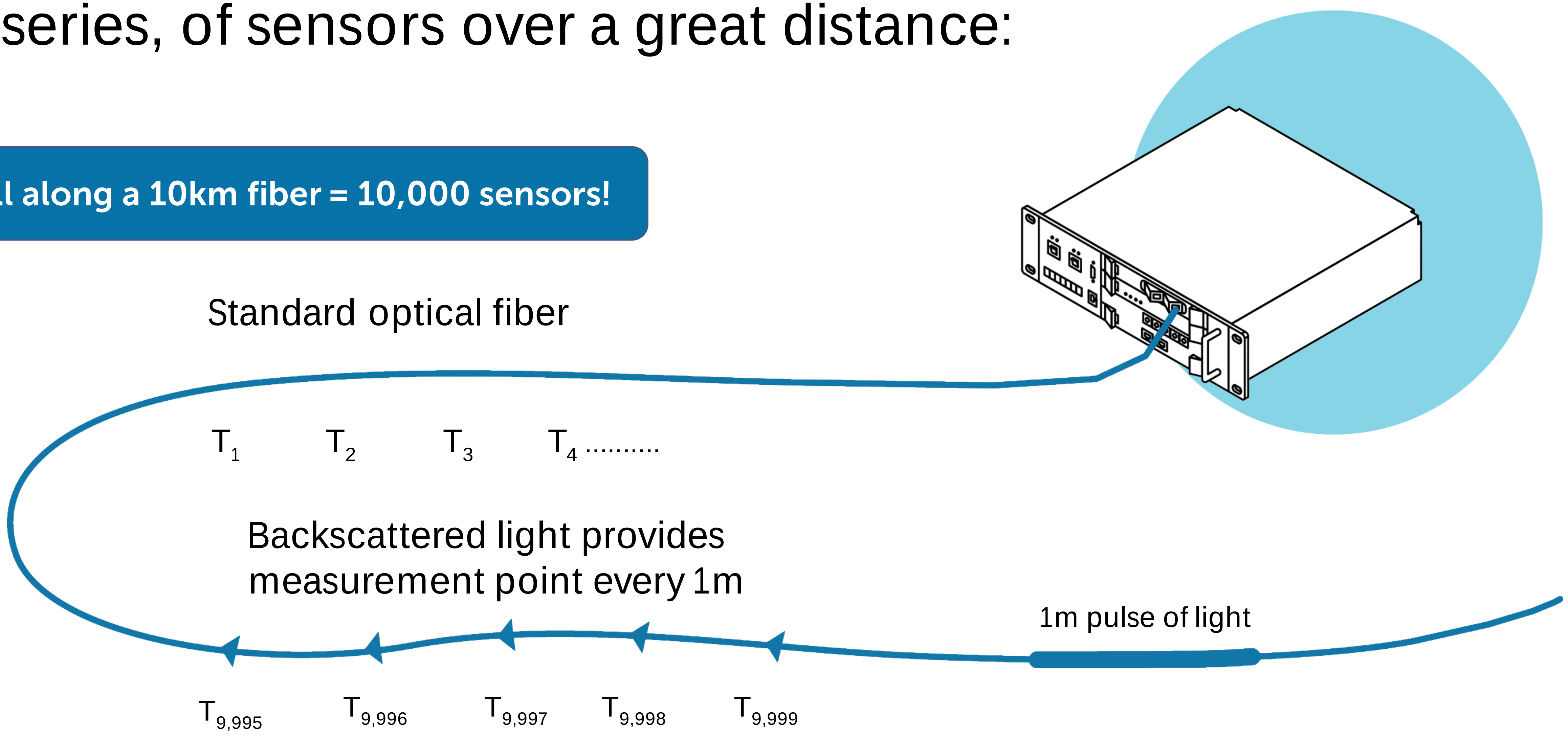
Fiber optic sensing applied

The (fully) distributed sensing option

In Distributed Sensing, the fiber itself acts as a large number, or series, of sensors over a great distance:

Measurements all along a 10km fiber = 10,000 sensors!

The fiber is the sensor



Fiber optic sensing applied

Distributed sensing implementations

Five types of distributed sensing used today:

- **DTS**—Distributed Temperature Sensing
- **DAS**—Distributed Acoustic Sensing
- **DSS**—Distributed Strain Sensing
- **DTSS**—Distributed Temperature & Strain Sensing
- **DPS**—Distributed Pressure Sensing

➔ **Two types most often used by electric utilities: DTS and DAS**

Fiber optic sensing applied – general

Distributed sensing used by electric utilities – Distributed Temperature Sensing (DTS)

- Raman-based (typically)
- Measurement ranges up to:
  - Using multimode fiber, up to 25 miles (40 km)
  - Using single-mode fiber, up to 63 miles (100 km)

Fiber optic sensing applied – general

Distributed sensing used by electric utilities – Distributed Temperature Sensing (DTS)

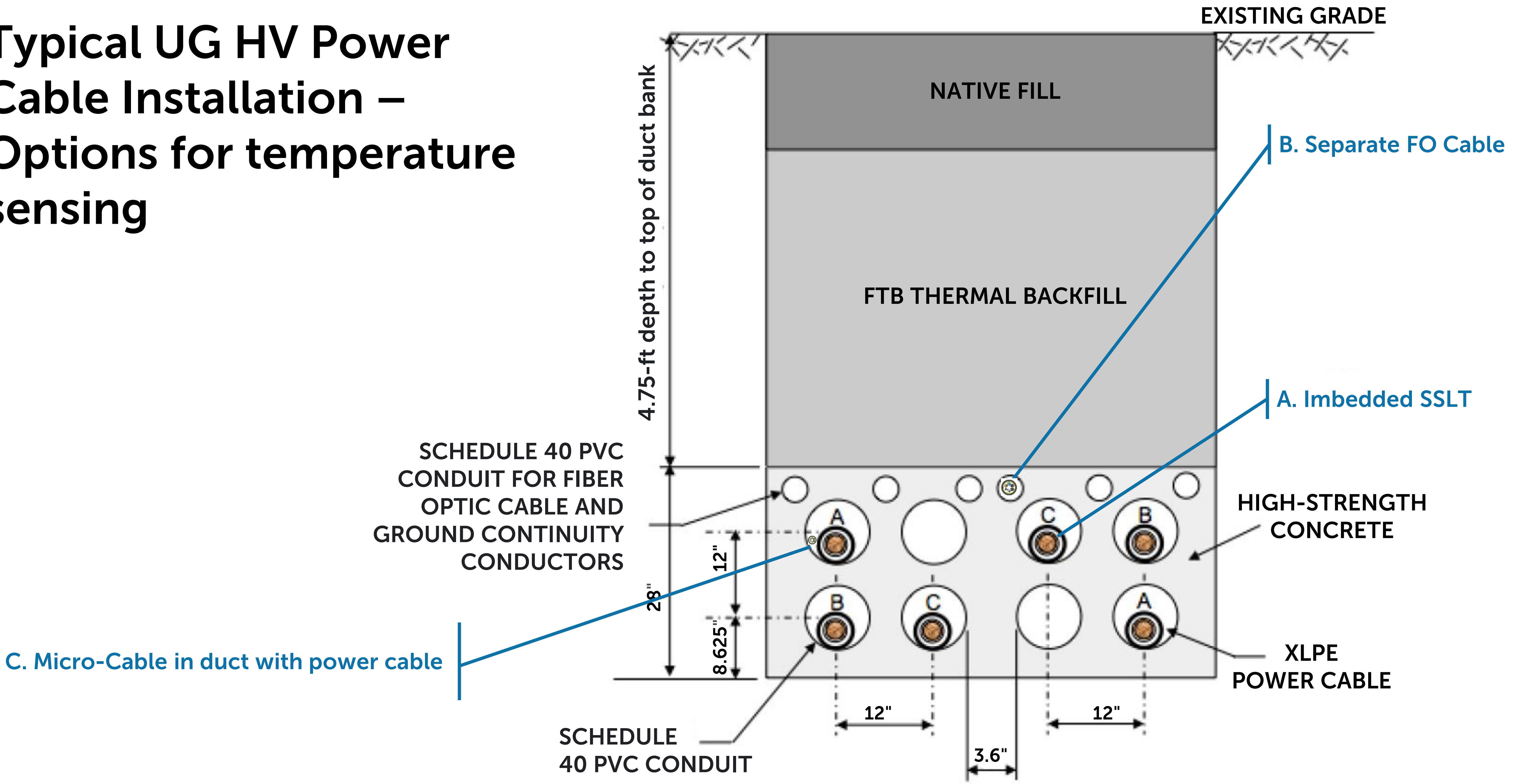
- Fully commercial with extensive track record
- Commonly used for reservoir and pipeline monitoring
- Can also be used for fire detection
    - In buildings or tunnels
    - Could use in ADSS or OPGW
        - * Early detection to direct resources quickly and effectively
        - * "Fire-rated" to support reaction time

Fiber optic sensing applied – general

Distributed sensing used by electric utilities – Distributed Temperature Sensing (DTS)

- Often used to monitor HV underground power cable systems (typically, 115 kV and above) in 1 of 3 ways:
  A. Stainless steel loose tube (SSLT) imbedded in cable sheath
     * Most accurate both for temperature and responsiveness
     * Complicates both electrical and optical splicing
       ➔ Consider: A failure of one effectively takes out the other too
  B. Separate cable installed in the same duct bank
     * Sacrifices accuracy and responsiveness to improve installation and reliability
  C. Third Way? Micro-cable design (blown-in type design) installed in the same duct with the power cable

Typical UG HV Power Cable Installation – Options for temperature sensing



Fiber optic sensing applied – general

Distributed sensing used by electric utilities – Distributed Acoustic Sensing (DAS)

- Based on “Coherent Rayleigh Backscattering”
  - Uses interferometry (specifically, swept-wavelength interferometry [SWI]) to measure phase shifts in the backscatter (in contrast to amplitude)
    - ➔ Frequency domain analysis rather than time domain analysis
- Measurement ranges up to 31 miles (50 km)

Fiber optic sensing applied – general

Distributed sensing used by electric utilities – Distributed Acoustic Sensing (DAS)

Commercialized since 2009, but still a developing technology

- Excellent for “Interference monitoring” = security
  - Intrusion detection around buildings, substations, and other facilities
  - Can detect plus classify excavation activity by type to filter out extraneous ones

    *Requires “tuning” the system to differentiate activities

- Can “Tag Team” DAS with DTS
  - Monitor the temperature of an HV underground power cable system while DAS can alert you if there is any digging nearby

    ➔ To prevent dig-ins, a leading cause of damage to UG cable systems of all types!

    “A lot more backhoes than tornados”

Fiber optic sensing applied – general

Distributed sensing used by electric utilities – Distributed Acoustic Sensing (DAS)

- DAS could also be used for lightning detection
  - Using OPGW or ADSS to get location, intensity, and duration data

    *Data can be used to better allocate resources for inspections to find possible damage
- DAS also used for detecting leaks in pipelines, monitoring borders and other sensitive perimeters, oil & gas monitoring, and even monitoring seismic activity

Fiber optic sensing applied – general

Available distributed sensing options –

Distributed Strain Sensing (DSS) &
Distributed Temperature & Strain Sensing (DTSS)

DSS and DTSS are so closely related, we discuss them together

- Both based on Brillouin Scattering
- Measurement ranges up to 156 miles (250 km) using single-mode fiber

Fiber optic sensing applied – general

Available distributed sensing options – Distributed Strain Sensing (DSS) & Distributed Temperature & Strain Sensing (DTSS)

- Three implementations of this technology:

  A. Brillouin Optical Time-Domain Analyzer (BOTDA)

  — Uses stimulated Brillouin scattering

  — Requires a fiber loop (two fibers, A – B – A) with light in both directions which yields strong interaction (the "stimulation")

  ➔ Best option when precision is most important

Fiber optic sensing applied – general

Available distributed sensing options – Distributed Strain Sensing (DSS) & Distributed Temperature & Strain Sensing (DTSS)

- Three implementations of this technology:

  B. Brillouin Optical Time-Domain Reflectometer (BOTDR)

  — Uses spontaneous Brillouin scattering

  — Requires just one fiber with access to just one end

  ➔ Best option when distance is most important

Fiber optic sensing applied – general

Available distributed sensing options – Distributed Strain Sensing (DSS) & Distributed Temperature & Strain Sensing (DTSS)

- Three implementations of this technology:

  C. Brillouin Optical Frequency Domain Analysis (BOFDA)

  – Newer technology which tries to get the distance of BOTDR with the precision of BOTDA

  – Still developing

Fiber optic sensing applied – general

Available distributed sensing options – Distributed Strain Sensing (DSS) & Distributed Temperature & Strain Sensing (DTSS)

- “Buy DSS and get DTSS for free!” (sort of)
  - Consider: Both strain and temperature change Brillouin scattering. So…
    - ➔ Can the effects be separated?
  - Yes: Two possibilities…
    - A. BOTDR technology available to separate the two effects up to a certain temperature
    - B. Using BOTDA and two fibers, one with strain, one without, can separate the two effects

Fiber optic sensing applied – general

Available distributed sensing options –
Distributed Strain Sensing (DSS) &
Distributed Temperature & Strain Sensing (DTSS)

- Mostly commonly used for pipeline monitoring
- Great options for monitoring strain in structures
  - Utility applications
    *Use in optical phase conductor (OPPC) to measure sag and temperature on transmission lines
    ➔ Could get **real-time**, dynamic line (ampacity) ratings!
    *Use at critical structures such as those at river crossings
    ➔ Stress or fatigue
    *Hydro-electric power plants
  - Other applications: Bridges and mines

Fiber optic sensing applied – general

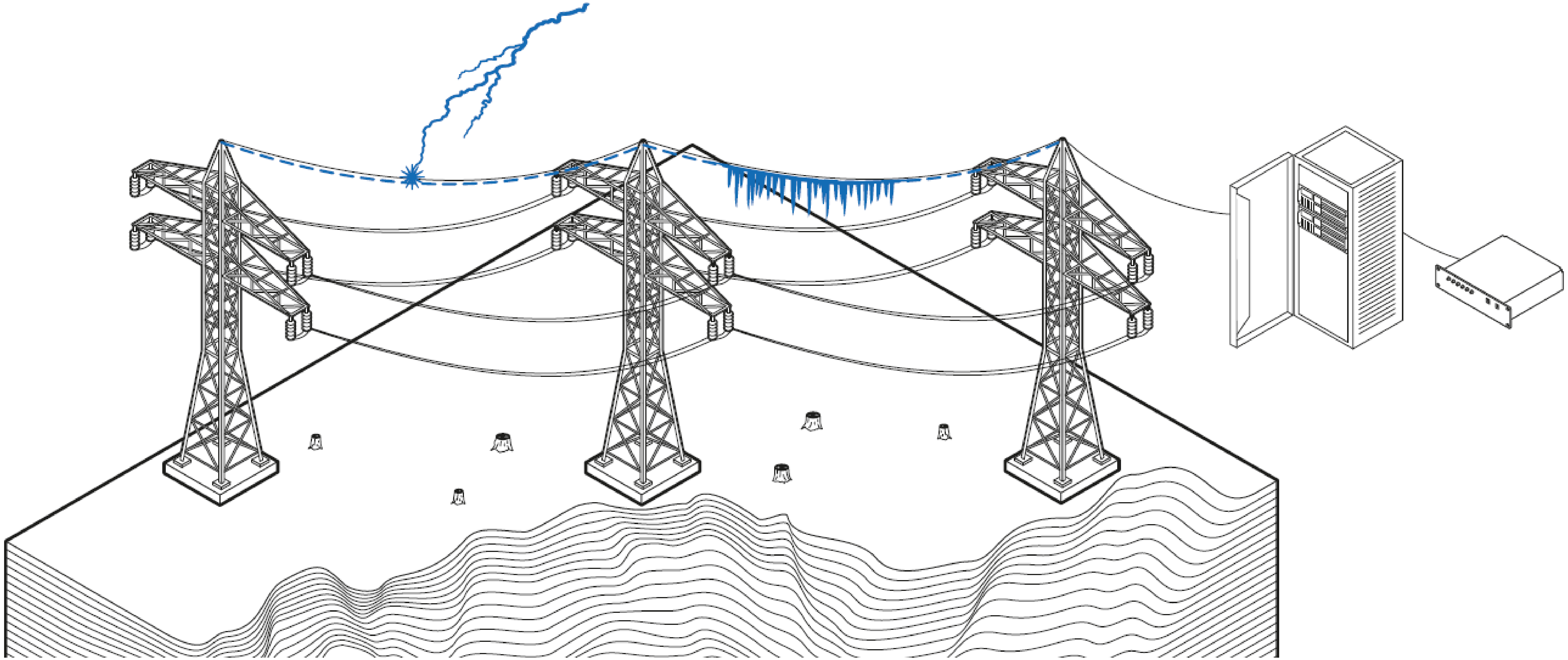
Available distributed sensing options – Distributed Pressure Sensing (DPS)

- Very new and fast evolving technology
- Some demonstration projects
- Expect more in the future – "The one to watch"
  — For lightning detection?

Fiber optic sensing applied –

Electric utility specific

Here are some applications which are using optical cables as distributed sensors for high-voltage lines



Fiber optic sensing applied –

Electric utility specific - aerial

	Monitoring	Sensing Technology			Type of cable			Type of system
		DTS	DAS	DSS	OPGW	OPPC	ADSS/ Lashed	
1	Detection of short-circuit points in the high-voltage line	-	+	-	+	+	-	T
2	Detection of lightning strike points	-	+	-	+	-	+	T
3	Detection and monitoring of phase conductor temperature	+	+	+	-	+	-	W
4	Detection and monitoring of icing occurrence	-	-	+	+	+	+	W
5	Control of condition of high-voltage line insulators	-	+	-	+	+	+	T
6	Detection of activity near the high-voltage line	-	+	-	+	+	+	W
7	Temperature control during ice melting on ground wire (Extreme cold locations)	+	+	+	+	-	-	W

- Warning (W). The system warns about a potential emergency and allows to take timely measures for its prevention;
- Troubleshooting (T). The system identifies the emergency location, reducing time and material expenditures to detect failures.

Fiber optic sensing applied –

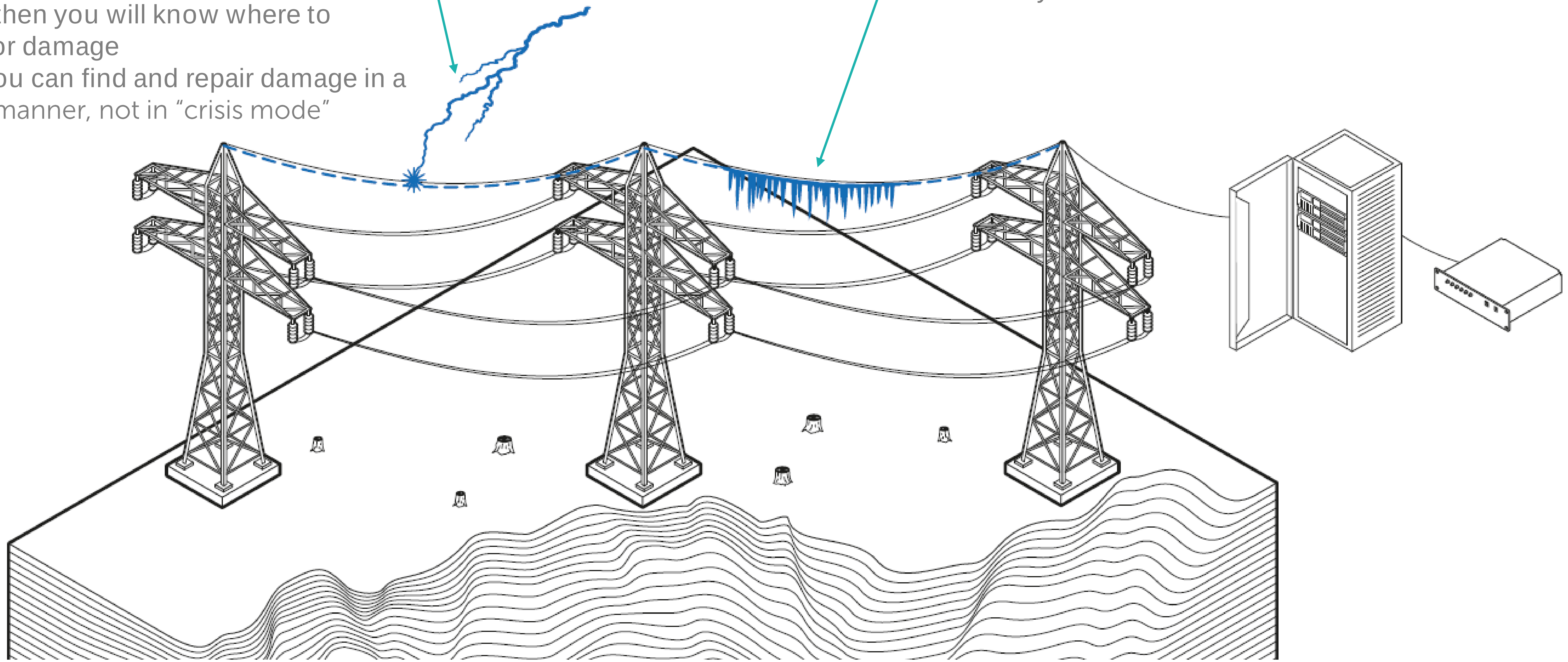
Electric utility specific – definitely can do!

Detecting lightning strikes

— If a failure, then can pinpoint the exact location
— If not, then you will know where to inspect for damage
➔ You can find and repair damage in a planned manner, not in "crisis mode"

Detecting ice loading

For information that clearances may have problems or that cable or structure failure may be imminent



Fiber optic sensing applied –

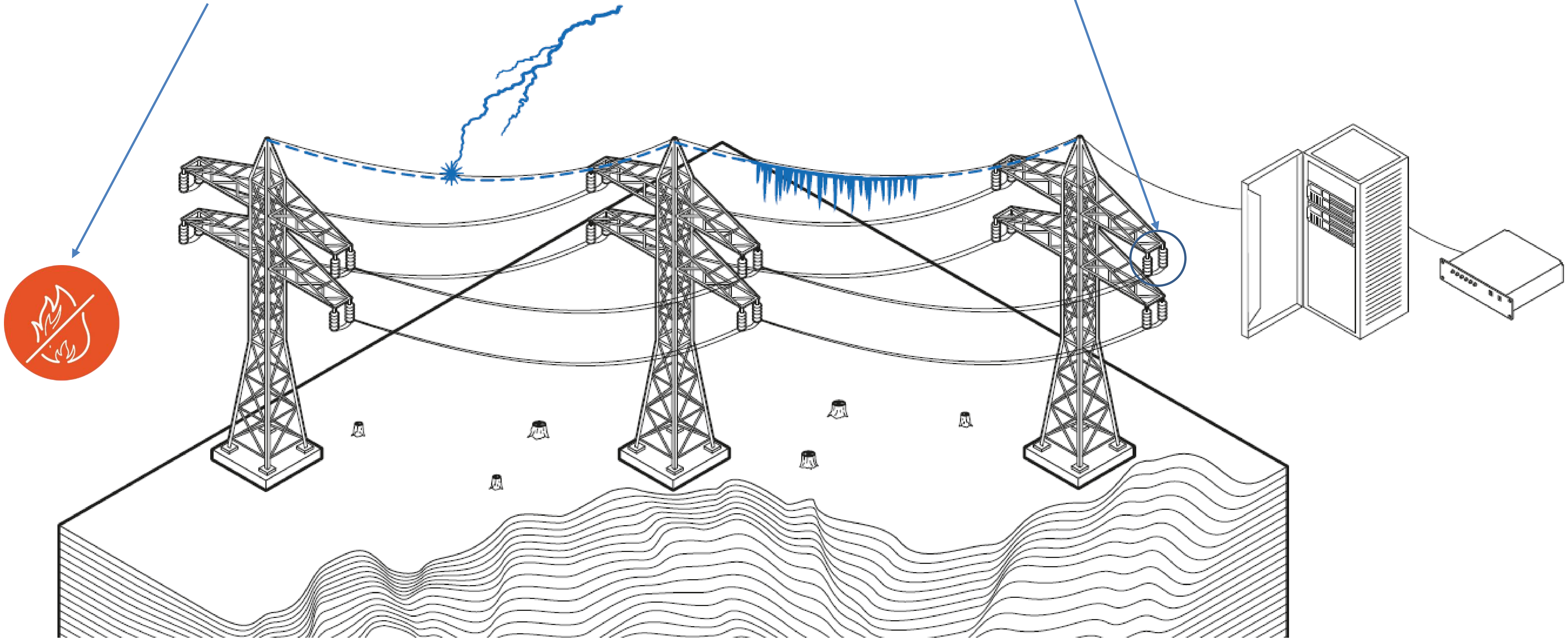
Electric utility specific – possibly can do

Detecting fires

- DTS = yes! ADSS, OPPC, OPGW
- DAS = maybe? Filtering out noise is the challenge

Detecting insulator problems?

By acoustic signature of corona discharge or similar, but again, filtering out noise is a challenge



Fiber optic sensing applied –

Electric utility specific – aerial examples

Testing lightning detection using DAS

Incab test set up

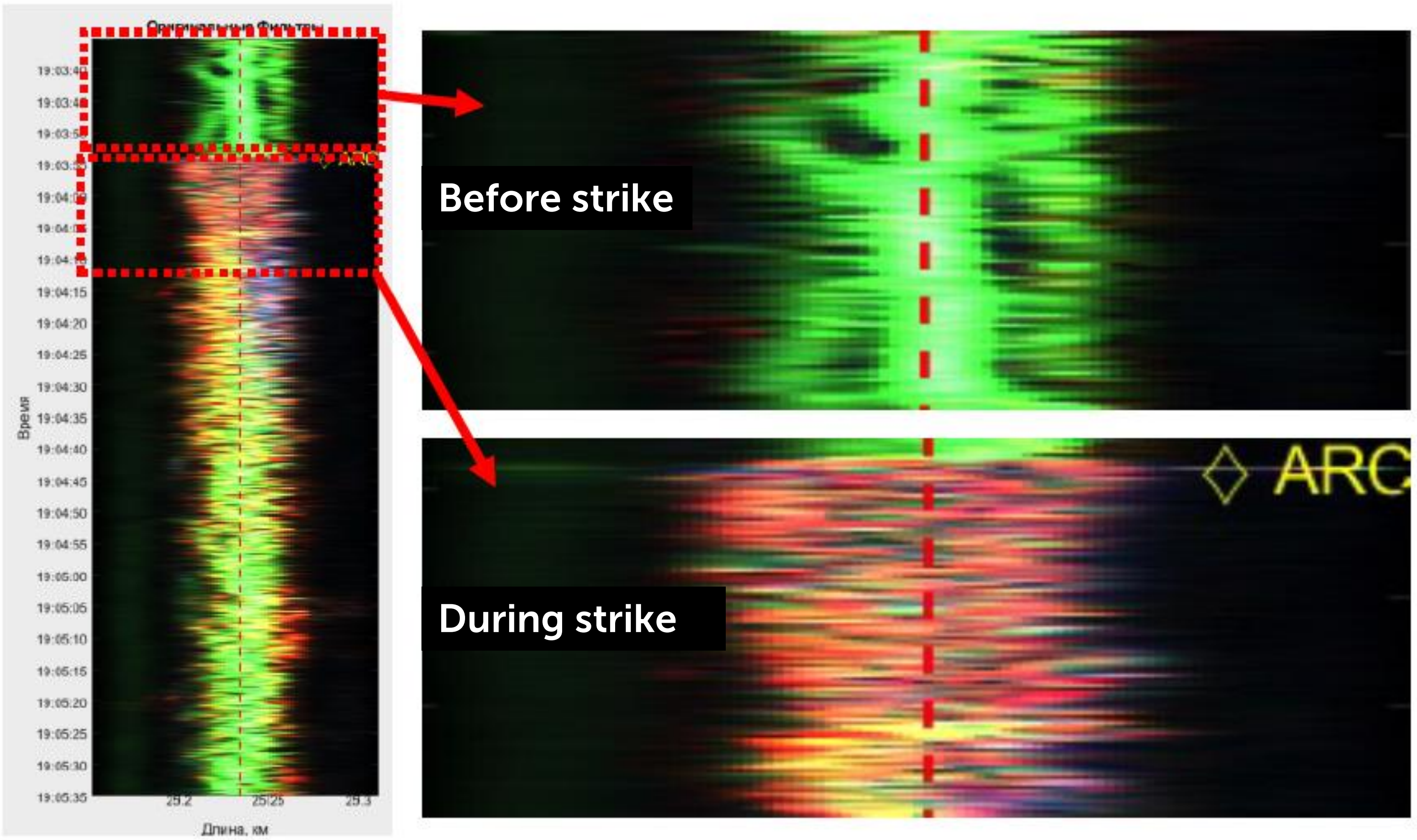
The lightning discharge was simulated by discharges with a duration of 0.25 sec and a total charge of 50 coulombs as well as with a duration of 0.40 sec and a total charge of 100 coulombs (≈ 200 amps current in both cases)

Fiber optic sensing applied –

Electric utility specific

Detecting lightning using DAS

How that looked



Returning to normal

Fiber optic sensing applied –

Electric utility specific – aerial examples

Detecting ice loading using OPGW (or OPPC or even ADSS)

Incab span test

- Used BOTDR implementation of DSS
- Weights used to simulate ice loading
- Observed that fiber elongation returned to normal after weights removed

Consider:
If you know the load on your OPGW, then you can closely estimate what it is on your phase conductors!

Fiber optic sensing applied –

Electric utility specific – aerial examples

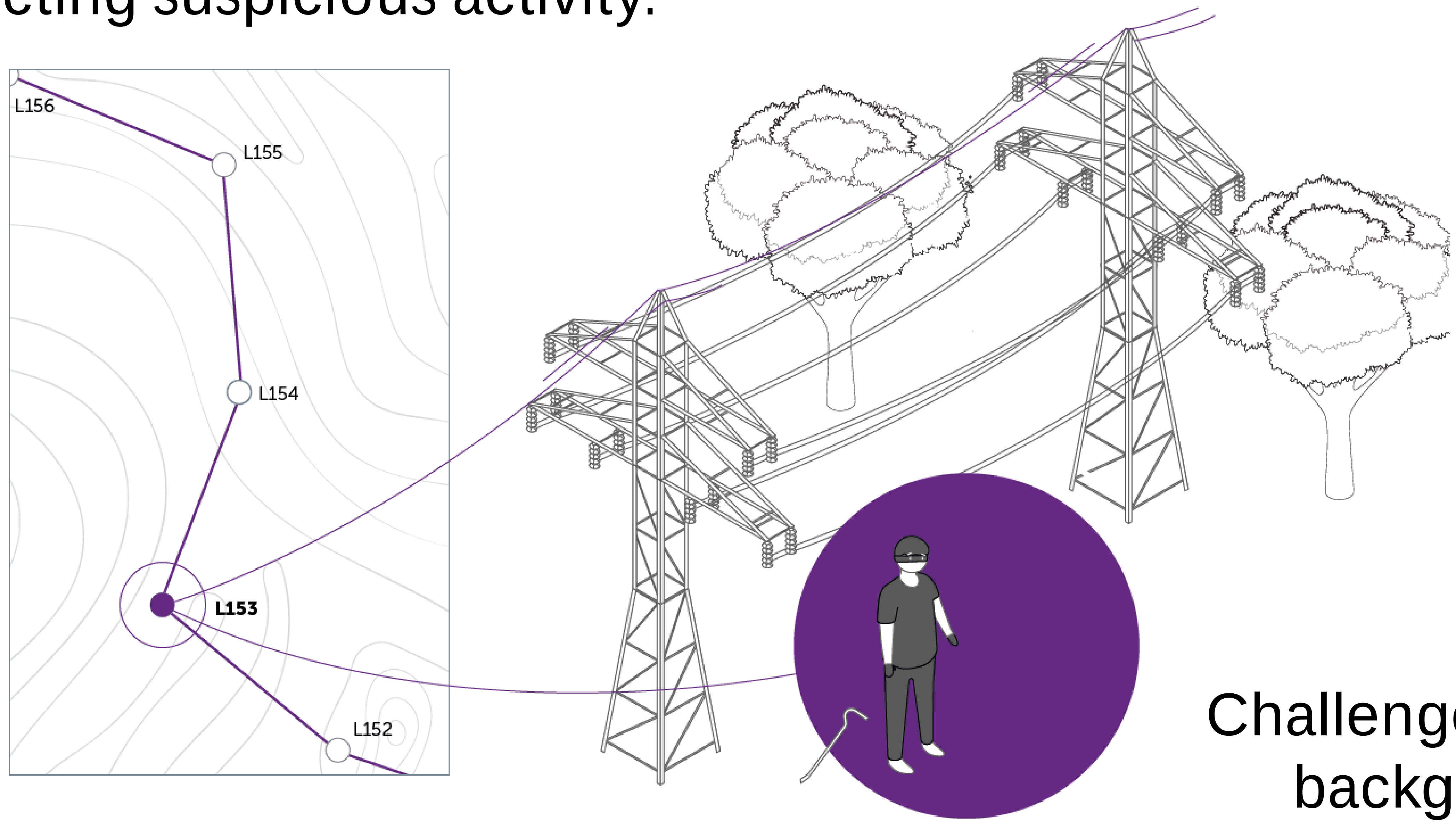
Detecting ice loading using OPGW (or OPPC or even ADSS)

How that looked

Fiber optic sensing applied –

Electric utility specific – aerial possibility

Detecting suspicious activity.



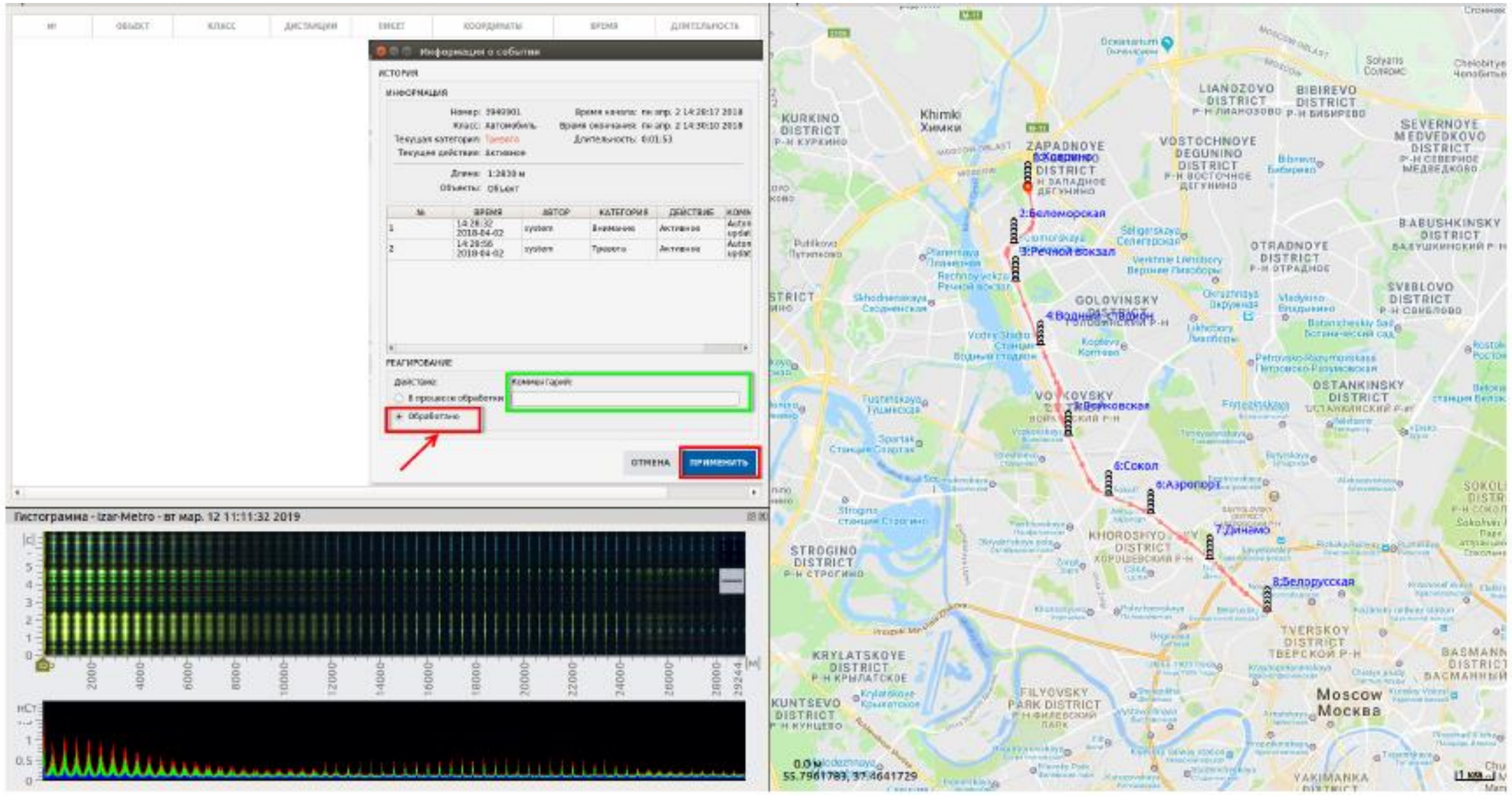
Challenge is filtering out background noise

Fiber optic sensing applied –

Electric utility specific – aerial possibility

Detecting suspicious activity.

How that might look

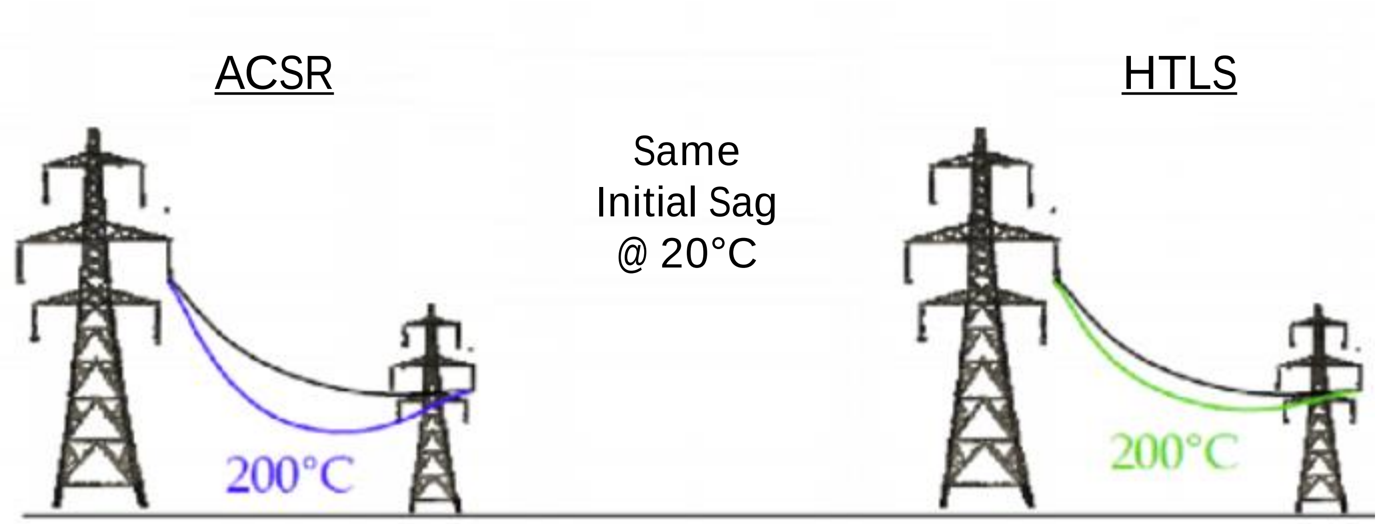


Fiber optic sensing applied –

Electric utility case study, Belgium 2021 Background

- Utilities around the world are trying to get more power down existing rights-of-way
  - The reasons can vary

- One option can be replacing conventional ACSR with "High Temperature Low Sag" type conductor
  - Less weight + higher strength + lower thermal expansion = less sag at a given temperature
  - Less sag = more amps possible
  - Ampacity increase can be up to 2x!



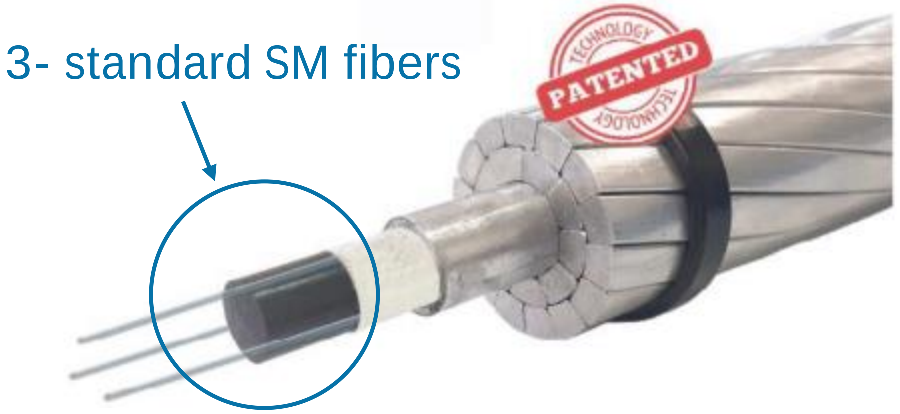
Thermal response of ACSR versus HTLS
Source: (Lancaster, 2011)

Fiber optic sensing applied –

Electric utility case study, Belgium 2021

Distributed Fiber Optic Sensing (DFOS) Monitoring system in a HTLS conductor

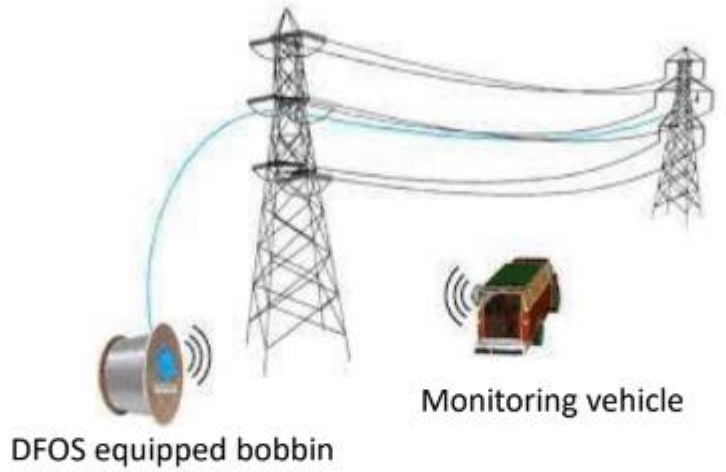
- HTLS conductor used is "Aluminum Conductor, Composite Single-Strand" (ACCS) type design
- Plus, integrated optical fibers to monitor temperature, strain, <u>bending</u>, vibration, and (maybe) more! ➔ ACCS-SENS
  - To ensure the cable is properly installed (Biggest killer of HTLS type conductor)
  - Three fibers is "just right" for this



Fiber optic sensing applied –

Electric utility case study, Belgium 2021 Pilot project completed, now rolling out

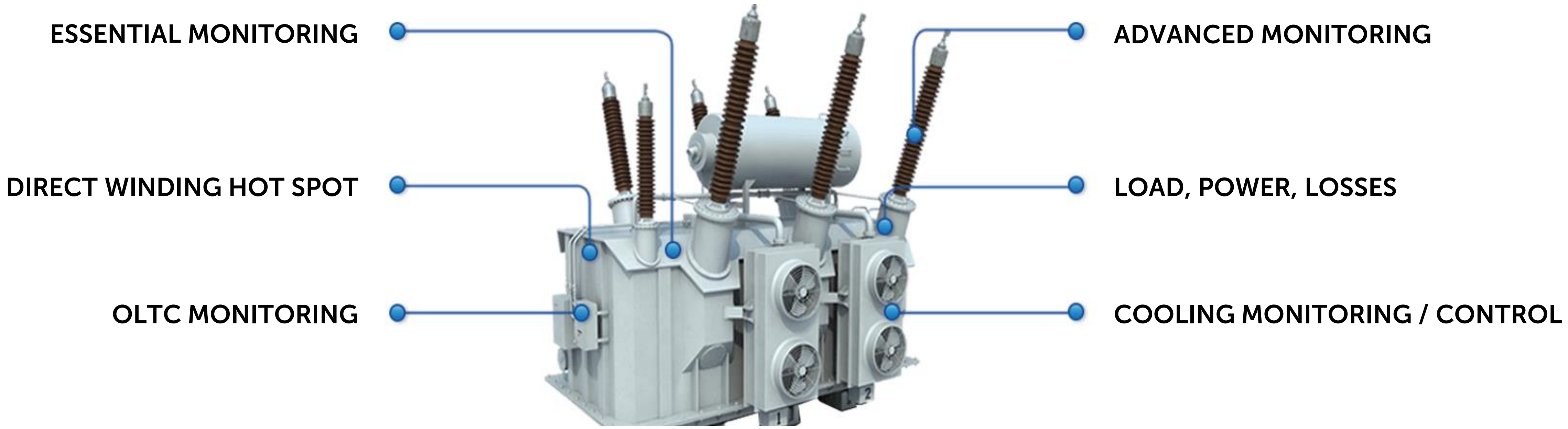
- Monitoring during installation
  - — Work underway to develop accessories (dead-ends) to allow monitoring during operation
- Two-year R&D and pilot project completed in April 2021
  - — By "Elia" (the Belgium national grid owner/operator), Wires&Bytes (our sister company), and DeAngeli Prodotti (Italy)
- Now continuing with 3,300 km planned over next 4 – 5 years



Fiber optic sensing applied –
Lastly, I nearly overlooked

Fiber optic sensing should also be part of your "Smart Grid" toolkit!
Consider that just at your substations, you can monitor

— Power Transformers. Look at these possibilities:



— You have similar options for monitoring your:
* Breakers
* Switchgear
* Reactors, etc.

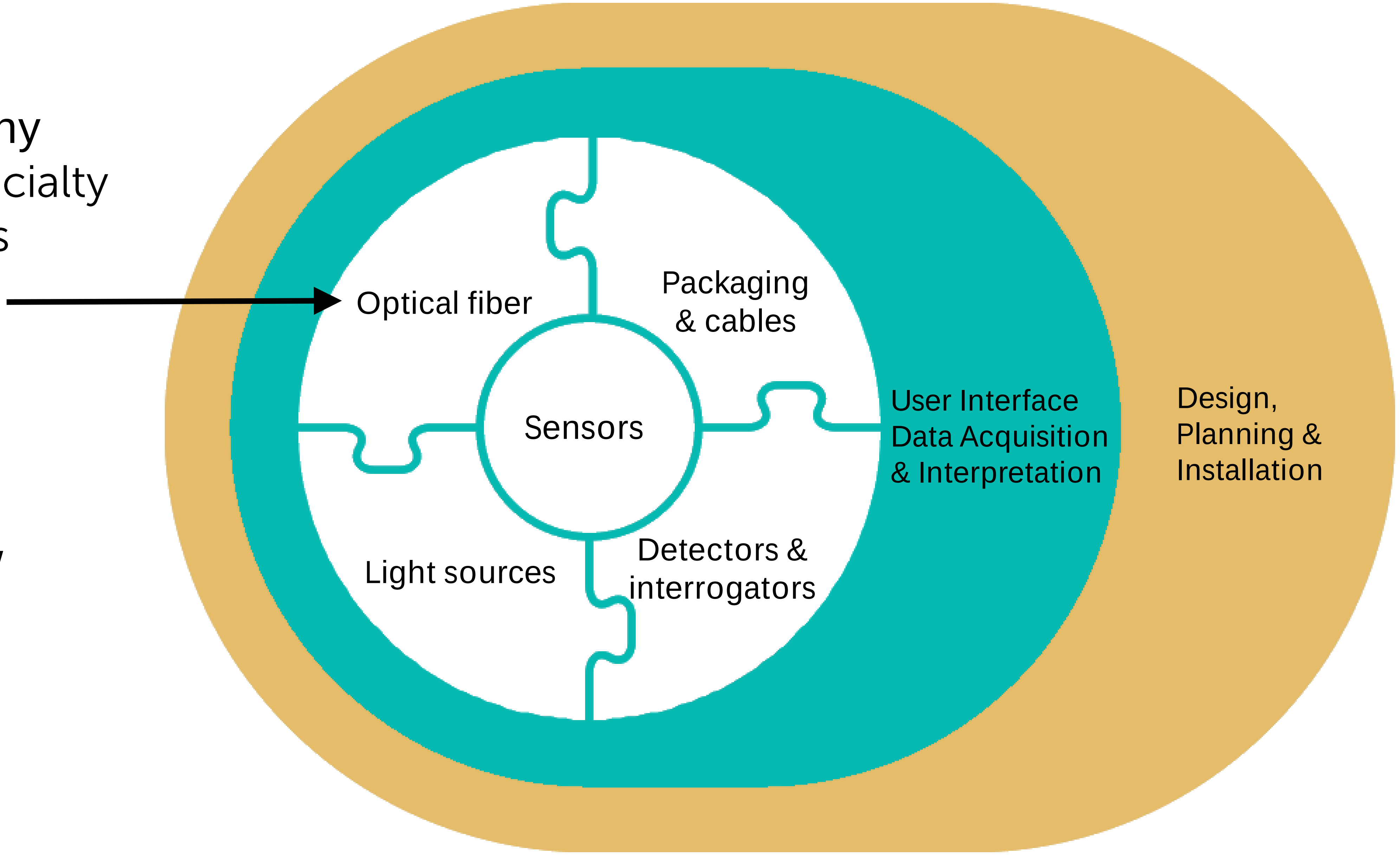
*Photo courtesy of Rugged Monitoring

Fiber optic sensing system

Key building blocks

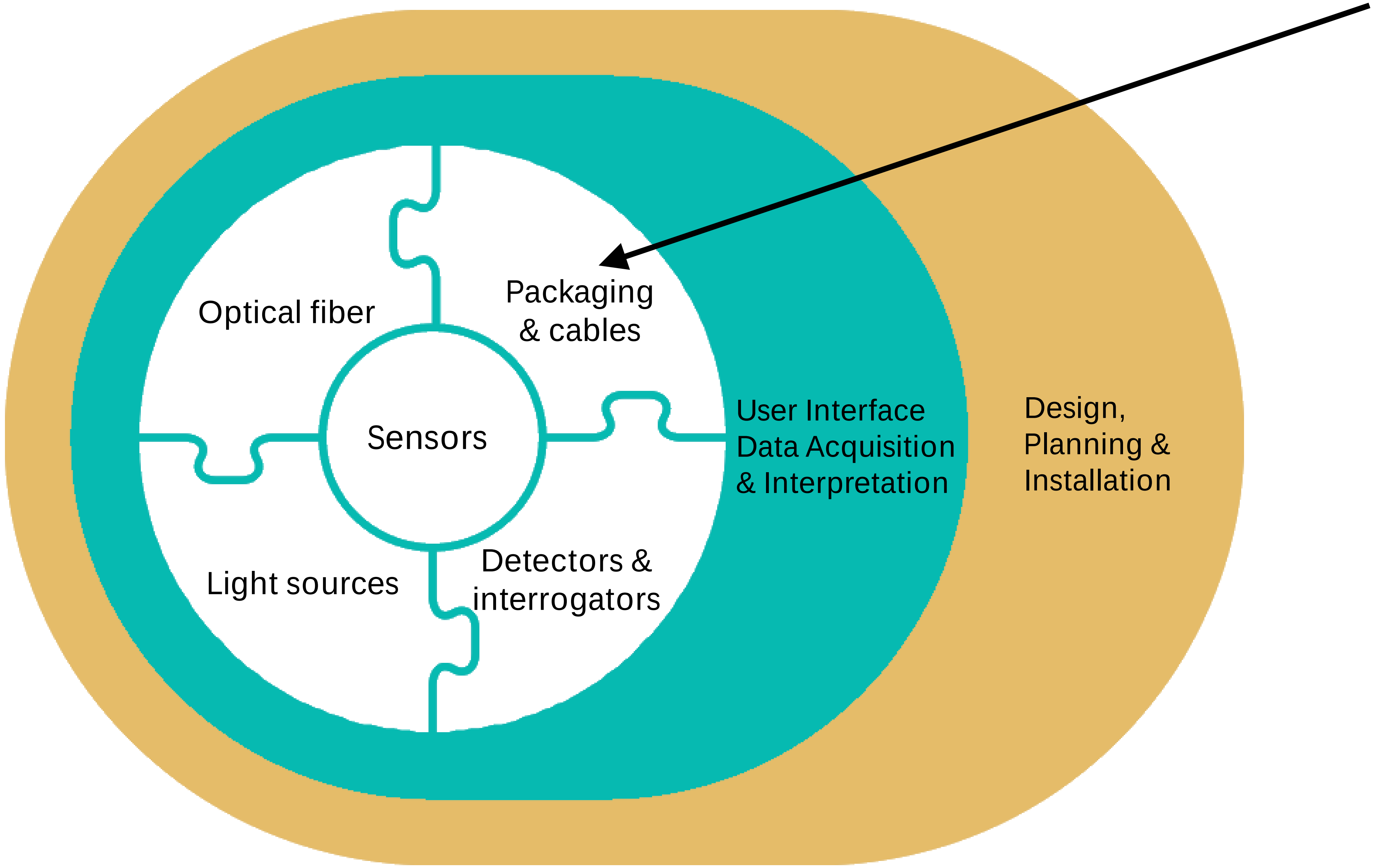
Standard fibers in many applications, but “Specialty Fibers” are sometimes necessary.

Examples:
— High temperature
— PMD maintaining
— Spun (high and low birefringence)



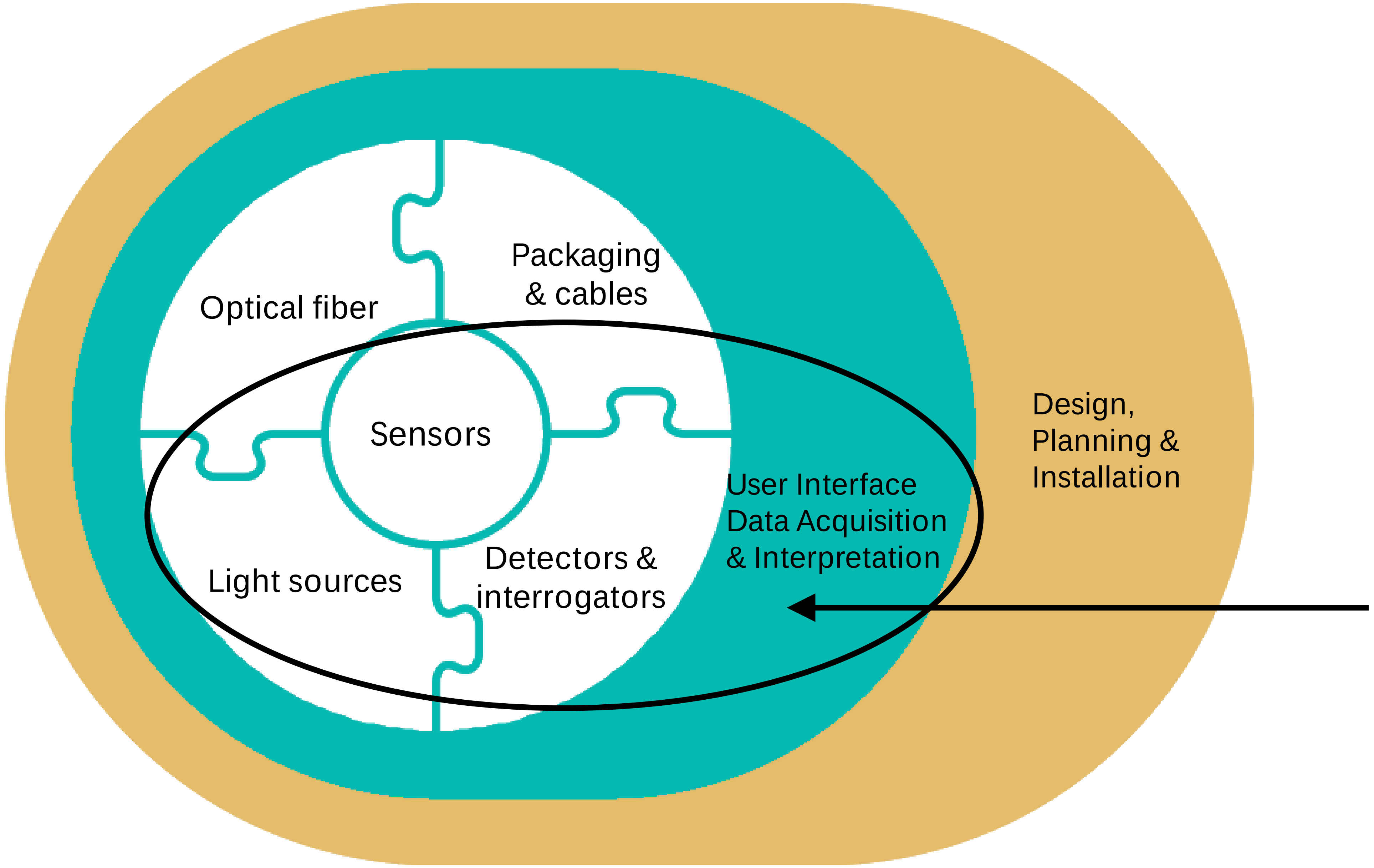
Fiber optic sensing system

Key building blocks



Fiber optic sensing system

Key building blocks

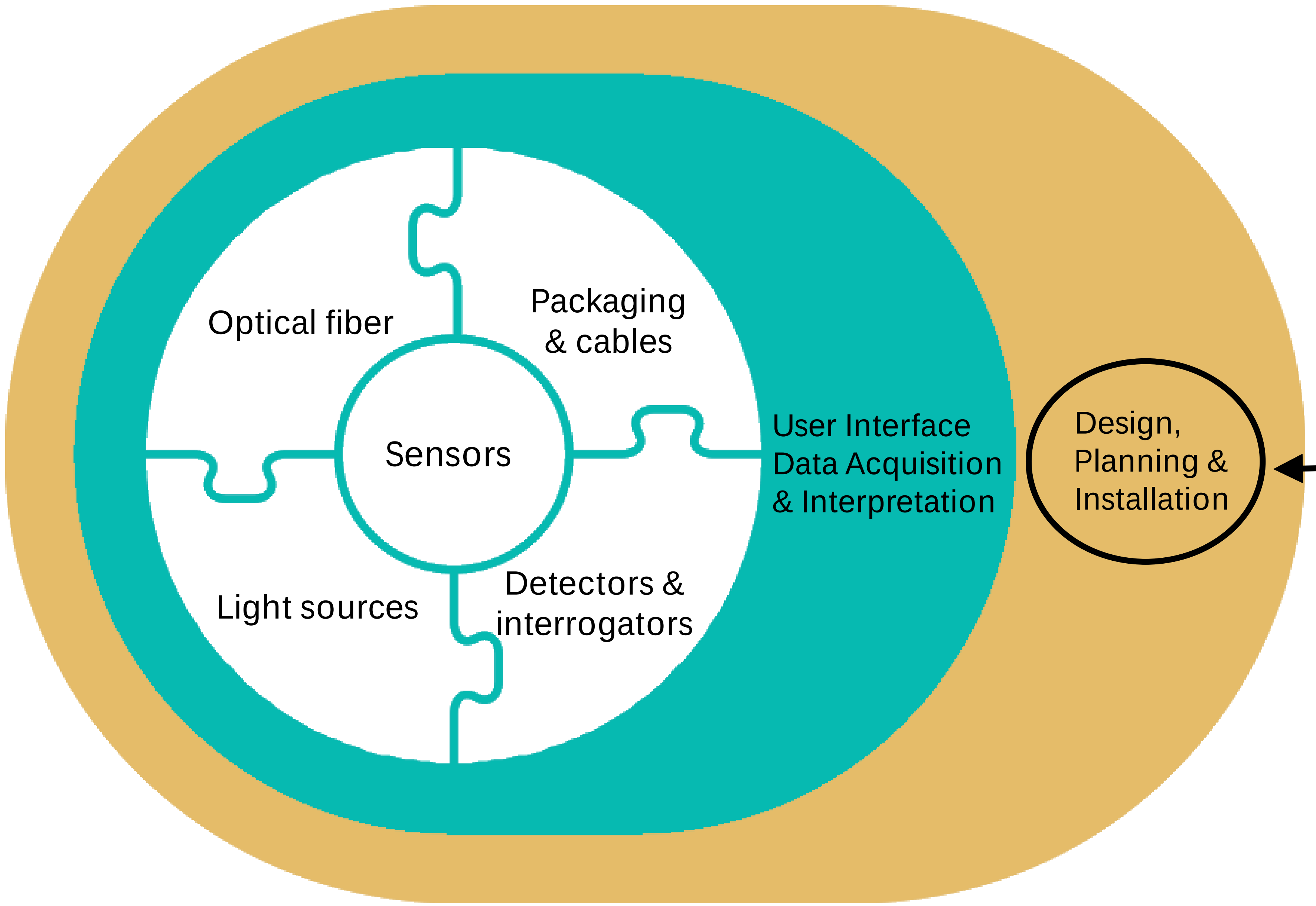


Specialized electronic suppliers.

We recommend: AP Sensing (www.apsensing.com)

Fiber optic sensing system

Key building blocks



Success requires a "Team Effort" between the end-user and the suppliers: Fiber, Cable, Electronics, and Installer

Thank you!

Mike Riddle
webinar@incabamerica.com

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