Co-funded by the European Union

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Northern EU Gateways project

Feasibility Study on Sensing Applications of a Subsea Fiber Optic Cable in the Arctic Ocean

Lead Contractor

Technical University of Denmark

Department of Electrical and Photonics Engineering

January 2024

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Executive summary

In this deliverable, a feasibility study on sensing applications of subsea fiber optic cables is provided. This is done in relation to Work Package 5 Task 3 Sensing Cable Technologies in the "Northern EU Gateways" project, co-funded by the European Commission under CEF Digital programme. The study completes the task and is conducted in the period from April to December 2023.

The study is based on input from a submarine cable vendor, general research literature, other similar sensing projects and consultations with relevant researchers and companies. As vendor Alcatel Submarine Networks (ASN) has been chosen, as ASN fulfills the initial requirements for consultancy and has relevant Climate Change SMART nodes in their product portfolio and roadmap. The inputs from the scientific communities have been received mainly through the 'Science Opportunities on Polar Connect' workshop, organized under the Northern EU Gateways project, with possibility for extensive dialogues and engaging discussions.

In the deliverable the following is investigated:

- Which fiber sensing technologies are relevant to Polar Connect and for Artic cable systems in general?
- What applications do current fiber sensing technologies offer?
- What future applications are requested by Arctic scientists?
- The feasibility of meeting the requests of the scientists by the capabilities of fiber optic sensors.

Polar Connect will be an unprecedented long-haul fiber optic link going through the Arctic from Europe to Asia. Today, it is possible to use fiber optic cables for sensing in addition to telecommunication. Since the Arctic Ocean is relatively unexplored due to its remoteness and extreme climate, and since studying the Arctic Ocean is important within climate research, applying fiber optic sensing on Polar Connect is a unique and unprecedented opportunity. Having reliable and continuous measurements in the Arctic is highly wished by scientists on Arctic research.

Numerous optical fiber sensing technologies are available today, but only a select few offer the required range of thousands of kilometers necessary for Polar Connect, including 1) forward transmission-based sensing, 2) repeatered distributed acoustic sensing (DAS), and 3) SMART point sensors as provided by Alcatel Submarine Networks (ASN). We assess that the most relevant options for Polar Connect are repeatered DAS and SMART sensing. DAS offers an array of densely packed sensors of medium sensitivity, while SMART offers widely separated sensors of high sensitivity. Both sensing technologies have many, but different, applications which are all relevant to scientists doing Arctic research. The applications include, but are not limited to, monitoring of whales, earthquakes, ocean currents, sea temperature and sea level rise.

Deploying optical fiber in the Arctic is challenging. That is, the deployment ship requires escort of one or more icebreakers (of which only a few exist in the world) to move through the thick ice. The same challenges are present for ships doing repair operations on the Polar Connect cable. In addition, both repeatered DAS and SMART sensing are technologies which are still under development by ASN and have not yet been field tested. Both technologies have still only been tested in laboratories. Applying those non-mature technologies to Polar Connect may cause risks due to the challenges of deployment and repair operations.

Four scenarios are defined as a guide for the next phases of the deployment process. These four scenarios span from no sensing, via self-monitoring to combined use of repeatered DAS and SMART CC point sensors. For each scenario the requirements in terms of fiber usage, qualitative cost estimations and risk are briefly assessed. In scenarios including repeatered DAS or point sensors, it is highly recommended to closely observe deployments of similar systems in less extreme environments before deploying in the harsh Arctic conditions. Including point sensors is the only feasible way to measure temperature variations with accuracy as requested by the ocean sciences. The same ocean sciences request measurement of salinity, which is not included in the presented point sensor version.

While the current point sensor technologies allow for a few dedicated sensor types, the science communities have shown interest for a future where the cable system could be a more generic enabler for external sensors supported by Underwater Autonomous Vehicles (UAV) measuring e.g., salinity in the water column. Such SMART++ future is briefly touched.

In conclusion, applying sensing on Polar Connect is a big opportunity for scientists doing Arctic research. The most relevant technologies are repeatered DAS and SMART which cover many of the requests wished by the scientists. Applying sensing with the described technologies is ambitious, difficult and potentially associated with risks. However, the current deployment visions for Polar Connect allow time for field testing and improving/maturing the technologies.

It is therefore recommended to collect experiences from upcoming deployments in less hostile environments in addition to closely observing the available set of sensors for the SMART nodes to suit the scientific requirements. Applying sensing capabilities will be a major step forward for the scientific disciplines and the scientific exploration of the Arctic.

1 Polar Connect – Connecting Europe and Asia

In an era marked by a data explosion across research and education sectors, Polar Connect emerges as a transformative initiative driven by the Nordic national research and education networks (NRENs). Recognizing the escalating demand for efficient data infrastructures, Polar Connect not only addresses the capacity needs of existing intercontinental collaborations but also pioneers innovative collaboration models, supporting the ongoing digital transformation. This initiative is strategically positioned to harness the Arctic route from Europe to Asia and North America, unlocking new realms of connectivity and resilience.

The collaboration explores groundbreaking initiatives, envisioning the establishment of the first submarine cable system between Europe, Asia, and North America through the Arctic Ocean. The Arctic region, devoid of submarine cable systems thus far, offers a unique opportunity to significantly enhance connectivity resilience.

Figure 1. Visualization of the possible routes of the Far North Fiber (yellow) and the Polar Connect fiber (green).

European involvement in these initiatives is pivotal for strengthening digital autonomy. Polar Connect positions itself as a strategic investment in fundamental digital infrastructure, fostering regional development in the Nordics and Northern Europe. Beyond enhancing digital resilience, these cables bring sustainability benefits, tapping into the ample renewable energy resources of the Nordic countries. The initiative not only promotes the efficient hosting of data centers in the North but also aligns with the growing demand for renewable, low-carbon energy in Europe. The emphasis on moving consumption closer to energy production points toward improved efficiency and sustainability.

While Polar Connect envisions a groundbreaking submarine cable system through the Arctic, the region poses unique challenges, particularly in the realms of power availability and cabling infrastructure. The harsh Arctic environment, characterized by extreme temperatures and remote locations, presents obstacles to ensuring a reliable power supply for submarine cabling systems.

Apart from digital resiliency and shortest communication path between Northern Europe and Asia, the fiber optics also allows for sensing applications where the submarine cable system can be used for measuring underwater activities, thus facilitating ocean, marine and seismic sciences.

Adding such fiber sensing will add to the power requirements in the harsh Arctic environment.

To navigate these challenges, Polar Connect is embarking on a comprehensive feasibility study. This study aims to identify and evaluate opportunities and obstacles in deploying sensing cable technology in the Arctic.

At the core of Polar Connect's mission is its commitment to advancing scientific exploration in the Arctic. The feasibility study extends its focus to assessing the impact of sensing cable technologies on scientific disciplines critical to the region's understanding and global significance. Specifically, the study will delve into the implications for climate change research, oceanography, and seismology, highlighting the potential contributions and advancements that sensing cable technology can bring to these fields.

As Polar Connect embarks on this feasibility study, it reaffirms its dedication to overcoming challenges, fostering innovation, and laying the groundwork for a resilient, interconnected Arctic that not only meets the demands of today but also paves the way for a sustainable and scientifically enriched future.

The feasibility study will delve into the technical feasibility of implementing sensing cable technologies in the Arctic environment.

1.1 Challenges of fiber sensing in the Arctic

Deploying an optical fiber link across the Arctic Ocean is a challenging and non-trivial task. Some identified difficulties are:

- Due to the thick ice sheet, one or more icebreakers are needed to escort the cable deployment ship. Today, only a few icebreakers in the world can move through the ice in the Arctic. The deployment operation may only be possible during the summer.
- The icebreakers are needed not only for deployment but also for repair/maintenance. Repair/maintenance may only be possible during summer.

- The response time from failure to repair may be very slow. Not only may the repair only be possible in the summer, but the icebreakers (of which only a few exist) also need to be available during that period. In addition, the cable will be far from human settlements, and the speed of the ships moving through the thick ice will be slow.
- Repairs are likely very expensive since the operation requires help from one or more icebreakers and since the operation is expected to be slow.

In addition to these points, one should also consider that only recently researchers have started employing optical fiber telecommunication networks for sensing purposes. That is, optical fiber links have been used for communication purposes for a long time, but sensing is new. Therefore, optical fiber sensing using telecom links cannot be regarded as mature as telecommunication itself. Using the Polar Connect cable for telecom purposes is an unprecedented project since a long-haul fiber link has never been deployed across the Arctic Ocean. Adding sensing to the fiber link makes only the project even more ambitious. As it shall be shown in this deliverable, many of the most promising fiber sensing technologies capable of sensing 1000s of km across lang-haul fiber links are still under development. This in combination with difficult deployment and difficult repair options make Polar Connect very ambitious and the associated risks have to be addressed. If the sensors for some reason fail or need adjustments, it may be very difficult, slow, and expensive to repair them in the remote and harsh conditions of the Arctic. While these are difficult conditions, it is expected that the maturity and development of the sensors and related technologies will evolve heavily in the coming years before the final deployment plans are laid out. Thus, they are considered ambitious yet realistic.

1.2 Report structure

In this deliverable, the current state-of-the-art subsea optical fiber sensing technologies which are relevant to Polar Connect are investigated. This covers both the engineering aspects of optical fiber sensors, possible applications, and discussions of the feasibility of applying sensing in the Arctic. The deliverable is structured as follows:

- In Section 2, different fiber optic sensing techniques which are relevant to the Polar Connect project are introduced. The focus is on OTDR sensing (Raman, Brillouin, DAS), transmission sensing (interferometric, polarization), and SMART sensing. The section addresses the engineering aspects of sensing technologies.
- In Section 3, the focus is on the applications of the relevant fiber optic sensing techniques. These include application studies done in the past which are relevant to the Polar Connect project.
- Section 4 deals with the requests and requirements from the scientific community for a sensing cable in the Arctic region. In particular, the requirements from the scientific communities of marine biology, geology/seismology, and oceanography are highlighted.
- In Section 5, the Polar Connect project is compared to other existing subsea fiber optic sensing projects.
- In Section 6, the feasibility of sensing in the Arctic is assessed. This is done by comparing the requests from scientists to the current capabilities of fiber optic sensors. Several realistic

solutions are presented as part of some scenarios for fiber optic sensor systems on Polar Connect, ranging from scenario 0 (no sensing) to scenario 4 (full-fledged sensing system). A short risk assessment follows for the relevant sensing technologies.

- In Section 7, a couple of visionary pointers for enabling the cable system as a platform for scientific research are provided. While these are far from deployable technologies, they are included to pave the way for future road mapping.
- Section 8 concludes the deliverable.

2 Fiber Optic Sensing Techniques

This section is focused on the utilization of fiber optic sensing (FOS) techniques. The sensors primarily employ optical fiber as the sensing medium. Nevertheless, consideration is also given to point sensors where the fiber functions solely as a communication medium for data transmission and reception from the sensor. The point sensor under review within this report is the Alcatel Point Sensor, recognized as SMART sensors.

In this report the terms Fiber Optic Sensing and Fiber Sensing are used arbitrarily.

In all sensing techniques utilizing the fiber as the sensing medium, laser light, typically at a wavelength of 1550 nm, is injected into the end of the fiber. Subsequently, the sensor readings are conducted either on the light transmitted through the fiber or on the light reflected from the fiber.

Changes in temperature, strain, twist etc. affect the physical properties of the fiber. This alters the refractive index, which is an essential parameter governing the behavior of light within the fiber. Such external perturbations and consequently altered properties of the fiber modify the characteristics of the light propagating within it, encompassing changes in phase, amplitude, state-of-polarization, or frequency, which are all detectable.

For sensing employing optical fiber as the sensing medium, there exist a vast amount of sensing techniques, of which the most relevant will be elaborated in subsequent sections.

Two main categories of fiber optic sensing exist:

- Sensors detecting the light *transmitted* through the fiber.
- Sensors detecting the light *backscattered* from the fiber.

Each of these sensor groups comes with its own set of advantages and drawbacks. For sensors using back-scattered light, the spatial resolution, or the smallest detectable change, is typically in the order of meters. In other words, it is in principle possible to distinguish or resolve between multiple relatively closely spaced objects or features providing a higher resolution and thus more detailed sensing.

For sensors using transmitted light, the fiber lacks spatial resolution, resulting in a resolution equivalent to the fiber's length. While this can be utilized for detecting that something is happening, it is not suitable for locating where on the fiber length it is happening.

On the other hand, sensors utilizing backward scattered light are usually constrained within a range of <200 km, whereas sensors utilizing forward propagating light can sense over distances equal to the length of the entire optical link (>10,000 km). The forward sensing of transmitted light can often be combined with data transmission.

These distinct sensing techniques will be elaborated upon in subsequent sections for a better understanding.

2.1 Sensors using the back-scattered light.

The principle of sensors using the back-scattered light is as shown in Figure 2. An interrogator launches laser pulses into the fiber and precisely measures the properties of the backscattered light, including its intensity and phase. By analyzing the changes in these properties, the interrogator can detect and locate various events such as sound waves, vibrations, or any disturbances affecting the fiber.

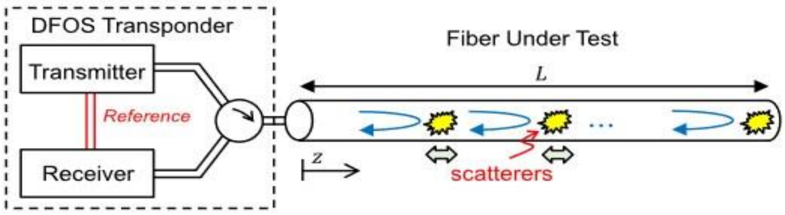

Figure 2: A generic setup of a distributed fiber optics sensor (DFOS). A DFOS transponder (interrogator) launches a pulse into the fiber under test. Scattering mechanisms along the fiber results in back-reflected light which is detected by the transponder. Source [1].

The backscattering is due to either Rayleigh scattering, Raman scattering or Brillouin scattering. These three types of scattering arise from different physical phenomena, where Rayleigh scattering is a linear scattering phenomenon, and where Raman and Brillouin scattering are non-linear scattering phenomena as illustrated in Figure 4.

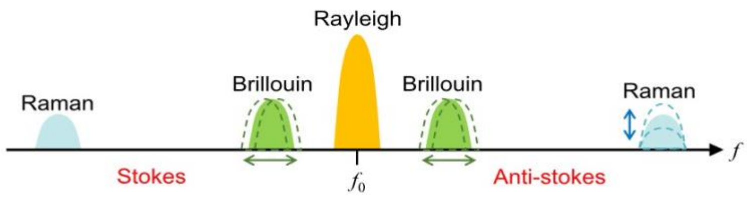

Figure 3: The different scattering types which can be applied for OTDR sensing, Rayleigh, Brillouin, and Raman. f_0 is the frequency of the input light pulse, and f is the frequency of the scattered light. Source: [1]

The principle is like a one-dimensional radar with the medium of propagation being the optical fiber. Since the properties of the back-scattered light (phase, amplitude, state-of-polarization, frequency) depend on the properties of the fiber, e.g., the refractive index, perturbations to the refractive index of the fiber can be measured. The refractive index depends on both temperature and strain, and thus these effects can be measured. A general review article on these sensing techniques is found in [1]. An example of an interrogator for DAS is provide in Figure 4.

Figure 4: An example of a DAS interrogator unit. Similar interrogator units are used for Brillouin and Raman OTDR. Source: ASN.

In this report, the focus is on sensors employing optical time domain reflectometry (OTDR) as opposed to optical frequency domain reflectometry (OFDR). OTDR uses time-based analysis, measuring reflected light to locate faults in fiber, offering a snapshot of events. OFDR relies on frequency shifts in reflected light, providing high-resolution, continuous measurements along the entire fiber for precise distributed sensing applications.

This is done, since OFDR typically only offers ranges <1 km, whereas OTDR offers ranges of <200 km. The latter, with the ranges offered by OTDR, is preferred for sensing applications as discussed in this project. The OTDR principle is shown in Figure 5.

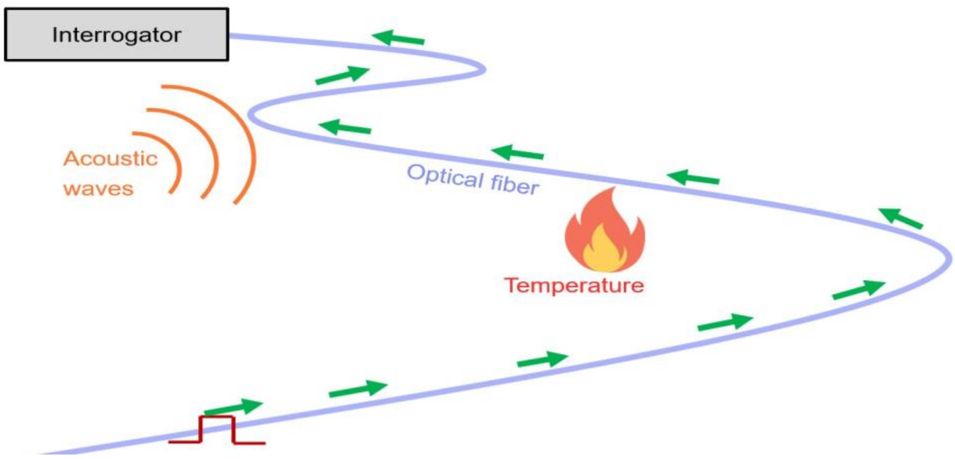

Figure 5: A sketch of the OTDR principle, where the properties of the backscattered light (green) depend on temperature and strain/vibrations. Adapted from https://www.epfl.ch/labs/gfo/page-60916-en-html/page-61501-en-html/

For many of the applications discussed, the sensing of acoustic waves arising from e.g., earthquakes, ships, whales, swells, sea currents. To measure these, a fast sensor is needed, and among the presented techniques, only the Rayleigh based sensor is suitable.

To measure the slowly varying temperature (over several minutes/hours) along the optical fiber, the Raman or Brillouin based sensors are suitable. In this case, the Brillouin based sensor is especially suitable since it offers the longest reach. The three types of sensors will be briefly elaborated in the coming sections. It should be noted, however, that once the fiber optic cable is installed, all the sensing techniques can be applied. That is, none of the techniques (Rayleigh OTDR, Brillouin OTDR or Raman OTDR) require special optical fibers, they all just need the same standard single mode optical fibers, as is also normally used for telecommunication. If the end of the optical fiber can be easily accessed, the sensing units can be installed and uninstalled easily.

It should also be noted that the sensing reach of FOS depends on the location of the first optical isolator. Since optical isolators block light from propagating backwards, they will effectively blind the sensor. Optical isolators are often installed in Erbium optical amplifiers (EDFA) which are located along a fiber optical communication link as part of the repeaters. That is, if the first optical isolator is located within the first 100 km of the optical fiber link, the reach of the FOS will be limited. The sensors using Rayleigh, Brillouin, and Raman OTDR are compared later in Table 1.

2.1.1 Rayleigh OTDR (DAS)

Rayleigh optical time domain reflectometry (OTDR) is a sensing principle based on Rayleigh back-scattering of an optical pulse launched into the end of the fiber. As the pulse propagates in the fiber, Rayleigh back-scattering occurs at all positions along the fiber. The backscattered light is detected at the end of the fiber, and by signal-processing it is possible to detect the phase of the light which contains information of the temperature and strain along the fiber.

A Rayleigh OTDR is often denoted distributed acoustic sensor (DAS). The name comes from the fact that the sensor can measure acoustic waves. That is, acoustic waves will make the fiber vibrate, and the vibrations translate into strain in the fiber which can be detected. Acoustic waves up to the kHz regime can be detected with a spatial resolution of ∼10 m and a maximum reach of approx. 150 km. Essentially, this means that the DAS sensor is an array of microphones located every 10 m along the entire reach of 150 km (resulting in an array of approx. 15,000 microphones).

2.1.1.1 Repeatered DAS

The main range limitation stems from the repeater spacing and the desired resolution. The repeaters (EDFA type) typically include isolators allowing light only in the forward direction, and without amplification in the backward direction the sensing light becomes too weak. Thus, a limiting factor is the amount of optical power that can be received from long distances.

In research literature, the longest reach demonstrated for DAS without using amplifiers is 171 km[2]. However, currently research is being done on increasing the length by inserting amplifiers along the fiber modified for dedicated DAS applications.

Raman amplifiers are another type of amplifiers where isolation is not generally needed. With inline Raman amplification and no isolators, DAS with a range of >1000 km has been demonstrated [3]. With inline bi-directional Erbium doped fiber amplifiers, DAS with a range of 300 km was experimentally demonstrated in [4] along with numerical simulations predicting that the system could be extended to 2500 km. However, for both of the systems [3], [4] the sampling frequency is determined by the total link length, meaning that the increased length comes with the disadvantages of lower bandwidth and sensitivity.

In addition, Alcatel Submarine Systems (ASN) is working on a repeatered DAS system where the standard telecommunication repeaters (Erbium amplifiers) are slightly modified, enabling amplification along the fiber, see Figure 6. In this configuration, the sampling frequency is determined by the repeater span length (and not the total link length). In the laboratory, ASN has demonstrated 1000's of km of repeatered DAS system with acoustic sensing of kHz bandwidth and sensitivity similar to non-repeatered DAS interrogation directly on a 100 km long fiber. One repeatered DAS unit can be placed on each side of the sensing fiber, such that the range of a repeatered DAS system needs to be half of the total link length for full coverage. Remark that using this sensing principle, all DAS interrogators are located on land, and thus no extra electronics (other than repeaters) need to be in the wet. It is important to note that the repeatered DAS operates on a dedicated fiber pair and thus is independent from the telecom fibers of the system.

However, all the repeatered DAS systems mentioned in this section are still only preliminary studies, and more studies and field trials need to follow up to mature the technologies. It is expected, though, that the repeatered DAS will be mature for deployment before fiber deployment.

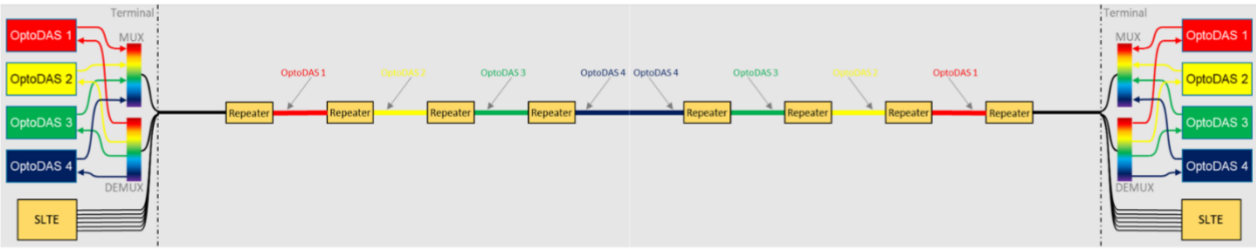

Figure 6: Sketch of the repeatered DAS system currently under development by ASN. Multiple DAS interrogators (named OptoDAS) are wavelength division multiplexed using into a fiber pair, where all the interrogators use different frequency channels for sensing on different sections of the fiber. A repeatered DAS system can be applied to each end of the fiber. Source: ASN.

As briefly described above, the reason why the optical amplifiers installed in conventional optical communication links cannot be employed for DAS is that the amplifiers contain optical isolators which block back-scattered light from propagating backwards. The sensing range of DAS is therefore limited by the position of first EDFA which is typically in the order of 50-100 km. For amplifiers to be useful for DAS, they must not contain isolators.

2.1.2 Brillouin OTDR

Brillouin optical time domain reflectometry (Brillouin OTDR) is a sensing principle based on Brillouin back-scattering of an optical pulse launched into the end of the fiber. The sensing mechanism has many similarities to Rayleigh OTDR, except that the physical scattering mechanisms are different. As the pulse propagates in the fiber, spontaneous Brillouin backscattering occurs at all positions along the fiber. The back-scattered light is detected at the end of the fiber, and by signal-processing it is possible to detect the frequency of the light which contains information of the temperature and strain along the fiber. Brillouin OTDR has a reach which is like that of Rayleigh OTDR, approximately 100 km, in addition to a similar spatial resolution, approx. 10 m. However, the measurement time for Brillouin OTDR is much longer (in the order of minutes), meaning that the sampling rate is in mHz (as opposed to kHz for Rayleigh OTDR). Therefore, Brillouin OTDR cannot be used for acoustic sensing. Instead, Brillouin OTDR has the advantage of measuring slowly varying temperature or strain variations for which it outperforms Rayleigh OTDR. The accuracy is typically in the order of 1 K.

As for Rayleigh OTDR, the reach of Brillouin OTDR is limited by the loss of optical fibers. By using remotely pumped amplification, the reach of Brillouin OTDR can be extended up to approx. 250 km as shown in preliminary studies [5]. Using locally pumped amplifiers, the reach can likely be extended much more (as shown with repeatered DAS), but this is still to be investigated. Similar to what was discussed for Rayleigh OTDR, Brillouin OTDR cannot use amplifiers with optical isolators.

2.1.3 Raman OTDR

Raman optical time domain reflectometry (Raman OTDR) is a sensing principle based on Raman back-scattering of an optical pulsed launched into the end of the fiber. An optical pulse with a wavelength of 1550 nm is launched into the end of the fiber, generating Raman backward scattering along the propagation. Based on the optical power of the Raman backscattering (ratio of Stokes and anti-Stokes powers), the temperature of the optical fiber can be determined with an accuracy in the order of 1 degree K.

In contrast to Rayleigh and Brillouin OTDR, Raman OTDR is not sensitive to strain, making the measurements sensitive to only temperature. That makes Raman OTDR preferable or a supplement for applications where it is hard for Rayleigh and Brillouin OTDR to distinguish between temperature and strain. The sensing range of Raman OTDR is <30 km, ultimately limited by the loss of optical fibers. The sensing range is lower than for other OTDR principles since Raman scattering is relatively weaker than Brillouin and Rayleigh scattering. The range can possibly be extended using amplifiers, but more research would be needed to showcase this. The spatial resolution of Raman OTDR is approx. 10 m.

2.2 Sensors using the transmitted light.

In this section, we elaborate on Fiber Optic Sensing using the transmitted light in the optical fiber, i.e. the forwarding propagating light. The advantage of this group of sensors is that the range is >10,000 km, which is much longer than what is readily possible with sensing techniques based on the back-scattered light. However, forward sensing does not provide the same possibility of resolving the fiber into segments as e.g., DAS. In addition, the sensitivity of forward sensing is expected to be very low compared to DAS since much noise is accumulated during the transmission of the light. Forward sensing is still in the early research stage, with the first (to the best of our knowledge) publication on the topic published in 2018[6]. Since then, a few other publications have followed up[7]–[9]. Forward sensing has been proved using two different sensing techniques:

- A technique where the absolute phase of the transmitted light is detected (denoted as: interferometric).
- A technique where the state-of-polarization (SOP) of the transmitted light is detected (denoted as: polarization)

Forward sensing works using the already installed subsea telecom fibers with repeaters/amplifiers. Only small changes to the transmitter or receiver of the communication link are needed to enable forward sensing. Moreover, the sensing can be performed on fibers simultaneously with transmitting data, and therefore no dark fibers are needed.

In the following, the two difference forward sensing techniques are briefly described.

2.2.1 Interferometric sensor

The interferometric sensor is still on the early research level. It was first described in 2018[6], and since then only a few additional scientific papers have been published on the topic [7]. An ultra stable laser with low phase noise is needed for the measurement setup. The laser light is launched into a submarine optical fiber link and propagates back and forth in the optical fiber link via a connecting loop at the far end of the link. The phase of the light after propagation is measured using an interferometric measurement. The fiber link is a conventional communication fiber pair with Erbium-doped fiber amplifiers installed every 50-100 km, and thus no special sensing optical fiber link is needed. The communication link can be in the order of 10,000 km. For the sensing, some spectrum of the communication link needs to be dedicated to the measurement.

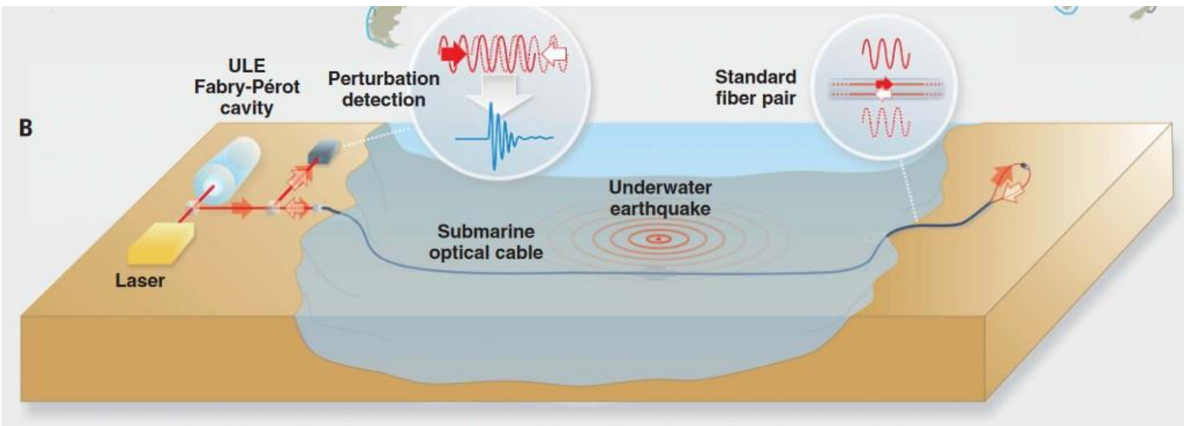

Figure 7: Setup of the interferometric sensor. Source [6].

The sensor can detect phase changes of the propagated light. The phase changes can be due to e.g. vibrations of the fiber caused by earthquakes. The first generation of the sensor provided no information on which part of the fiber that causes a phase change, and thus the sensor is not spatially resolvable[6]. However, the last generation of the sensor provided a spatial resolution given by the spacing between the repeaters in the optical link (typically 50-100 km), which was demonstrated on 5860 km submarine cable from Southport, UK, to Halifax, Canada[7]. The spatial resolution was made possible with the aid of high-loss loopback (HLLB) installed in the repeaters. Details from this study is further addressed in Section 3.3.

2.2.2 Polarization

Using the state-of-polarization (SOP) for sensing is a new technique with only a few studies presented in literature, with the first studies being presented in 2021[8], [9]. However, the sensing principle has some advantages which make it worth mentioning in this report. In comparison with the forward interferometric sensor, the SOP sensor does not need an ultra-low phase noise laser. Instead, it has been demonstrated to work with a standard telecom grade laser. The SOP sensor has been used to sense vibrations from earthquakes. However, so far localization has not been demonstrated using the SOP sensor, and thus only accumulated vibrations of the whole fiber can be sensed.

2.3 Summary of the fiber-based sensors.

It is worth summarizing the fiber-based sensors before addressing the point sensors from ASN in the following section.

- What the sensors in the former subsections have in common is that they employ fiber as the sensing medium. This contrasts with the point sensors (SMART) to be presented in the next subsection where the fiber is only used as a communication channel.
- Conventional OTDR-based sensing offers medium sensitivity, high spatial resolution (~10 m) and many well-proven applications, but it has the downside of limited range due to the loss in the optical fibers. Therefore, repeatered versions of OTDR using optical amplifiers are needed for sensing on long cables (>150 km) such as submarine cable systems.
- Forward transmission-based sensors based on polarization or phase/interferometric are another class of sensors which can readily cover 1000s of km fiber but comes with the downside of low sensitivity and limited spatial resolution in the range of 50 - 100 km. In addition, forward transmission-based sensing is still in the early research stage.
- Although fiber-based sensors have many applications, they do not have sufficient sensitivity for specific applications. For example, measuring temperatures with mK accuracy or measuring sea levels with cm accuracy is not possible with fiber-based sensors. For such sensitivities, dedicated point sensors (SMART) are needed.
- Fiber-based sensors respond only to mechanical vibrations and temperature variations. Measuring other parameters, for example chemical parameters such as water salinity, will not be possible using conventional fiber-based sensing principles.

2.4 Point sensors from ASN (SMART)

In this section, the SMART sensors from Alcatel Submarine Networks (ASN) are described. The information provided in this section is largely based on a system description which ASN has provided as a part of the studies done for this report. The ASN system description is protected under a non-disclosure agreement, and therefore this section only provides a summary of the most important information which is not confidential.

The Science Monitoring And Reliability Telecommunications (SMART) network[10] is a system provided by Alcatel Submarine Networks (ASN). The ASN SMART product has been designed in accordance with the definition work conducted by the SMART joint task force (JTF) group. The JTF group is led by 3 major UN agencies and has participation of scientific institutes and suppliers[10]. The SMART network is a fiber communication link with attached Climate Change (CC) nodes. The CC nodes are points sensors which are connected to the fiber. An illustration of a CC node attached to the optical fiber cable is shown in Figure 8. Each CC node contains in the current version four sensors for scientific research as follows (with some of the key parameters from the data sheets provided):

- Thermometer.
  - Accuracy: 2 mK accuracy.
  - Drift: 2 mK/year.
  - Sampling rate: 1 Hz.
- Pressure sensor.
  - Accuracy: < 1 cm (and possibly better).
  - Drift: < 10 mm/year (assuming the Node is equipped with recalibration option to account for drift).
  - Sampling rate: 1 Hz.
- Accelerometer.
  - Configuration: 3-axis
  - Sensitivity: 5 V/g
  - Bandwidth: 0.1-200 Hz
- Seismometer.
  - Configuration: 3-axis
  - Sensitivity: >700 V/m/s
  - Bandwidth: 120 s – 100 Hz

The SMART network and the CC-nodes are still in the development phase with the product qualification expected in 2025. Thus, no field trials have been performed so far, but the first SMART projects are planned in 2025/2026 in the Atlantic, South Pacific and Asia. Although no field trials have been completed so far, the SMART system is based on conventional optical fiber communication infrastructure which is a well-tested technology. Reusing many components from conventional communication link lowers the risks of the SMART system.

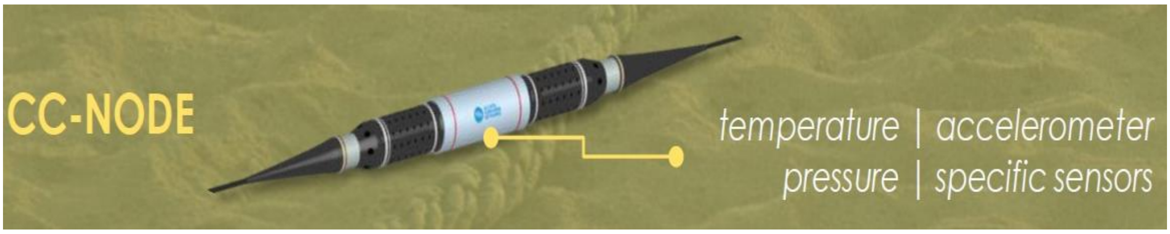

Figure 8: Illustration of the CC node provided by ASN. Source: ASN.

2.4.1 Hardware description of SMART

The CC node is built using a mechanical housing like a conventional and well-tested repeater for optical communication. Only minor modifications are made compared to conventional repeater housing. The node contains all parts which are necessary for sensing and communication. Some of the sensors can stay inside the housing (seismometer, accelerometer), while the other sensors (thermometer, pressure sensors) need to be in contact with water outside the housing. With the high accuracy of the thermometer (2 mK), the CC-node design must ensure that heat dissipation from the repeaters and other electronics inside the housing do not disturb the temperature measurements of the sea water.

The CC-nodes can be deployed to depths of up to 6,000 m. The minimum distance between two CC-nodes can be reduced to a minimum of 7 times the water depth, with the lower bound being due to constraints for repair operations. The nodes can be placed at a geographical coordinate with an uncertainty of 5-10 % of the water depth, meaning that for 2000 m water depth the uncertainty will be approximately 100-200 m.

The communication principle of the SMART network is shown in Figure 9.

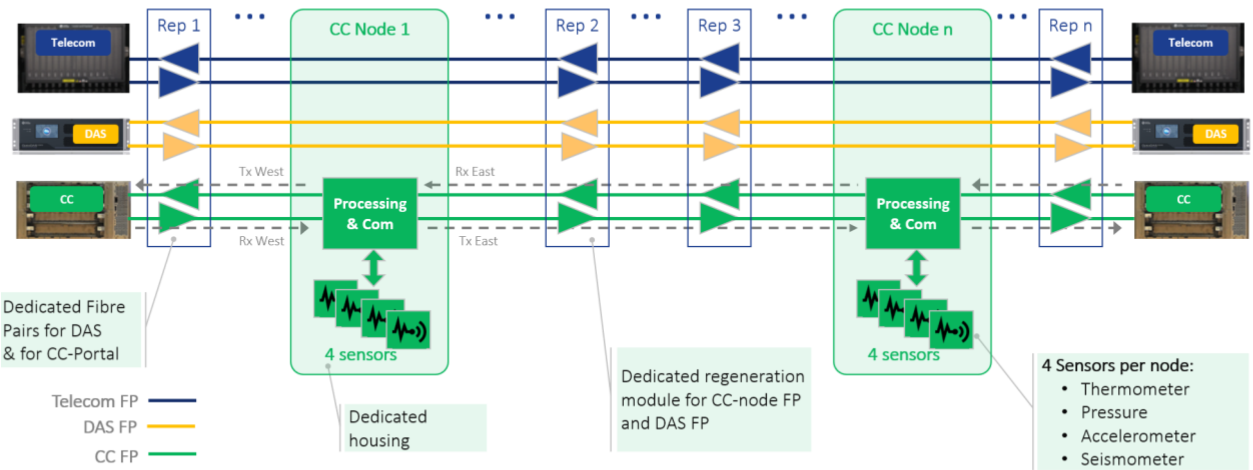

Figure 9: Communication principle of the SMART network. Note that this diagram also includes fiber pairs for repeatered DAS, which is optional. Source: ASN.

Power to the CC-nodes is provided from the same copper wire in the cable which supplies the repeaters. Extra power needs to be supplied to the CC-nodes in addition to the power needed for the repeaters. The necessary power depends on the cable length as most of the power is dissipated as loss in the copper wire, but the power consumed by each CC-node is expected to be similar to a repeater.

For repair and maintenance of CC-nodes, routine repair procedures from telecom repeater reparation can be followed. However, in the remote Arctic Ocean full of thick ice, the repair of telecom repeaters and CC-nodes may more challenging, slower, and more expensive, as the repair in addition to cable-laying vehicles also need typically two icebreakers for extensive ice management.

It is important to note that the telecom fibers and the sensing fiber pair are well separated in this system. It is also important that the repeaters and CC-nodes are not co-existing as heat dissipation from the repeaters in principle can influence the temperature measurements in the CC-nodes.

As also shown from Figure 9, the SMART sensing solution from ASN can co-exist with a repeatered DAS system.

2.4.2 Applications of sensing with SMART

Some of the possible applications of the CC-nodes are earthquake detection (accelerometer), ocean wave measurements (pressure sensor), sea water currents (temperature and pressure sensors), sea level rise (pressure sensor), sea bottom temperatures and sea bottom movements (accelerometer, pressure sensor)[10]. However, as the sensors are currently under development and not yet put into operation, the actual sensor performances still need to be investigated in real deployment scenarios.

2.4.3 Comparison of SMART to other sensing solutions

As compared to non-repeatered DAS and interferometric/polarization sensing, the SMART network requires more special hardware/fibers installed in the cable and is probably a more expensive solution. Compared to repeatered DAS, the hardware requirements and cost are expected to be very similar. The hardware requirements of SMART include: a dedicated fiber pair, repeaters, CC-nodes, a power line, and cable landing stations including transceivers and data processing hardware. On the other hand, the SMART sensors are expected to provide high sensitivity, and therefore they are more suitable for measuring accurately. Examples include sea level rise and sea bottom temperatures which require high accuracy measurements of pressure and temperature.

2.5 Comparison of sensing technologies

The sensors discussed in this section are summarized and compared in Table 1.

	Raman	Brillouin	Rayleigh (DAS)	Phase	Polarization	Point sensor (SMART by ASN)
Technique	Backward OTDR			Forward transmission sensing		Point sensors
Acoustic measurements?	No		Yes			
Temperature measurements?	Yes (~1K accuracy)		Only relative changes.	Not known		Yes (~2 mK accuracy)
Range	<30 km	<100 km	<150 km (repeatered DAS: >2000 km)	>10,000 km		
Sensitivity	Medium			Low		High
Spatial resolution	~10 m			~50-100 km (span between repeaters)	None (integrated signal)	Point sensor (No. of locations limited to <200)
Fiber requirements	Dark fiber required.		Non-invasive co-existence with data transmission[3], [11]. (Repeatered DAS: Dedicated fiber pair required)	Spectral band required	No impact on data channels.	Dedicated fiber pair required.
Equipment requirements	A single Interrogator unit (For repeatered DAS, additional hardware is needed: Several interrogators, repeaters, larger data processing infrastructure)			Ultra-stable laser source	Software update of transceivers	CC nodes. Power delivery. Communication hardware.
Sensor maturity	Commercially available (repeatered DAS under development)			Early research stage		In product development phase.
Applications	Measurements of slowly varying temperature or strain.		Sea vessel detection. Earthquake/seismic detection. Storm detection. Swell detection. Whale sound detection. Cable threat monitoring.	Earthquake/seismic detection.		Temperature. Pressure. Seismic acceleration.
Relative cost	Low (repeatered DAS: High)			Low		High
References		[12], [13]	[14]–[21]	[6], [7], [22]	[8], [9]	[10]

Table 1: Comparison between the relevant sensing techniques for sensing on subsea fiber optic cables. Part of the table adapted from [23].

2.6 Data collection and management

The current study addresses the feasibility of fiber optic sensing and point sensing with e.g. ASN CC nodes (SMART). Although not detailed here, the sensing environment should also include land-based equipment for sensing data collection, data processing and management.

Following components and functionality should be considered for (repeatered) DAS and CC nodes:

- Data collection and preprocessing in DAS interrogators. This data should then be forwarded to a DAS server.

- Data collection from CC-nodes. The amount of data is not considered to be a challenge and they should be forwarded to a CC-node portal or similar.

For forward travelling methods like polarization or interferometric sensing, similar data collection and processing is needed at the fiber ends.

Further processing of the data and collection and correlation from several probing points might be conducted either on a cable landing site or in a remote/central location. Correlation of timestamps and forward travelling methods can be used for rough localization estimation.

While these are relevant points to consider in close collaboration with the consortium responsible for actual deployment, they are not considered to have an influential significance on the overall cost nor risk assessment. Hence, they are not addressed further in this context.

3 Existing applications of subsea fiber sensing

In this section, we address the applications of the fiber optic sensing techniques presented in the former sections. We focus on applications which have been documented in existing scientific literature, and we focus entirely on applications which are relevant to subsea optical fiber sensing.

3.1 Applications of Brillouin/Raman OTDR

For Brillouin OTDR, temperature and strain measurements with resolution of $\pm 1^{\circ}$C and $\pm 10\mu\epsilon$[1] are possible[12]. The sensor is often applied on subsea high voltage cables to monitor the temperature and strain along the cables. The strength of the Brillouin/Raman OTDR compared to Rayleigh OTDR, is that they are more suitable for measuring the absolute temperature/strain. Contrarily, Rayleigh OTDR (DAS) is suitable for measuring temperature/strain changes over a short time. Brillouin/Raman OTDR has many applications which are not relevant for sensing on the seabed, for example monitoring of bridges, rails, and pipelines. The authors of this report have not been able to find any studies on using Brillouin OTDR on existing fiber optic network cables, and therefore this application remains unexplored.

3.2 Applications of DAS

DAS is a well-tested technology with many proven applications. Some of the applications are sketched in Figure 10. The applications include, but are not limited to:

- Earthquake localization. There exists many studies of using DAS for detecting seismic events[14], [16], [20], [24], [25]. Using DAS, the wave fronts of the S- and P-waves from earthquakes of different magnitudes can be measured. DAS has also been employed to detect micro seismicity, coming for example from human activities such as mining or underground gas storage.
- Ocean current measurements. In [21] and [26], measurements of the ocean current velocities in respectively the Gibraltar strait and off the coast in southern France have been demonstrated.
- Sea level (tide), and swell sizes. In [25], the low frequency tidal waves with periods of 12 h or 24 h were studies using DAS off the coast in Japan. In [21], similar results were obtained from a cable in the Gibraltar strait.
- Whale sounds. In [20], [27], sounds from different baleen whales were measured using DAS on a cable in Svalbard.
- Storms. Waves generated by storms have been measured by DAS, as shown in[20], [21].

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[1] Strain (ε) is a measure for how much the fibre has been extended. Strain is calculated as ε = dL/L, where L is the length of a piece of fibre extended with dL.

- Ship positions and speeds. Using DAS on the acoustic noise generated from ships, it has been demonstrated that the trajectory and speed of ships can been determined[19], [20].
- Temperature. In [25], DAS was used to measure temperature changes on the ocean bottom off the coast of Japan. In this case, DAS can only be used to measure relative changes, while Raman or Brillouin OTDR is needed for measuring absolute temperatures.
- Marine sediment characterization. Using the information encoded in the phase fronts of seismic waves impinging an optical fiber cable on the bottom of the ocean (tomography), DAS has been used to characterize the sediment layers below the sea floor[28]. DAS has also been used in combination with air guns for subsurface imaging which could be relevant to CO_2 storage[29], [30].
- Cable threat monitoring. DAS is used for detection, localization and tracking of seabed activities like bottom trawling fishing, anchorage, dredging and other subsea operations within a corridor of ±3 km around the cable. This could in principle be used for warning vessels before accidentally damaging the cable infrastructure thus providing savings by reducing repair costs.

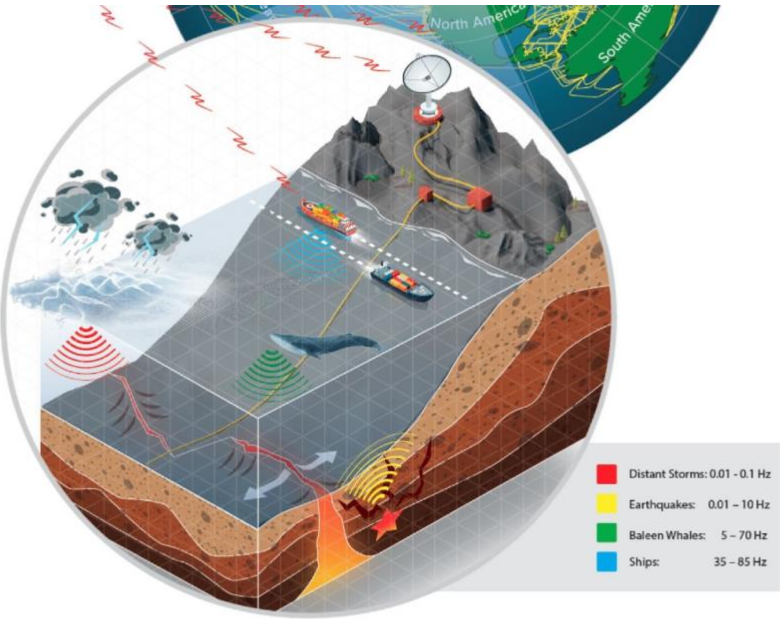

Figure 10: Conceptual drawing of the different applications of distributed acoustic sensing. Figure adapted from [20].

3.3 Applications of polarization/interferometric sensing

For forward transmission sensing using the techniques of state-of-polarization (SOP) and interferometry, only teleseismic waves from earthquakes have been measured so far. There are two main reasons why only strong earthquakes have been measured so far:

- The sensitivity of this type of sensor is relatively low.
- The sensors are still in the early research phase with the first study published in 2018[6].

In [7], researchers used the interferometric sensing on a fiber optic cable between Southport, UK, and Halifax, Canada. They were able to measure and localize earthquakes with magnitude M_w 7.5, see Figure 11b. A similar study was done using forward transmission based SOP sensing[8], where researchers used a 10,000 km subsea fiber optic link between Los Angeles, USA, and Valparaiso, Chile, to detect and localized earthquakes with magnitudes > M_w 4.4, see Figure 12.

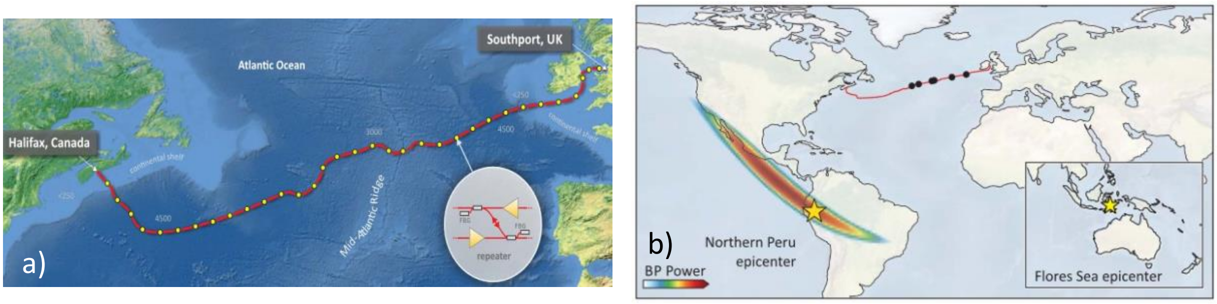

Figure 11: Results of the study [7] on forward transmission based interferometric sensing. In a) is shown the map of the fiber optic link which is used for the measurements. In b) are shown the measurement results, where it was possible to localize an earthquake in South America. Figure taken from [7].

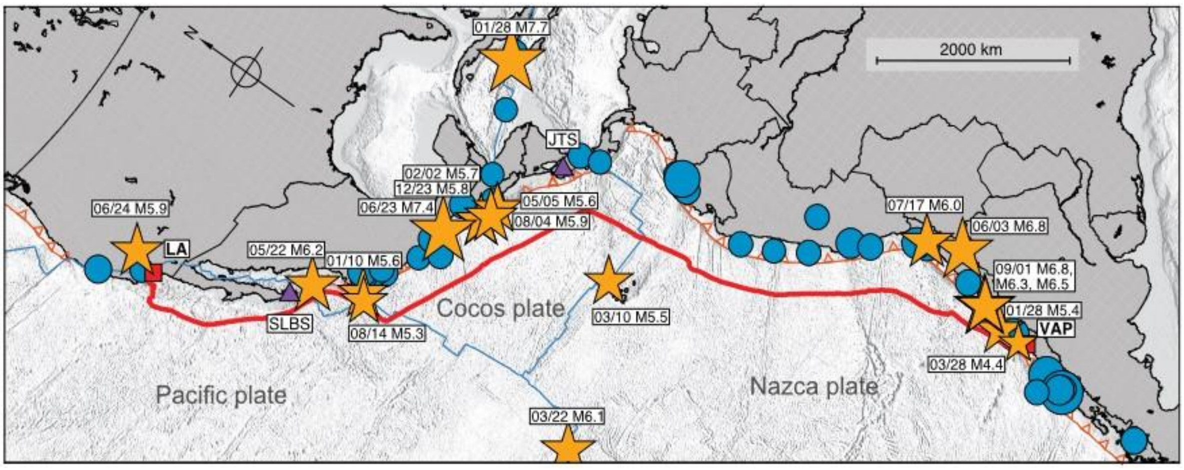

Figure 12: Results from the study [8] on forward transmission based polarization sensing. The fiber is shown in red; the blue dots show the history of earthquakes of Mw >7.5 since 1900, and the orange stars show the earthquakes detected with the sensor in the period Dec. 2019 to Sep. 2020. Figure taken from[8].

3.4 Applications of SMART sensing

The sensors available in the ASN SMART CC-nodes are thermometers, pressure sensors, accelerometers, and seismometers. The sensors are expected provide high sensitivity compared to DAS and polarization/interferometric sensing. The sensors are from the same technology and suppliers as existing systems such as “Deep-ocean Assessment and Reporting of Tsunamis”-buys (DART) or terrestrial seismic sensors, and therefore the performance of the CC-nodes are expected to reach the same level. However, the CC-nodes with integrated sensors are still to be tested in the field. Field tests are projected to start by 2025 on submarine cables in Portugal. As we shall see in Section 5, there exists similar projects to the ASN SMART sensors such as S-net in Japan and NEPTUNE in Canada. These projects can be used as a reference to assess the feasibility of such a sensor system.

3.5 Section summary

- For polarization/interferometric forward sensing, only strong earthquakes have been measured so far. However, since this sensing system works with existing communication fiber links, and since only small changes to the transceivers are needed for the sensing, this type of sensor is of low cost and low complexity compared to other sensor technologies.
- SMART sensing is a relatively complex and expensive sensor system, but it is expected that these sensors will have high sensitivity compared to the rest of the fiber sensor technologies. Therefore, SMART sensors possibly enable sensing of phenomena which the other fiber sensors do not offer. The SMART sensors are still in the development phase, and therefore it is difficult now to conclude on the performance and capabilities of these sensors.
- OTDR sensing, with DAS included here, is the most mature fiber sensor technology which is discussed in this report. DAS sensing with the reach of <150 km is considered mature, while long distance repeatered DAS sensing is still to be considered in the early research phase. Many field studies in the oceans have been conducted with DAS (non-repeatered), where applications include detection of sea mammals, earthquakes, ocean currents, storms, marine sediment characterization and cable threat monitoring.

4 Sensing as enabler for Arctic science and research

In this section it is discussed how Arctic researchers can benefit from sensing on the Polar Connect cable. That is, in previous sections of this report it was discussed what has already been demonstrated using fiber sensing. On the other hand, in this section the focus is on what climate researchers wish to sense using the Polar Connect cable. It is assessed whether the researcher's wishes are feasible using the current fiber sensor technology or the fiber sensor technology under development. Arctic researchers were gathered at the 'Science Opportunities on Polar Connect' workshop in Oslo, Norway, in October 2023, and much of the information provided in this section is what was presented at the workshop.

4.1 Geology/seismology

In seismology, the Arctic Ocean is still an unexplored region[31]. In the Arctic, it is of interest to study:

- Tectonics. Long term monitoring of the seismic activity in the Arctic will increase the knowledge of tectonic evolution.
- Sedimentary packages. Long term monitoring will also increase the knowledge of the dynamic interaction between sedimentary surface layers.
- Natural resources. Characterizing the sedimentary layers can reveal natural resources.

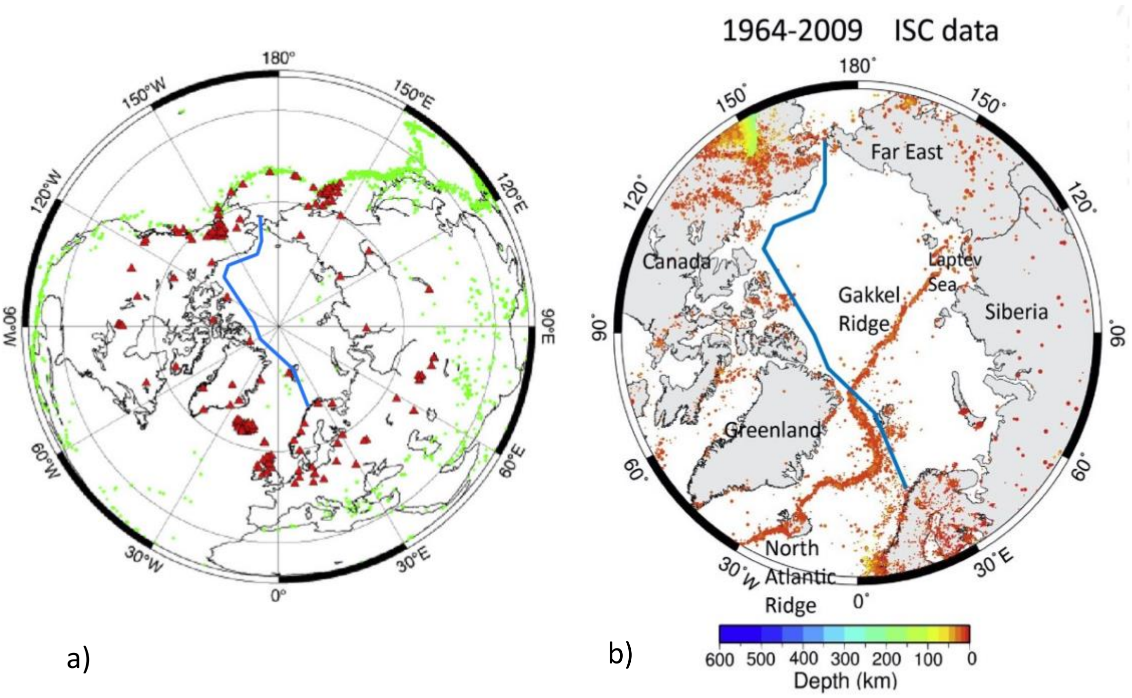

Figure 13: Maps of a) the permanent Global Seismographic Network (GSN) stations, and b) the seismic activities in the period 1964-2009. In blue is shown one of the potential routes of the Polar Connect cable. Figures are adapted from[31].

These topics can be investigated using vibration sensing of seismic activity including earthquakes. Vibration sensing can be realized using either point sensors (seismometers/accelerometers), DAS or forward transmission sensing (interferometric/polarization). Maps of the current seismic sensing stations and the seismic activity centers are shown in Figure 13.

From Figure 13a, we notice that the number of seismic sensors in the Arctic is limited, and that the Polar Connect cable goes through regions without existing seismic sensors. We also notice that the Polar Connect cable is expected to cross areas of high seismic activity, making the cable relevant for seismic sensing.

4.1 Oceanography

In the field of oceanography, researchers are interested in studying the ocean currents in the Arctic Ocean. The ocean currents contain information on the climate change of the Earth as the ocean currents are responsible for transporting large amounts of heat energy via e.g., the Gulf stream.

A map of the currents in the Arctic region is shown in Figure 14.

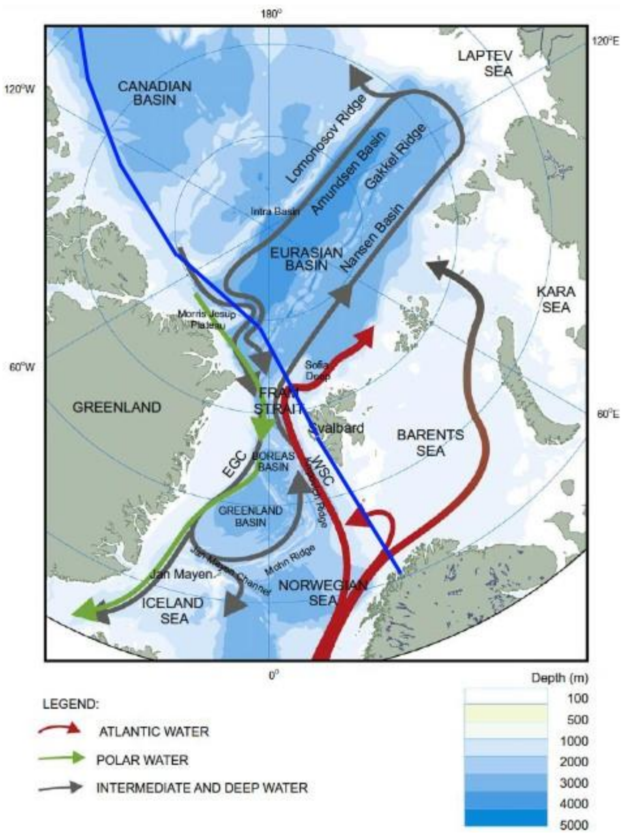

Figure 14: Map of the ocean currents in the Arctic region. The dark blue line shows one of the potential routes of the Polar Connect cable. Figure adapted from[32].

It is seen that the Gulf stream ends up in the in the Arctic Ocean and that polar water streams south from the Arctic Ocean next to Greenland. However, today the ocean currents in the high northern latitudes are not well studied which is a problem since these currents have a large impact on the climate of the Earth. Figure 15 shows an example of a current measurement setup using moorings for measuring oceanic parameters in the Arctic. Using moorings for measurements is time-consuming and difficult in the Arctic because of the ice sheet, especially in the winter.

According to oceanographers, four important physical parameters to measure to study the oceans are:

- Water temperature (with a resolution of 1 mK or below). The resolution of 1 mK is motivated from Figure 16 which shows the measured temperature at 4000 m depth North of Svalbard in a one-year span, showing that the variability is ~1 mK.
- Pressure. These are used to measure the height of the water column above the sensor. The data in Figure 17 shows that the resolution must be below 0.1 dbar = 10 mbar. 10 mbar corresponds to a delta of ~1 mm in a water column
- Water salinity. This data is used to measure different water masses, for example to distinguish salty water from the non-salty glacial water.
- Ocean current velocities.

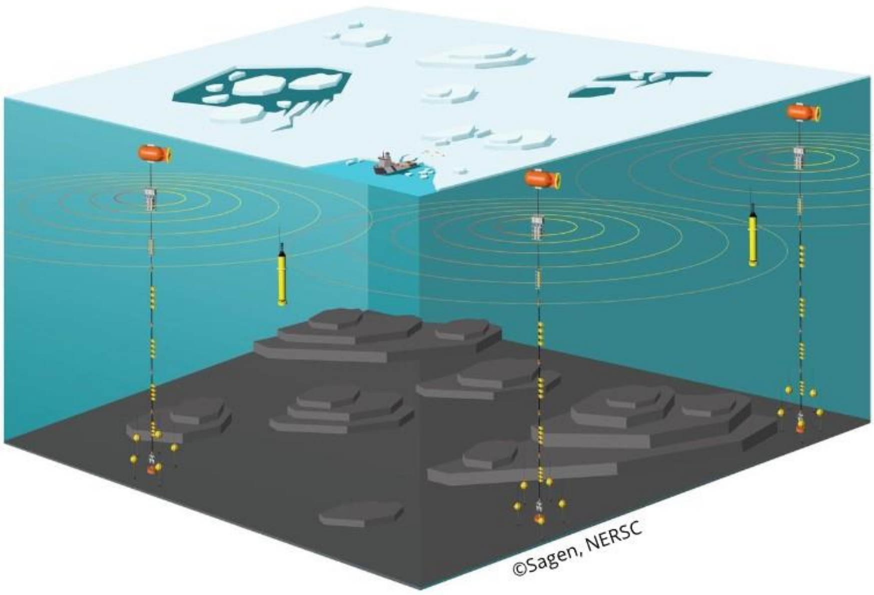

Figure 15: Sketch of mooring measurement in the Arctic (the High Arctic Ocean Observing System, Horizon Europe project 2023-2027). Figure source: Sagen, Nansen Environmental and Remote Sensing Center.

In addition to these physical parameters, oceanographers highly stress that having continuous and long-term measurements are crucial, as changes in the ocean water happen over the time scale of months to years. Figure 16 and Figure 17 show the measured temperature and pressure data at 4000 m depth from the NERSC1 instrument located north of Svalbard. The figures show how the parameters change slowly with time and that high resolution measurements are needed. In the ideal world, the oceanographers wish to map the ocean parameters (temperature, pressure, etc.) in a 3D space below the water surface since different layers of the ocean water contain different currents.

With SMART point sensors, it is possible to measure water temperature and pressure, two of the four important parameters for studies in oceanography. In addition, with DAS it is possible to measure ocean currents as described in a former section. The last of the four parameters, salinity, cannot be measured with current fiber sensor technologies, and a salinity sensor would need to be added to the sensing network as a point sensor.

The planned Polar Connect route crosses important ocean currents in the Arctic, for example the Gulf stream, as seen Figure 14. Therefore, a large amount of sampling points at the Gulf stream are of high interest for oceanographers.

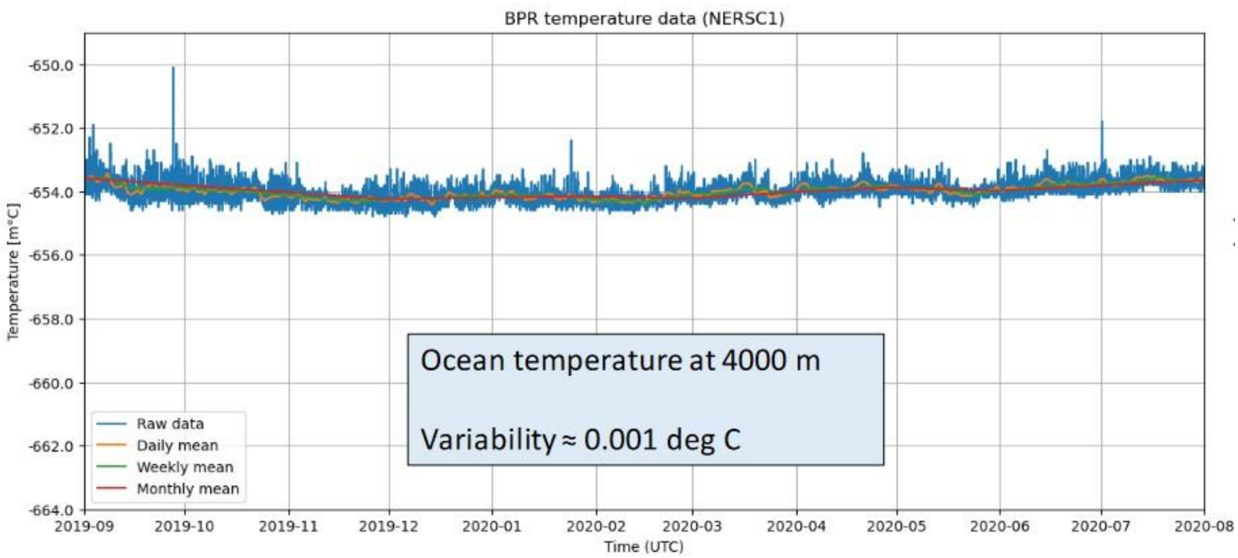

Figure 16: Measured temperature versus time in a one-year span from Sep. 2019 to Aug. 2020, measured at 4000 m depth at the NERSC1 measurements station located north of Svalbard. Source: Nansen Environmental and Remote Sensing Center, slide from Polar Connect workshop in Oslo, October 2023.

As of today, the ocean parameters are studied using sensors on moorings. These kinds of measurements are time consuming, happen only in a limited time window, and are difficult to do in the winter. This means that especially data from winters are limited now. During the 'Science

Opportunities on Polar Connect ' workshop[2], which took place in Oslo, Norway in October 2023, scientists argued that observations of the Arctic Ocean from below 700 m (below 50 m in winter) are still missing. However, oceanographers also have some concerns that need to be addressed for sensors in the Arctic. One concern relates to sensor precision and accuracy. Because of the high precision and accuracy needed for the temperature and pressure sensors (and possibly also other sensors), sensor drift is a concern for oceanographers. Therefore, low sensor drift must be ensured, or alternatively regular re-calibrations must be done. Another concern is that the ocean bottom sensors may be covered with sediments.

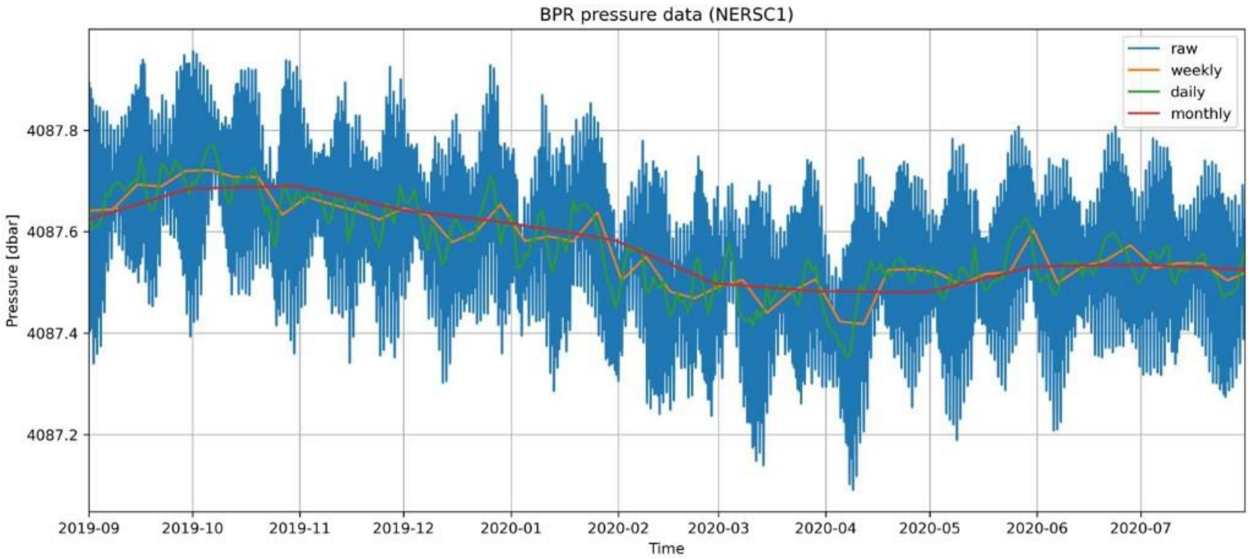

Figure 17: Measured pressure versus time in a one-year span from Sep. 2019 to Aug. 2020, measured at 4000 m depth at the NERSC1 measurements station located north of Svalbard. Source: Nansen Environmental and Remote Sensing Center, slide from Polar Connect workshop in Oslo, October 2023.

4.2 Marine biology

In the field of marine biology, the monitoring of animals is important. There is a lack of knowledge of how different types of animals are affected by for example ship traffic, climate change or seismic activity[33]. Maybe fish and marine mammals may stop feeding, or their fecundity will be reduced? These are questions that still need to be investigated. For marine biologists, there is a great interest in getting a high-resolution picture of the soundscape in the Arctic and in particular long-term monitoring. This is especially relevant now as human activity in the Arctic is expected

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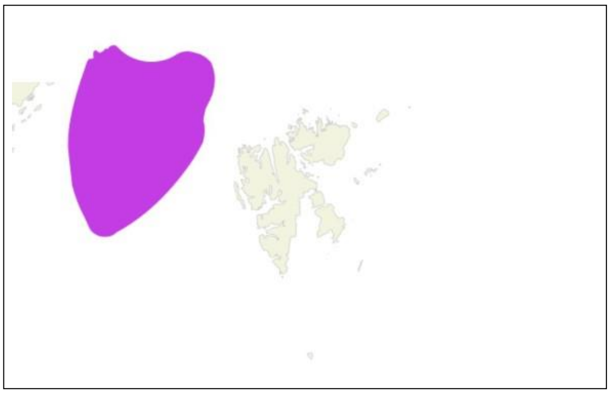
[2] 'Science opportunities on Polar Connect' workshop was organized under the Northern EU Gateways project, co-funded by the European Commission under CEF Digital programme. The workshop carried out under WP5 Task 3 Fibre Sensing Technologies as part of research engagement activities. Workshop report submitted as part of project deliverables and can be found on the project website: https://northern-eu-gateways.nordu.net/publications/science-opportunities-workshop-report/

to increase in the coming years. In addition, if data of marine life sensing can be accessed in real time, better protection of endangered species can be obtained.

As an example of the relevance of the Polar Connect cable, in Figure 18 is shown a map of the area of feeding baleen whales and a map of endangered species around Svalbard. From the maps it is apparent that the Polar Connect cable will cross approximately these areas, making the data from the Polar Connect cable relevant for monitoring the animals in these regions. It should be mentioned that these maps are limited to only the area around Svalbard, and possibly there are more critical zones along the route of Polar Connect.

a)



b)

Figure 18: Maps of Svalbard and the surrounding ocean showing a) the areas of baleen whale feeding in the summer, and b) the areas of endangered species. Source: Lise Doksæter Sivle, Institute of Marine Research Norway, slides from Polar Connect workshop in Oslo, October 2023. Data from www.imr.no.

The most relevant fiber sensor principle for marine mammal monitoring is DAS[20], where the voice of whales are detected. As fish also emit sounds of <1 kHz, the monitoring of fish using DAS is in principle possible if the sound is strong enough, although this has not yet been demonstrated or investigated. Today, both whales and fish are conventionally monitored using hydrophone point sensors. On the other hand, other marine animals such as plankton are monitored using echo-meters. Echo-meters cannot be replaced by current fiber sensors, and therefore point sensors are needed in this regard.

5 Existing subsea fiber optic sensing projects

In this Section, we compare the Polar Connect project to other similar subsea fiber optic sensing projects which are already in operation. This should provide an idea of the feasibility of the Polar Connect project.

5.1 The NEPTUNE project

A project, which has many similarities to the Polar Connect project, is the NEPTUNE project (Northeast Pacific Time-Series Undersea Networked Experiments) from Canada[34], [35]. NEPTUNE is 800 km fiber optic network with 130 attached instruments (as of 2013), operated by University of Victoria in British Columbia.

As shown on the map in Figure 19, NEPTUNE is located on the northern part of the Juan de Fuca tectonic plate, off the shore of Vancouver Island in British Columbia. The main scientific themes addressed are: plate tectonics, earthquakes, ocean/climate dynamics and impact on marine biota, deep-sea ecosystem dynamics, and dynamic processes of seabed fluid fluxes and gas hydrates[34].

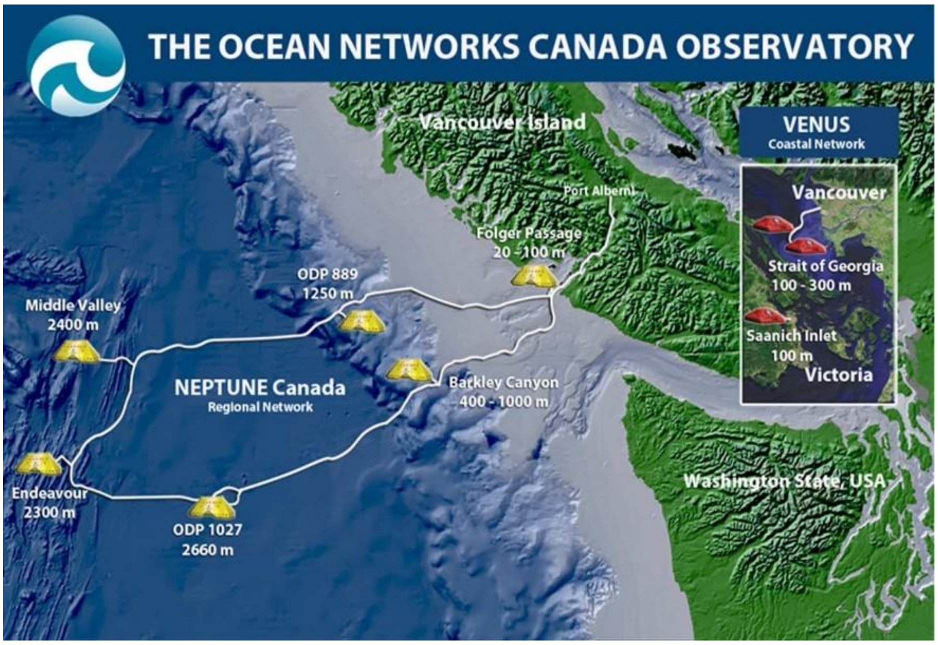


Figure 19: Map of the fiber optic cable for the NEPTUNE sensing project. The inlet shows NEPTUNE's sister project, VENUS. Figure provided from [32].

The network was installed in the period 2007-2012 with an expected lifetime of 25 years. It was the company Alcatel Submarine Networks who was awarded the contract to design, manufacture and install the infrastructure, including cables, repeaters, branching units, and nodes for scientific instruments. A sketch of the network topology of NEPTUNE is shown in Figure 20.

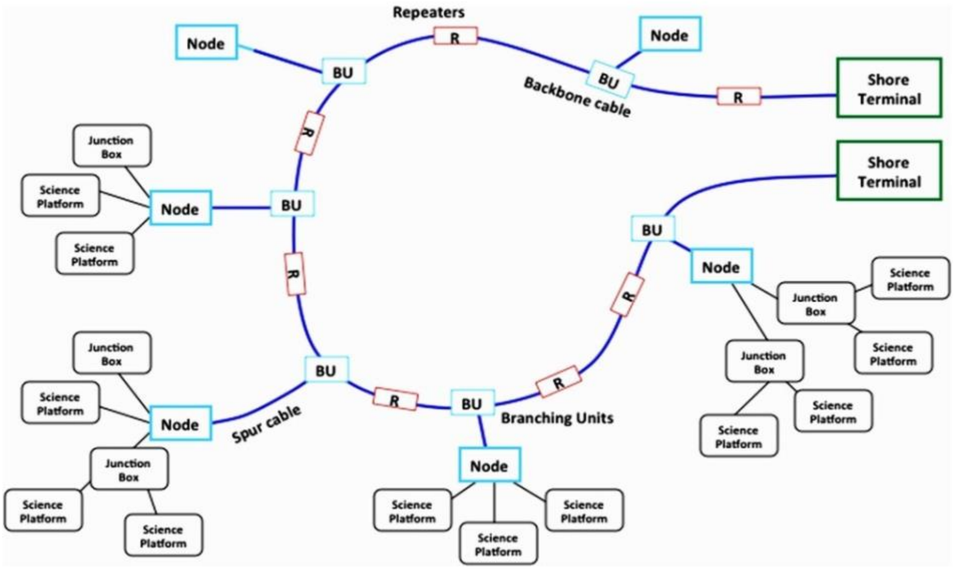


Figure 20: Network topology of the NEPTUNE network. R: repeater. BU: branching unit. Figure provided from [34].

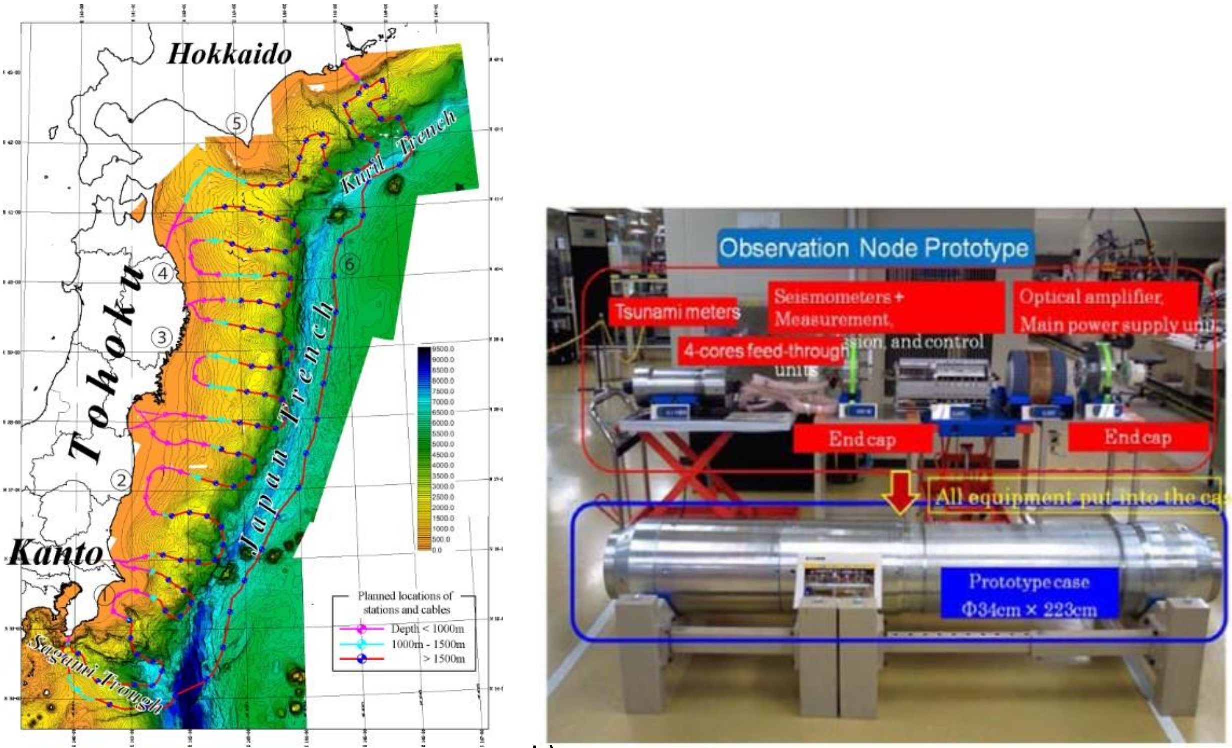
An overview of technical details on power budget, communication bandwidth and data management can be found in [34]. Some of the main scientific accomplishments as of 2013 of the NEPTUNE project described in [34] are provided in the list below:

- Tsunami warning: Pressure sensors to detect changes in the water column equivalent of 1 mm in 2700 water depth were installed in order to develop a tsunami warning system[36].
- Earthquakes/tectonics: Piezometers, broadband seismometers as well as pressure sensors across the network were installed to provide information on tectonic processes and earthquakes.
- Gas hydrates: Leakage from deposits of gas hydrates below the sediment surface is a growing concern since released methane results in enhanced global warming. To monitor leakages, a range of sensors were installed, including pH, oxygen, methane sensors and cameras.
- Marine biology/ecology: Concerns on overfishing, pollution, threats to endangered marine animals, habitat destruction are examples of reasons to intensify studies of the subsea biology/ecology. Installed sensors include hydrophones (for listening to the animals), cameras[37], and sensor for measuring hydrothermal vents and water currents.

The NEPTUNE project shows the feasibility of using a fiber optic cable as the communication infrastructure for subsea scientific instruments. A strength of NEPTUNE is that it provides a general communication link to which a variety of sensors can be connected. This allows for installing new types of sensors and updating existing ones. The NEPTUNE project is very similar to the DONET project (Dense Ocean-floor Network system for Earthquakes and Tsunamis), a sensor network in the seas of Japan[38]. However, due to the similarities between the projects, the DONET project (and other similar projects) will not be discussed in detail here.

5.2 The S-net project

Another project, which is technically very similar to the SMART sensor technology, is the S-net in Japan[39]. The S-net is an earthquake and tsunami warning system based on many sensors located off the east coast in Japan. The sensors are series connected via optical fibers, see Figure 21a. The sensors (seismometer and pressure-sensor) are located within a sensor node which is the same principle as the CC-nodes from the ASN SMART system, see Figure 21b.



a) b)

Figure 21: a) Map of the sensor network of S-net. b) Picture of the S-net sensor node. Figures provided from[39].

The advantage of the integrating all the sensors within a sealed sensor node is that it is easy and quick to deploy, at least as compared to the solution in the NEPTUNE project, where the installation of the sensors is a more difficult and time demanding task. The S-net project started in 2009, and it shows the feasibility of the SMART network from ASN which is still under development. A final note to the S-net sensor nodes is that a more compact version of a sensor node with seismometers was developed by University of Tokyo, also for monitoring earthquakes in the oceans around Japan[40].

5.3 The GEO-TOC project

The Geo-TOC project [41] is very similar to the ASN SMART cable project. It consists of a fiber-optic cable with attached sensor nodes (like the ASN CC-nodes), where each node contains pressure sensors, hydrophones, temperature sensors and accelerometers, including the same three sensor types as in the ASN CC-nodes. The Geo-TOC sensor cable was installed in 1997 between Japan and Guam with a total length of 2659 km, see Figure 22a. The Geo-TOC sensor node is sketched in Figure 22b, where the similarity between the ASN CC-nodes and the Geo-TOC sensor node should be noticed.

The Geo-TOC sensors have successfully measured earthquakes [41], but apart from that, we have not been able to find many scientific results from the project in the research literature.

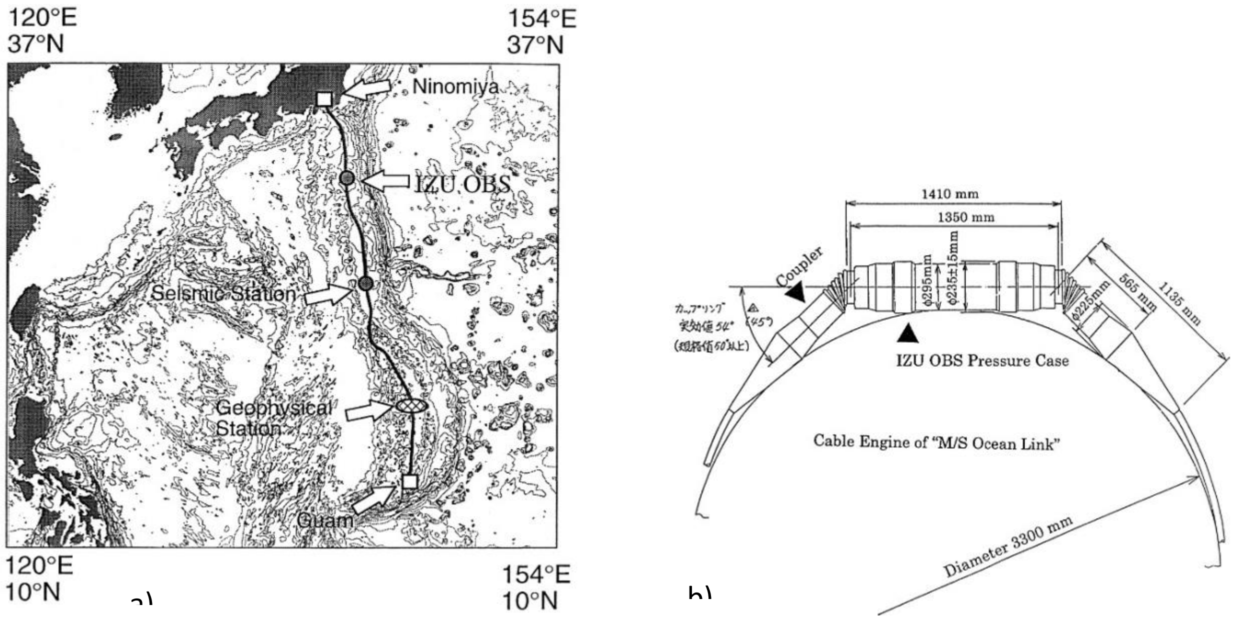


Figure 22: a) Map of the Geo-TOC cable. b) Sketch of the Geo-TOC sensor node attached to the fiber optic cable. Figures taken from [41].

6 Scenarios for introducing sensing in Polar Connect

In this section, a mapping is given, which maps the requests and requirements from researchers for sensing in the Arctic Ocean to the solutions offered by current fiber sensing technologies. First, the main findings of requests and solutions are summarized in a table. Next, to make things clear, we set up scenarios of fiber sensing solutions from scenario 0 (no sensing at all) to scenario 4 (full scale sensing solution with multiple fiber sensing technologies).

6.1 Summary of fiber sensing requests and solutions

The table below shows a summary of the requests from scientists of the different fields. Each request from the science communities is mapped to a relevant fiber sensing technology that could meet the needed requirements.

Scientific field	Request and requirement	Relevant fiber sensing technology	Additional notes
Geology/ seismology	Seismic sensing (vibrations)	● SMART (seismometer /accelerometer) ● Repeatered DAS ● Polarization/ interferometric	
Oceanography	Temperature with ~1 mK accuracy.	● SMART (can offer 2 mK resolution)	● Sensor drift is a concern. ● Continuous and long-term measurements are of high importance. Offered by all fiber sensing technologies. ● Mapping of measurements in vertical axis of the water is wished, but not feasible.
	Pressure with ~10 mbar accuracy.	● SMART (can likely offer the close to required accuracy depending on the actual tolerance)	
	Water salinity	● None (as salinity sensors are not integrated in SMART)	
	Ocean current velocity	● Maybe repeatered DAS (but more investigations need to be done here)	
Marine biology	Mammal monitoring (acoustic sensing)	● Repeatered DAS	

Table 2: Summary of the requirements from the scientists compared to the relevant fiber sensing technologies.

In summary, it can be concluded that DAS and SMART fiber sensors are the most relevant solutions for meeting many of the requests and requirements from the research communities.

It is worth noting that there are limitations (up to ~200) to the number of CC nodes that can be installed on a cable stretch. The limitations stem from the amount of data that can be transmitted from the accumulation of sensors. Also, only a limited part of the cable may be interesting for repeatered DAS. In these cases, key geographical locations of high scientific interest should be located.

Key geographical locations of high interest have not been studied in depth in this report, but areas of high importance could be:

1) the area around Svalbard for mammal monitoring.
2) the area around the mid-Atlantic ridge for seismic studies.
3) the area between Svalbard and Norway's mainland and the area north of Greenland for studying oceanography.

It should also be noted that mapping the requests and requirements of the artic researchers is a result of a short study. They are based on a 2-day workshop (in Oslo) with relevant researchers in addition to some literature study done by the authors[3] of this deliverable. Therefore, there are likely many more relevant applications. Despite this, it is still expected that DAS and SMART sensors are the most relevant sensing technologies for many of the forementioned applications. It is also expected that adjustments to the sensor specifications and type of sensors may be introduced over the coming years.

6.2 Scenarios

This section introduces some scenarios regarding fiber sensing on the Polar Connect cable. The scenarios range from the baseline scenario 0 (no sensing at all) to scenario 4 (full scale sensing system with multiple fiber sensing technologies).

6.2.1 Scenario 0: Baseline, no sensing at all.

6.2.1.1 Description

In this scenario no sensing is applied at all, and all fiber pairs are dedicated for telecommunications. Even though this scenario is chosen initially once the Polar Connect cable is deployed, one may be able to install the sensing for scenario 1 after deployment as scenario 1 requires no dedicated fiber pairs for sensing.

6.2.1.2 Sensing capabilities:

No sensing capabilities are inherent in this scenario; however, it is possible to upgrade to Scenario 1 by adding equipment at the fiber ends.

[3] The main author of this deliverable is expert in fiber sensing and not in Artic climate research disciplines.

6.2.1.3 Cost and risk

There are no additional associated risks nor costs with this scenario.

6.2.2 Scenario 1: Sensing using no dedicated fiber pairs.

6.2.2.1 Description

In this scenario no dedicated fiber pairs for sensing are applied, meaning that all fiber pairs can be used for telecom.

The used sensing technologies can be transmission-based polarization and/or interferometric sensing. Note that for all scenarios 2-4, forward-based transmission sensing can also be applied.

In addition, non-repeatered Distributed Acoustic Sensing (DAS) and Brillouin/Raman OTDR can be applied, which have a range of <150 km from the shore or down to the first repeater.

6.2.2.2 Sensing capabilities

Forward transmission-based sensing is a relatively cost-efficient sensing method, but it also comes with relatively low sensitivity and limited ability to geographically localize earthquakes.

This scenario would also allow for sensing for self-monitoring of the cable. That is, DAS applied to the cable section in the shallow water close to coasts can be used for cable threat monitoring. These DAS measurements down to the first repeater can be made in non-invasive coexistence with live transmission of telecom traffic with no impact on the transmission performance of the traffic-bearing fiber[11].

Furthermore, to extend the range for cable protection beyond the first repeater, any new submarine cable system can be equipped with one additional fiber in the shore-end sections to serve as a dedicated sensing fiber. If such non-provisioned fibers are added to the cable this will also facilitate Brillouin and Raman OTDR.

6.2.2.3 Cost and risk

There are no additional costs for the cable itself as the sensing has no impact. However, there might be minor costs for land-based equipment like updated receivers and DAS interrogators for non-repeatered DAS.

No associated technological risks for the cable system are envisaged. Even though no dedicated sensors are deployed, geopolitically and regulatory the use of sensing in contested waters, territorial waters and exclusive economic zones might cause challenges. For forward transmission-based sensing, these challenges are probably limited as the technologies in their current form only to a very limited extent enable localization. For non-repeatered DAS on the first <150 km of the link, localization is possible and geopolitical and regulatory factors should be considered.

6.2.3 Scenario 2: Repeatered DAS only

As mentioned in the former section, two sensing techniques are of high interest for the Polar Connect Cable: Repeatered DAS and SMART sensing. In this scenario, we consider the case where only repeatered DAS is applied.

6.2.3.1 Description

In this scenario, a single dedicated fiber pair for repeatered DAS is needed. Several repeaters along the fiber are needed (the same as for telecom), as well as one DAS interrogator for each section of ~100 km of sensing cable. In addition, data processing and storage hardware are needed at the shores. The required hardware is also shown in Figure 9.

6.2.3.2 Sensing capabilities

- DAS provides an enormous amount of sensing points (one every ~10 m) and many sensing applications, but it comes with the downside of lower sensitivity than point sensing.
- Repeatered DAS may be applied to the full cable length or only a part of the cable of high interest, for example around the Arctic Ocean or close to the mid-Atlantic ridge.
- In this scenario, many sensing applications are possible as shown in Table 2. This includes mammal monitoring, ocean current velocity sensing and seismic monitoring. In addition, all the sensing applications mentioned in Section 3.2 are possible, including marine sediment characterization, sea vessel monitoring, cable threat monitoring and sensing of storms/waves.
- The lists of applications of DAS in Table 2 and Section 3.2 are likely not complete. Scientific applications of DAS are investigated heavily these years, so likely in the future more applications will be discovered, and existing sensing applications will mature.

6.2.3.3 Cost and risk

Repeatered DAS is a relatively expensive solution with a price which is expected to be not very different from the price of SMART sensing. The main additional costs stem from the use of dedicated fibers, specially designed repeaters, and an array of DAS interrogators at each end of the cables. Note that each DAS segment requires an interrogator for proper operation. It might be possible to design the system with options for repeatered DAS and later enable sensing in each DAS segment by adding land-based equipment like interrogators. The components in repeatered DAS are, however, primarily slightly modified standard telecommunication components, which can make a basis for reduced costs in a future deployment scenario.

Although non-repeatered DAS is a mature technology, repeatered DAS is a technology still under development by ASN. Consequently, this provides risks as the technology has not been field tested yet. However, since repeatered DAS operates on a dedicated fiber pair, the sensing and telecom transmission is physically fully separated and do not interfere. The repeatered DAS does not introduce any increased risk to the telecom system. It is recommended to closely follow field application with repeatered DAS in other projects.

From a regulatory and geopolitical perspective, the repeatered DAS might not be allowed in contested waters, territorial waters, and exclusive economic zones as it provides the possibility to localize events and activities quite precisely. This could be mitigated by only enabling sensing on specific DAS segments.

6.2.4 Scenario 3: SMART sensing only.

In this scenario, we consider the case where only the SMART sensing solution from ASN is applied.

6.2.4.1 Description

In this scenario, a single dedicated fiber pair is needed for connection of the CC nodes of the SMART sensing network. Several repeaters are needed (the same as for telecom), as well as several CC-nodes (up to ~200 along the fiber). Compared to telecom, the SMART sensing fiber link requires slightly more power due to the added CC-nodes. In addition, data processing and storage hardware are needed at the shores. The required hardware is also shown in Figure 9.

6.2.4.2 Sensing capabilities

Generally, the sensing capabilities follow the specifications of the deployed sensors. The currently investigated CC nodes include accelerometer, seismometer, thermometer, and pressure sensor.

SMART sensing provides high sensitivity, but it also comes with the downside of a limited number of sensing points.

As SMART sensing provides only a limited number of sensing points, one should decide carefully which geographical locations that are most interesting for sensing purposes. In this report, we have not investigated in depth which parts of the Polar Connect route are most interesting for sensing purposes. The Arctic Ocean as well as the area around the mid-Atlantic ridge could be interesting locations.

In this scenario, many applications are possible as shown in Table 2. This includes seismic sensing as well as temperature and pressure sensing which are important to oceanographers. Likely, more applications will show up in the future as results from field trials using the technology emerge.

In principle, the range of sensors in the CC node might change in future versions without modifying the overall working principle. This could enable sensing conductivity which could indicate the salinity of the water. This parameter is interesting for some of the scientific disciplines.

6.2.4.3 Cost and risk

SMART sensing is a relatively expensive solution with a price which is expected to be not very different from the price of repeatered DAS. The SMART sensing hardware is still under development by ASN. Of course, this provides risks as the technology has not been field tested yet and not in Artic areas. It is thus recommended to follow closely the results and deployment of similar cable deployments in less climatically hostile environments.

From a regulatory and geopolitical perspective, the deployment of CC nodes might not be allowed in contested waters, territorial waters, and exclusive economic zones as it may provide the possibility to localize events and activities within the vicinity of the sensor using the accelerometer. This can be mitigated by only deploying the CC nodes carefully in waters without any restrictions.

The deployment of CC nodes and sensors will increase the requirements to the power supply; however, the additional power usage is not considered to be significant.

6.2.4.4 Scenario 4: Combined repeatered DAS and SMART sensing.

This scenario is the high-end sensing solution combining repeatered DAS and SMART sensing with point sensors. This scenario is the most expensive solution, but it is also the solution with the highest sensing capabilities.

6.2.4.5 Description

In this scenario, the hardware requirements described in scenario 2 and 3 can be directly put together. Two dedicated fiber pairs are needed, one for SMART sensing and one for repeatered DAS. The schematic of the co-existence of DAS and SMART sensing is shown in Figure 9.

6.2.4.6 Sensing capabilities

In this scenario, the combination of high sensitivity from the SMART sensors in addition to the dense sensor array of repeatered DAS provides many sensing applications, of which some key applications are shown in Table 2. In this scenario, it should also be decided which geographical locations are most interesting for scientific studies. It may be possible to apply SMART sensing and repeatered DAS in separate locations. E.g. SMART sensing can be applied for oceanographic purposes to precise measure temperature and repeatered DAS can be applied in other segments to investigate seismic activity.

6.2.4.7 Cost and risk

The price is estimated to be high, likely around the price of scenario 2 and 3 combined.

The primary cost stems from the usage of two dedicated fiber pairs and installation of modified repeaters for DAS. In addition, there are additional costs for each CC node and enabling DAS segments with interrogators.

A cost reduction factor, however, is that it is then possible to reduce the number of CC nodes in places where repeatered DAS can do the job and vice versa.

The technologies behind SMART sensing and repeatered DAS are still under development. This provides risks, and field trials are still needed to prove the maturity of both technologies. It is thus recommended to closely follow the deployment and results from similar projects probably in less hostile climatic environments.

6.3 General comments to the scenarios

As mentioned, the Arctic climate causes difficulties in terms of deployment and maintenance of the Polar Connect fiber link. That is, icebreaker ships are needed for deployment and maintenance, and there exists only a few icebreakers in the world which are powerful enough to move through the ice sheets of the Arctic. Due to these harsh conditions, repair of a fiber optic cable in the Arctic may not be a trivial task for a telecom repair ship as it would certainly require escort of one of the world's few applicable icebreakers. In this context it should also be emphasized that once the cable is laid underneath the Arctic ice, then it is quite protected as no fishing activities and accidental anchoring can occur.

As mentioned, both repeatered DAS and SMART sensing are technologies which are still under development. Therefore, it is not without risks to deploy those sensors on the cable in the Arctic Ocean since repairs are likely very expensive and difficult. It may be wise to test both repeatered DAS and SMART sensing on cables in areas without a thick ice sheet (or at least in areas where repair and deployment are more of a routine task).

It should be noted, however, that a failure of one of multiple CC nodes will not directly impact the telecommunication part of the cable infrastructure and operation.

The risk of using forward transmission-based sensing, non-repeatered DAS, and Brillouin/Raman OTDR are considered much lower risk as those technologies require no (or only little) dedicated hardware for sensing.

6.4 Scenario summary

In this comprehensive evaluation of sensing solutions for Arctic research, researchers' requests were mapped to current fiber sensing technologies, resulting in the identification of two primary options: Distributed Acoustic Sensing (DAS) and SMART fiber sensors. These technologies emerge as the most relevant for meeting diverse scientific requirements, spanning geology, oceanography, and marine biology.

The chapter introduces scenarios ranging from a baseline with no sensing to a high-end solution combining repeatered DAS and SMART sensing. Each scenario is described, highlighting the associated sensing capabilities, costs, and risks. The conclusion underscores the expectation that DAS and SMART sensors will remain pivotal in addressing the diverse needs of Arctic researchers, despite the evolving landscape of sensing technologies. It emphasizes the ongoing development of these technologies and the necessity of closely monitoring field trials in less challenging environments to validate their efficacy in Arctic conditions.

7 General scientific platform vision: SMART++

During the engagement dialogues with Arctic scientific communities, a consistent desire emerged for continuous measurement of salinity and temperature throughout the water column, extending from the seabed to the surface. The current study, however, falls short of meeting this demand with its existing technologies and general concepts. Even the potential inclusion of salinity sensors, likely based on conductivity measurements, in future versions of the CC nodes would be insufficient for comprehensive water column measurements.

The SMART++ concept, envisaged for the future, presents an innovative solution by extending the sensing-enabled subsea communication cable infrastructure into a versatile platform for scientific research and various activities. Companies engaged in offshore industries currently utilize underwater power cabling for both charging and data offloading of Underwater Autonomous Vehicles (UAVs). In the SMART++ vision, these vehicles, whether small or large, could continuously perform relevant measurements in the water column and periodically return to the seabed for charging and data offloading.

SMART++ sensing represents a paradigm where the cable system not only facilitates sensing but also acts as an enabler for external scientific activities, supporting data offloading from external devices and/or recharging autonomous vehicles using communication methods such as acoustic or dedicated electromagnetic-based connectivity. These distinctions offer a clear framework for comprehending the evolving capabilities within SMART technologies.

It is important to note that SMART++ will significantly elevate the power requirements for the subsea infrastructure compared to a standard telecommunication system, whether with or without sensing. The actual power needs will ultimately hinge on the specified charging power accessible to the infrastructure. Additionally, the successful implementation of SMART++ necessitates a collaborative effort between classic telecommunication industries and offshore industries.

Polar Connect, being ~7 years away from deployment, is an excellent vehicle to explore these opportunities and that NORDUnet and the Nordic NRENs are well positioned to broker the possibilities of the telecoms industry and the sensing companies/offshore industries with the demands from the Arctic scientists.

8 Conclusion

Various fiber sensing technologies, including Raman/Brillouin/Rayleigh OTDR, interferometric/polarization forward transmission sensing, and SMART sensing, have been introduced. The most relevant options for Polar Connect are repeatered DAS and SMART sensing. While DAS, a well-tested technology, currently offers a range of ~100 km, ongoing development is extending it to ranges of thousands of kilometers. SMART sensing is also in product development with expected product qualification in 2025. Both SMART sensing and repeatered DAS are considered feasible for the Polar Connect project.

Applications for DAS and SMART, encompassing both existing and anticipated requests from Arctic scientists, underscore their relevance in monitoring whales, earthquakes, ocean currents, sea temperature, and sea level rise. The Polar Connect cable's route traverses unexplored, scientifically significant areas in seismology, oceanography, and marine biology, addressing the scarcity of sensors in the Arctic.

Identified risks include challenging deployment and repair operations, reliant on scarce icebreakers, coupled with potential geopolitical considerations. These, combined with the evolving nature of fiber sensing technologies, highlight the risks associated with the sensing component of Polar Connect.

In conclusion, this holistic evaluation aligns researchers' needs with cutting-edge fiber sensing technologies, emphasizing DAS and SMART fiber sensors as primary solutions for diverse Arctic research requirements. The scenarios presented delve into capabilities, costs, and risks, underlining the enduring significance of DAS and SMART sensors. The conclusion underscores the need to closely monitor ongoing technological developments and field trials to validate their efficacy in challenging Arctic conditions.

References

[1] E. Ip *et al.*, “Using Global Existing Fiber Networks for Environmental Sensing,” *Proceedings of the IEEE*, vol. 110, no. 11, pp. 1853–1888, Nov. 2022, doi: 10.1109/JPROC.2022.3199742.

[2] O. H. Waagaard *et al.*, “Real-time low noise distributed acoustic sensing in 171 km low loss fiber,” *OSA Continuum, OSAC*, vol. 4, no. 2, pp. 688–701, Feb. 2021, doi: 10.1364/OSAC.408761.

[3] E. Ip *et al.*, “DAS Over 1,007-km Hybrid Link With 10-Tb/s DP-16QAM Co-Propagation Using Frequency-Diverse Chirped Pulses,” *Journal of Lightwave Technology*, vol. 41, no. 4, pp. 1077–1086, Feb. 2023, doi: 10.1109/JLT.2022.3219369.

[4] C. Fan *et al.*, “300 km ultralong fiber optic DAS system based on optimally designed bidirectional EDFA relays,” *Photon. Res., PRJ*, vol. 11, no. 6, pp. 968–977, Jun. 2023, doi: 10.1364/PRJ.485701.

[5] T. Joy, T. Jostmeier, B. Marx, and W. Hill, “Increasing the Distance Range of Repeaterless Brillouin-OTDR to 250 km by Optical Amplification,” in *27th International Conference on Optical Fiber Sensors*, Alexandria, Virginia: Optica Publishing Group, 2022, p. W1.3. doi: 10.1364/OFS.2022.W1.3.

[6] G. Marra *et al.*, “Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables,” *Science*, vol. 361, no. 6401, pp. 486–490, Aug. 2018, doi: 10.1126/science.aat4458.

[7] G. Marra *et al.*, “Optical interferometry–based array of seafloor environmental sensors using a transoceanic submarine cable,” *Science*, vol. 376, no. 6595, pp. 874–879, May 2022, doi: 10.1126/science.abo1939.

[8] Z. Zhan *et al.*, “Optical polarization–based seismic and water wave sensing on transoceanic cables,” *Science*, vol. 371, no. 6532, pp. 931–936, Feb. 2021, doi: 10.1126/science.abe6648.

[9] A. Mecozzi, M. Cantono, J. C. Castellanos, V. Kamalov, R. Muller, and Z. Zhan, “Polarization sensing using submarine optical cables,” *Optica*, vol. 8, no. 6, p. 788, Jun. 2021, doi: 10.1364/OPTICA.424307.

[10] B. M. Howe *et al.*, “SMART Cables for Observing the Global Ocean: Science and Implementation,” *Frontiers in Marine Science*, vol. 6, 2019, Accessed: Nov. 02, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fmars.2019.00424

[11] M.-F. Huang *et al.*, “First Field Trial of Distributed Fiber Optical Sensing and High-Speed Communication Over an Operational Telecom Network,” *J. Lightwave Technol.*, vol. 38, no. 1, pp. 75–81, Jan. 2020, doi: 10.1109/JLT.2019.2935422.

[12] C. A. Galindez-Jamioy and J. M. López-Higuera, "Brillouin distributed fiber sensors: An overview and applications," *Journal of Sensors*, vol. 2012, 2012, doi: 10.1155/2012/204121.

[13] A. Motil, A. Bergman, and M. Tur, "[INVITED] State of the art of Brillouin fiber-optic distributed sensing," *Optics and Laser Technology*, vol. 78, pp. 81–103, 2016, doi: 10.1016/j.optlastec.2015.09.013.

[14] M. R. Fernández-Ruiz *et al.*, "Seismic Monitoring With Distributed Acoustic Sensing From the Near-Surface to the Deep Oceans," *J. Lightwave Technol., JLT*, vol. 40, no. 5, pp. 1453–1463, Mar. 2022.

[15] N. J. Lindsey, T. C. Dawe, and J. B. Ajo-Franklin, "Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing," *Science*, vol. 366, no. 6469, pp. 1103–1107, Nov. 2019, doi: 10.1126/science.aay5881.

[16] A. Sladen *et al.*, "Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables," *Nat Commun*, vol. 10, no. 1, Art. no. 1, Dec. 2019, doi: 10.1038/s41467-019-13793-z.

[17] E. F. Williams *et al.*, "Distributed sensing of microseisms and teleseisms with submarine dark fibers," *Nat Commun*, vol. 10, no. 1, Art. no. 1, Dec. 2019, doi: 10.1038/s41467-019-13262-7.

[18] F. Cheng, B. Chi, N. J. Lindsey, T. C. Dawe, and J. B. Ajo-Franklin, "Utilizing distributed acoustic sensing and ocean bottom fiber optic cables for submarine structural characterization," *Sci Rep*, vol. 11, no. 1, Art. no. 1, Mar. 2021, doi: 10.1038/s41598-021-84845-y.

[19] D. Rivet, B. de Cacqueray, A. Sladen, A. Roques, and G. Calbris, "Preliminary assessment of ship detection and trajectory evaluation using distributed acoustic sensing on an optical fiber telecom cable," *The Journal of the Acoustical Society of America*, vol. 149, no. 4, pp. 2615–2627, Apr. 2021, doi: 10.1121/10.0004129.

[20] M. Landrø *et al.*, "Sensing whales, storms, ships and earthquakes using an Arctic fibre optic cable," *Sci Rep*, vol. 12, no. 1, Art. no. 1, Nov. 2022, doi: 10.1038/s41598-022-23606-x.

[21] E. F. Williams *et al.*, "Surface Gravity Wave Interferometry and Ocean Current Monitoring With Ocean-Bottom DAS," *Journal of Geophysical Research: Oceans*, vol. 127, no. 5, p. e2021JC018375, 2022, doi: 10.1029/2021JC018375.

[22] Y. Yan, F. N. Khan, B. Zhou, A. P. T. Lau, C. Lu, and C. Guo, "Forward Transmission Based Ultra-Long Distributed Vibration Sensing With Wide Frequency Response," *Journal of*

Lightwave Technology, vol. 39, no. 7, pp. 2241–2249, Apr. 2021, doi: 10.1109/JLT.2020.3044676.

[23] M. Cantono *et al.*, “Seismic Sensing in Submarine Fiber Cables,” in *2021 European Conference on Optical Communication (ECOC)*, Sep. 2021, pp. 1–3. doi: 10.1109/ECOC52684.2021.9605838.

[24] N. J. Lindsey and E. R. Martin, “Fiber-Optic Seismology,” *Annu. Rev. Earth Planet. Sci.*, vol. 49, no. 1, pp. 309–336, May 2021, doi: 10.1146/annurev-earth-072420-065213.

[25] S. Ide, E. Araki, and H. Matsumoto, “Very broadband strain-rate measurements along a submarine fiber-optic cable off Cape Muroto, Nankai subduction zone, Japan,” *Earth Planets Space*, vol. 73, no. 1, p. 63, Mar. 2021, doi: 10.1186/s40623-021-01385-5.

[26] D. Mata Flores, A. Sladen, J. Ampuero, E. D. Mercerat, and D. Rivet, “Monitoring Deep Sea Currents With Seafloor Distributed Acoustic Sensing,” *Earth and Space Science*, vol. 10, no. 6, p. e2022EA002723, Jun. 2023, doi: 10.1029/2022EA002723.

[27] L. Bouffaut *et al.*, “Eavesdropping at the Speed of Light: Distributed Acoustic Sensing of Baleen Whales in the Arctic,” *Frontiers in Marine Science*, vol. 9, 2022, Accessed: Jul. 18, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fmars.2022.901348

[28] Z. J. Spica, K. Nishida, T. Akuhara, F. Pétrélis, M. Shinohara, and T. Yamada, “Marine Sediment Characterized by Ocean-Bottom Fiber-Optic Seismology,” *Geophysical Research Letters*, vol. 47, no. 16, p. e2020GL088360, 2020, doi: 10.1029/2020GL088360.

[29] E. B. Raknes *et al.*, “New wiggles from old cables: Acquisition, cable, and data aspects,” *GEOPHYSICS*, vol. 88, no. 6, pp. WC221–WC236, Nov. 2023, doi: 10.1190/geo2023-0069.1.

[30] R. Bachrach *et al.*, “New wiggles from old cables: Data processing and imaging considerations,” *GEOPHYSICS*, vol. 88, no. 6, pp. WC199–WC208, Nov. 2023, doi: 10.1190/geo2023-0115.1.

[31] M. Kanao, V. D. Suvorov, S. Toda, and S. Tsuboi, “Seismicity, structure and tectonics in the Arctic region,” *Geoscience Frontiers*, vol. 6, no. 5, pp. 665–677, Sep. 2015, doi: 10.1016/j.gsf.2014.11.002.

[32] H. R. Langehaug and E. Falck, “Changes in the properties and distribution of the intermediate and deep waters in the Fram Strait,” *Progress in Oceanography*, vol. 96, no. 1, pp. 57–76, Apr. 2012, doi: 10.1016/j.pocean.2011.10.002.

[33] R. Williams *et al.*, "Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management," *Ocean & Coastal Management*, vol. 115, pp. 17–24, Oct. 2015, doi: 10.1016/j.ocecoaman.2015.05.021.

[34] C. R. Barnes, M. M. R. Best, F. R. Johnson, L. Pautet, and B. Pirenne, "Challenges, Benefits, and Opportunities in Installing and Operating Cabled Ocean Observatories: Perspectives From NEPTUNE Canada," *IEEE Journal of Oceanic Engineering*, vol. 38, no. 1, pp. 144–157, Jan. 2013, doi: 10.1109/JOE.2012.2212751.

[35] C. R. Barnes, M. M. R. Best, F. R. Johnson, and B. Pirenne, "NEPTUNE Canada: Installation and initial operation of the world's first regional cabled ocean observatory," in *SEAFLOOR OBSERVATORIES: A New Vision of the Earth from the Abyss*, P. Favali, L. Beranzoli, and A. De Santis, Eds., in Springer Praxis Books. , Berlin, Heidelberg: Springer, 2015, pp. 415–438. doi: 10.1007/978-3-642-11374-1_16.

[36] R. Thomson *et al.*, "Observation of the 2009 Samoa tsunami by the NEPTUNE-Canada cabled observatory: Test data for an operational regional tsunami forecast model," *Geophys. Res. Lett.*, vol. 38, no. 11, p. L11701, Jun. 2011, doi: 10.1029/2011GL046728.

[37] K. Robert and S. K. Juniper, "Surface-sediment bioturbation quantified with cameras on the NEPTUNE Canada cabled observatory," *Marine Ecology Progress Series*, vol. 453, pp. 137–149, May 2012, doi: 10.3354/meps09623.

[38] K. Kawaguchi, S. Kaneko, T. Nishida, and T. Komine, "Construction of the DONET real-time seafloor observatory for earthquakes and tsunami monitoring," in *SEAFLOOR OBSERVATORIES: A New Vision of the Earth from the Abyss*, P. Favali, L. Beranzoli, and A. De Santis, Eds., in Springer Praxis Books. , Berlin, Heidelberg: Springer, 2015, pp. 211–228. doi: 10.1007/978-3-642-11374-1_10.

[39] T. Kanazawa, "Japan Trench earthquake and tsunami monitoring network of cable-linked 150 ocean bottom observatories and its impact to earth disaster science," in *2013 IEEE International Underwater Technology Symposium (UT)*, Mar. 2013, pp. 1–5. doi: 10.1109/UT.2013.6519911.

[40] M. Shinohara, T. Kanazawa, T. Yamada, Y. Machida, T. Shinbo, and S. Sakai, "New compact ocean bottom cabled seismometer system deployed in the Japan Sea," *Mar Geophys Res*, vol. 35, no. 3, pp. 231–242, Sep. 2014, doi: 10.1007/s11001-013-9197-1.

[41] J. Kasahara, H. Utada, T. Sato, and H. Kinoshita, "Submarine cable OBS using a retired submarine telecommunication cable: GeO-TOC program," *Physics of the Earth and Planetary Interiors*, vol. 108, no. 2, pp. 113–127, Jun. 1998, doi: 10.1016/S0031-9201(98)00090-9.