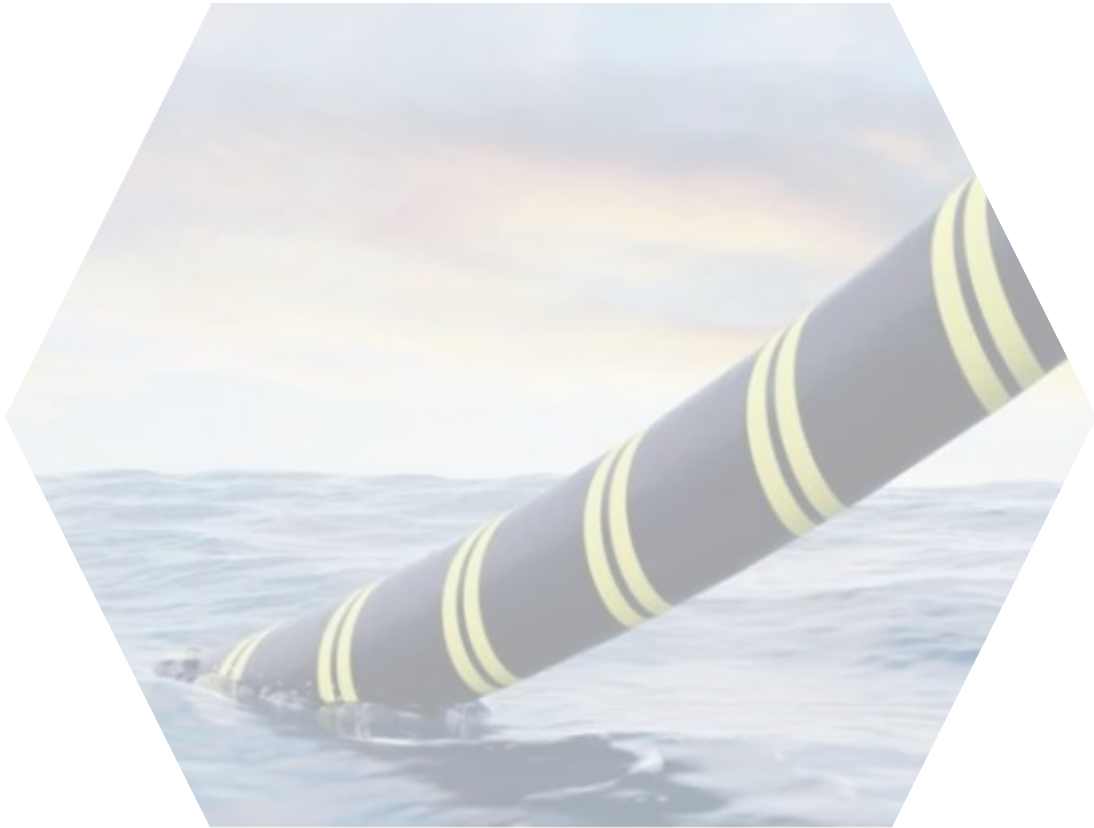




D6.1



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EXECUTIVE SUMMARY

This deliverable presents the development results of the proof-of-concept of long-range Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) for HVDC cable monitoring developed in Task 6.1. The team at AP Sensing designed, built and optimized coherent OTDR-based interrogators that combine a cost-effective and robust design with high performance DAS and DTS methods. They are based on polarization-insensitive OTDR using coherent detection and are compatible with optional Raman amplification for increased range. Extensive component selection, numerical modelling, algorithm development and laboratory integration were carried out to ensure that the prototypes would meet the performance targets at over 125 km distance range defined earlier in D3.3. Verification campaigns on two fiber routes simulating the Use Cases demonstrated that all functional, range and accuracy targets for both sensing modalities were fulfilled or exceeded, confirming the suitability of the chosen system architecture for integration into compact, stand-alone DAS and DTS interrogator units.



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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
DAS	Distributed Acoustic Sensing
DFOS	Distributed Fiber Optic Sensing
DTS	Distributed Temperature Sensing
DSS	Distributed Strain Sensing
FS	Fiber Stretcher
HVDC	High Voltage Direct Current
LO	Local Oscillator
OTDR	Optical Time Domain Reflectometry
SNR	Signal to noise ratio

1 INTRODUCTION

This deliverable report document D6.1 “DTS and DAS proof-of-concept” reports the results of the laboratory demonstration of monitoring temperature, strain and acoustic events at long ranges for HVDC cables performed in Subtask ST6.1.1.

First, the technical background of the developed DTS and DAS systems are presented, and the work performed for finding, preparing and building the proof-of-concept setups is described. Key design decisions are elaborated, and a system design overview is given. (Chapter 2)

Success of this subtask and deliverable are assessed by comparing the measurement performance of the demonstrated DAS and DTS systems with the requirements set in T3.3 and reported in D3.3.

To achieve this, the Use Case requirements are reviewed, and test setups used for verification of the DTS and DAS performance are explained, followed by a definition of the key performance metrics. (Chapter 3)

Next, measurement results achieved with the DTS and DAS proof-of-concept setups are presented and compared against the requirements. (Chapter 4)

Finally, this report will summarize the results, and explore potential applications beyond traditional cable monitoring, such as in power transmission grids or industrial settings, that could be addressed with the measurement performance of the demonstrated DTS or DAS systems.



2 Proof-of-concept for long-range DAS and DTS

This chapter firstly introduces the key fundamental physical and technical elements for DAS and DTS, specifically aimed at power cable monitoring. Next, the design of the new DAS and DTS systems with optical amplification processes for long-ranged measurements is presented. Distributed strain measurement using Brillouin backscattering based on the same technology as DTS and will not be discussed separately. Brillouin-based DFOS will be used for DTS in this project.

2.1 Technological principles of DAS and DTS

AP Sensing's DFOS interrogator technology is based on Optical Time Domain Reflectometry (OTDR). Laser pulses are injected into a sensing fiber which is embedded in or attached to a structure, e.g. a HVDC power cable. The forward travelling laser pulses interact with the glass material in the core of the optical fiber whereby a part of the optical power is backscattered and returns to the DFOS interrogator. The sensitivity of different backscattering processes to physical quantities is illustrated in Fig. 1. Environmental influence on a power cable with an embedded sensing fiber changes these physical quantities and the properties of the backscattered light. OTDR-based DFOS uses a time-of-flight principle to achieve distributed measurement with the capability of a localized measurement of these quantities. [1]

DTS (DSS): A temperature (strain) change in the power cable leads to a temperature (strain) of the sensing fiber which in turn changes the frequency or amplitude of Brillouin backscattering. This principle is used for long-range DTS (DSS).

DAS: Acoustical or vibrational influences of the cable create tiny variations of the optical path length in the sensing fiber. This changes the optical phase of the Rayleigh backscattered light. A DAS interrogator measures these changes and translates it into distributed information about acoustic activity in and around the power cable.

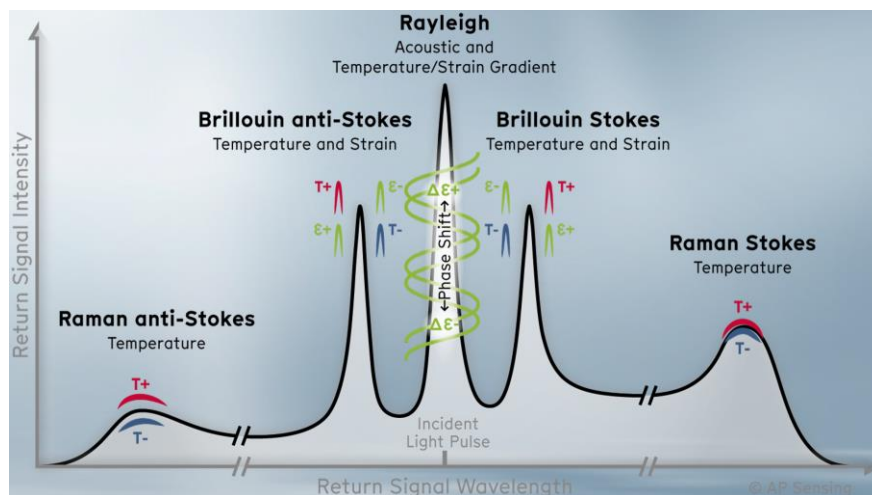


Figure 1: Backscattering processes in an optical fiber and their dependency on environmental parameters used to create DFOS interrogators. Illustration, not to scale.

2.2 Progress and conclusions of the proof-of-concept phase

During the proof-of-concept study, the goal was to find and test the most promising schemes for DAS and DTS according to the project's goals. Focus was to generate a system design that would achieve the required measurement performance; while at the same time ensure the subsequent development of interrogator units with sufficiently low power consumption, heat dissipation and processing capabilities in a rugged stand-alone device. The following tasks have been done

- Analysis of the previous in-house findings and scientific literature on DAS and Brillouin-based DTS systems.
- Simulations of backscattering processes with different pulsed interrogation and detection schemes, and with optical amplification processes (like distributed Raman amplification)
- Purchasing of a variety of (electro)optical components such as
 - laser, modulators and amplifiers,
 - fiber-optical couplers, polarization beam splitters,
 - photodiodes and electrical amplifiers and filters,
 - pump laser sources and driver electronics for optical amplification (optional)
 - Digitizer hardware (analog-digital-converters)
- Comparison of laser sources with low phase noise (low linewidth) for DAS. The phase noise level of the laser source is critical for good DAS performance since the optical phase of the backscattering is measured. Phase (frequency) variation of the light source contributes directly to the noise level of the measured acoustical signals along the fiber.
- Algorithm development for the processing of the raw data (digitized backscatter signals) into the quantity of interest. These algorithms were developed based on simulated data first and then using measured data from the laboratory setups. Trade-offs between measurement performance and estimated processing have been analysed.
- Setup, bring-up and optimization of variations of the DAS and DTS measurement schemes.
- Performance analysis against the performance requirements set in D3.3.

The following design decisions have been made based on the outcome of the tasks described above. Fig. 2 depicts the generalized system design for DAS and DTS. In all sub-assemblies (blue blocks) the choice of components, operational parameters and algorithms is specified and optimized for generating Rayleigh and Brillouin backscattering and analyzing the Rayleigh-phase and Brillouin-frequency/amplitude, respectively. For reasons of confidentiality of critical results, details about the utilized components, detection schemes and algorithms cannot be disclosed.



2.2.1 Detection system

A coherent detection system is implemented which utilizes a local reference light (also called local oscillator, short LO) which is mixed with the backscattered light signal. This enables multiple benefits for both DTS and DAS.

- 1) Shot-noise limited detection. Mixing with the LO provides optical amplification because the resulting mixed signal is proportional to $P_{mix} = 2 \cdot \sqrt{(P_{LO}P_{backscatter})}$. The LO power (mW regime) can be much stronger than the backscattered power (nW regime). The tiny backscatter signals are thereby 'lifted' above the noise levels of the electrooptical detection in photodiodes (dark noise, thermal or Johnson noise). The dominant noise source of the system is then the shot noise of the optical signals, which is a fundamentally low limit [1].
- 2) For DAS, the interference of backscatter and LO generates a mixed signal that is sensitive to the optical phase φ between the two signals $P_{mix} = 2 \cdot \sqrt{(P_{LO}P_{backscatter})} \cdot \cos(\varphi)$. This enables the measurement of the optical phase of the backscattered signal.
- 3) For Brillouin DTS, LO and backscattered signal can be adjusted to be shifted in frequency by approximately 10 to 11 GHz. This corresponds to the frequency shift of the Brillouin backscattering versus the exciting laser pulse. Mixing backscatter and LO this way allows to shift the detected signal to a lower frequency range. Thereby, the detection and digitalization components are lower in cost, complexity and power dissipation. The data rate and processing requirements are reduced, too.

Using coherent detection leads to a polarization-dependency of the detected mixed signal on the state of polarization (SOP) of the backscattered light: the optical interference is sensitive to the relative angle of polarization θ between LO and backscattering as in $P_{mix} = 2 \cdot \sqrt{(P_{LO}P_{backscatter})} \cdot \cos(\theta)$. The SOP of the forward-traveling pulse and the backscatter varies over distance in the fiber because of random birefringence. Thus, the detected mixed signal from some locations in the fiber may be close to zero (bad SNR). A multi-polarization detection is implemented for both DAS and DTS to counteract this drawback. This way, all backscatter information is detected, regardless of the local backscatter SOP.

2.2.2 All-optical signal amplification

The main limitation of the measurement range is the attenuation of optical power in the fiber due to scattering losses and point losses (e.g. splices). This loss amounts to usually 40 dB round-trip loss on a 125 km long fiber. An optical amplification process called 'Raman amplification' provides optical gain of the pulses and backscattering within the sensing fiber and regenerates the optical power of both – thereby the propagation loss of the fiber is countered, and the achievable distance range is enhanced.

For this process, 'pump light' with lower wavelength (higher energy) than the 1550nm signal is injected into the sensing fiber and creates the Raman amplification process by transferring energy from the higher energy pump to the lower energy pulse and backscatter signal.



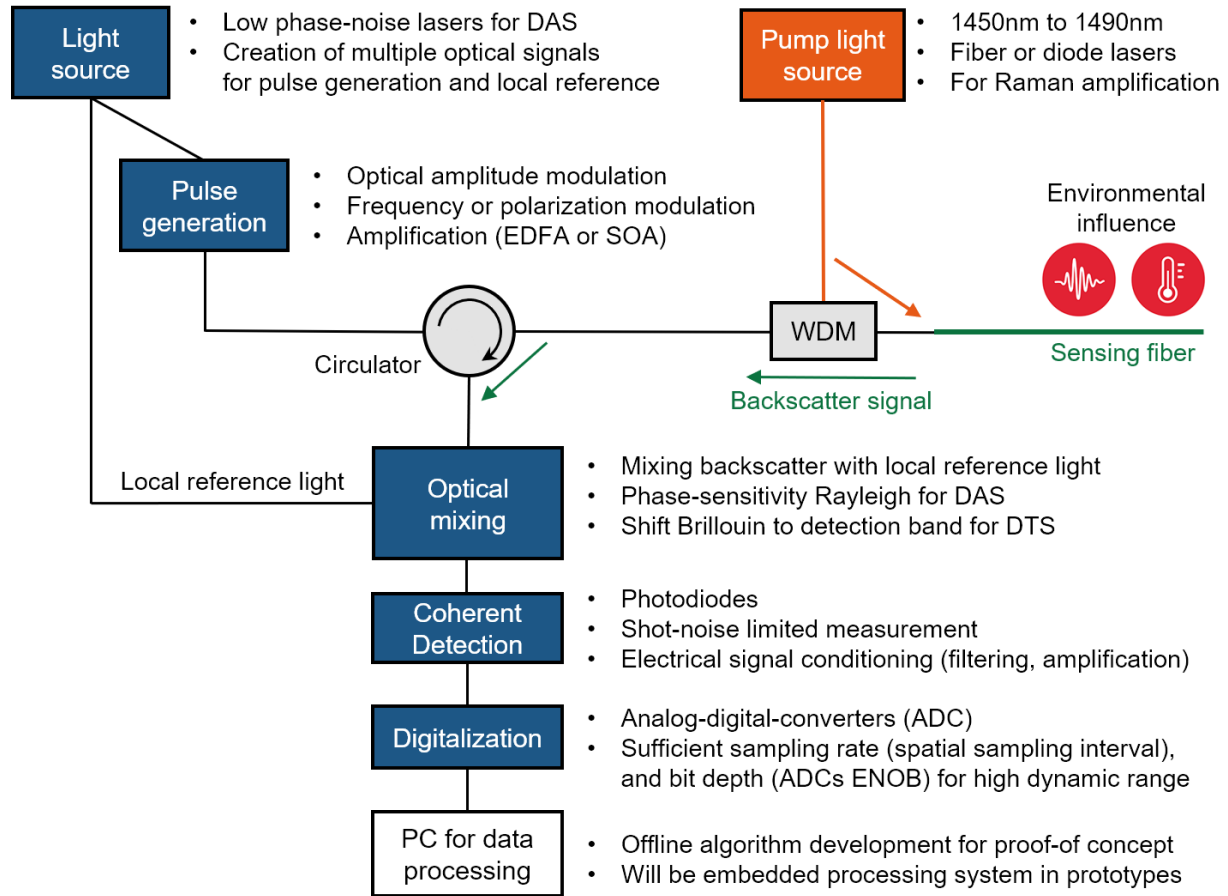


Figure 2: System design OTDR-based proof-of-concept laboratory setups with (optional) optical amplification for long-range DAS and DTS. WDM: wavelength-division multiplexer.

3 VERIFICATION TEST SETUP AND DEFINITIONS

This chapter first summarizes the performance criteria that the DAS and DTS performance is tested against. Next, the utilized test setups and performance metrics are presented.

3.1 Performance criteria

The performance criteria that shall be met by the DAS and DTS proof-of-concept setups as per the Deliverable report D3.3 are shown in the following tables. Only requirements applicable to the fundamental sensing measurement performance that are validated by the proof-of-concept laboratory setups are listed here.

Other requirements from D3.3 that are not listed below will be tested against the performance and quality of the DAS and DTS prototypes. Details on the definition of the parameters are given below.

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)
Distance range	15 km	> 125 km
Spatial resolution	≤ 10 m at 15 km	≤ 20 m at 125 km
Spatial sampling interval	≤ 1 m	≤ 5 m
Fibre compatibility	Single mode G.652.D	Single mode G.654 LL

Table 1: DAS performance requirements (taken from D3.3 report)

Parameter	Use Case 1 (STAT)	Use Case 2 (ENER)
Distance range	15 km	> 125 km
Spatial resolution	≤ 2 m at 15 km	≤ 10 m at 125 km
Spatial sampling interval	≤ 1 m	≤ 2 m
Temperature resolution	± 1.5 °C at 15 km	≤ 2.0 °C
Temperature range	-10°C to 100°C	-10°C to 100°C
Measurement time	≤ 30 min	≤ 20 min
Fibre compatibility	Single mode G652.D	Single mode G.654 LL

Table 2: DTS performance requirements (taken from D3.3 report)

3.2 Fiber routes and spatial resolution test setup

Two test routes are used to validate the performance of DAS and DTS for the two Use Cases. The output of DAS or DTS setups is connected to (a series of) fiber spools of the type and length defined by the Use Case requirements. The spools are in an isolated chamber to stabilize the temperature and reduce environmental acoustical/vibrational noise.

- For Use Case 1 (short range), 25 km of Corning SMF28e+ fiber are used [2].
- For Use Case 2 (long range), multiple spools of OFS TeraWave SCUBA 150 are used which comply with the G.654 standard and feature low loss (LL) of approx. 0.15 dB/km [3]. Such fibers are commonly used in long subsea HVDC cables.

Total additional losses of approximately 1 dB are introduced by fiber connectors and the SRES setup (see below).

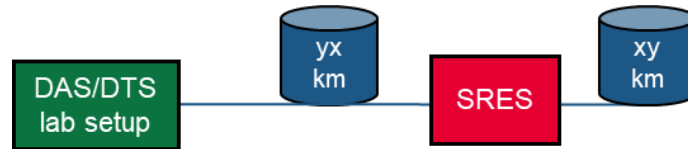


Figure 3: ‘Short-range’ test setup with 25 km G.652.D fiber for Use Case 1.

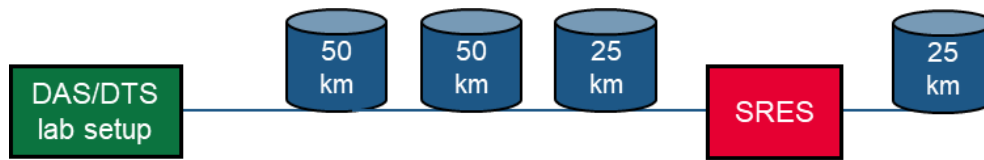


Figure 4: ‘Long-range’ test setup with 150 km G.654 LL fiber for Use Case 2.

The block ‘SRES’ is a setup for testing the spatial resolution (SRES). It is specific to DAS and DTS measurements:

For the DAS spatial resolution, a ‘Fiber Stretcher’ (FS) is used to simulate an acoustic event on the fiber [4], see Fig. 5. “A Fiber Stretcher, in the context of the Simulated Fiber Sensor, is a fiber wound on a piezoelectric cylinder. A voltage stimulus applied to the piezoelectric cylinder causes its diameter to increase or decrease so developing a voltage-proportional, uniform strain throughout the wound fiber length. The effective length of the fiber stretcher (...) is recommended to be greater than twice the gauge length of the interrogator being evaluated.”, from Ref. [5] Section 3.1.6. The effective length of 60 m is sufficiently larger than twice the 20 m target gauge length.

For DTS, a 100 m long section of fiber with elevated temperature is created in a temperature chamber which is stabilized to 70 °C. This setup is according to Ref. [6]. The fiber spools before and behind this ‘hot spot’ are at room temperature.

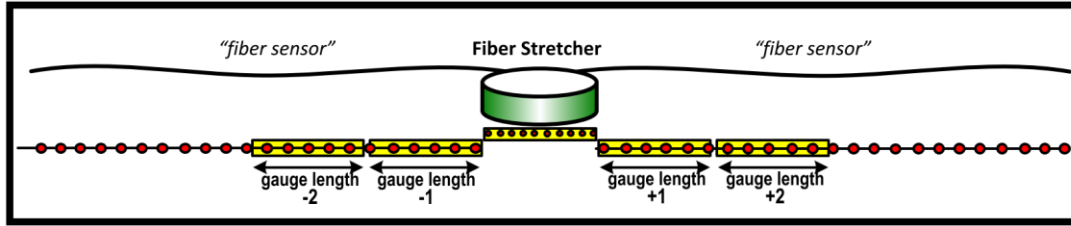


Figure 5: Depiction of a fiber stretcher test setup showing the gauge length and spatial sampling points (red dots). From Ref. [5].

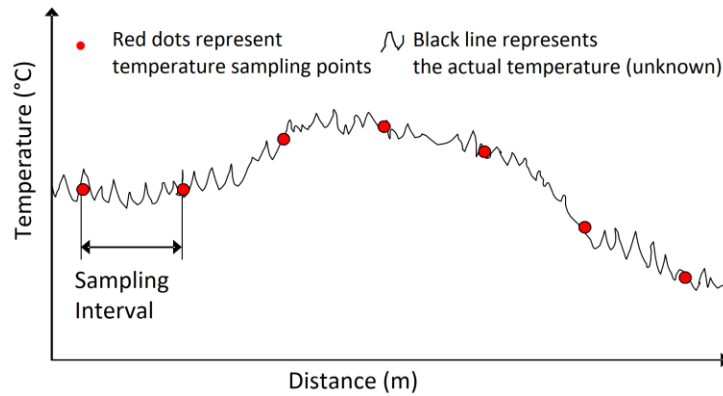


Figure 6: Example of a temperature trace with temperature sampling points spaced by the sampling interval. From Ref. [6].

3.3 Definition of performance parameters

3.3.1 Spatial sampling interval

For DAS, “the mechanical separation in meters between consecutive Spatial Sample Locations defines the Spatial Sampling Interval.”, from Ref. [5], Section 3.1.2.

For DTS: “The “sampling interval” is the difference in fiber distance between consecutive temperature sample points in a single temperature trace.”, from Ref. [6], Section 2.8:

See Fig. 6 for a visualization of a continuous temperature curve over distance which is sampled at discrete equidistant sampling points spaced by the sampling interval. For the end user, the sampling interval is usually experienced as the spatial distance between measurement points in the result that is displayed in the software GUI or exported measurement data.

3.3.2 Spatial resolution

For DAS, a good definition of spatial resolution is “the shortest fiber range distance within which the DAS system can spatially resolve localized acoustic or vibrational stimuli.”, from Ref. [5], Section 2. It is usually limited by a commonly used parameter called ‘gauge length’ which is defined as: “Gauge length is the distance (...) over which the IU measures the change in optical path length and, hence, the change in spatial integral of strain. (...)”, from Ref. [5], Section 3.1.5.

In DTS, the definition is “The smallest length of temperature affected fiber for which a DTS system can measure the reference temperature of this Hot Spot fiber condition.”, from Ref. [6], Section 3.2. We use the 10%-90% definition, as defined in Ref. [6], Section F 1.5.

For both systems, the spatial resolution can be interpreted as how fast the measurement result reacts to a change of the measured quantity on the spatial axis along the fiber, e.g. an abrupt increase in acoustic intensity, temperature or strain.

3.3.3 Temperature resolution

Temperature resolution refers to the noise level of the temperature measurement. A commonly used definition is the ‘temperature repeatability’ which is defined as: “The temperature repeatability is the random variation in calculated temperature between successive temperature traces, at a given fiber distance.”, from Ref. [6], Section 3.3. The single standard deviation (1σ) of 10 consecutive measurements is used to calculate this value.¹

3.3.4 Distance range

“The “distance range” is the maximum distance from the instrument for which the manufacturer will measure and guarantee a measurable standard of performance. For the specified “distance range”, all of the other key measurement specifications shall be stated.”, from Ref. [6], Section 2.4. This quantity states the physical distance in the fiber from the interrogator to a maximum position in the cable for which a defined measurement performance can be guaranteed.

For DTS, a commonly accepted definition of distance range for power cable monitoring is: the position at which the temperature repeatability exceeds 2°C (1σ). This has proven to provide the maximum distance range with the temperature noise level is sufficiently low for DTS-based features like hot spot detection or real-time conductor temperature rating (RTTR).

The maximum usable distance range for DAS depends strongly on the application and the type of events that shall be detected. A useful definition of the maximum acceptable DAS noise level was previously agreed on with TSOs in long-range power cable monitoring for detecting cable fault events. It uses the root mean square (rms) noise level of the measured phase data in acoustic frequency band above 5 Hz. It was found that an rms noise level below 1.4 rad is sufficient for the detection of loud short events such as cable faults. To ensure fault detection with low false alarm rate even at large fiber distances at locations with low SNR, the ‘ 3σ rms noise’² is a useful indicator.

¹ The temperature noise in a section of fiber for a single temperature trace could also be used. However, the repeatability is a more accepted and useful definition since it defines the distance range, see below. Furthermore, strain-induced Brillouin frequency deviations from the winding on fiber spools increase the spatial noise level artificially and thereby distort the results.

² The rms noise calculated from of the spatial samples within a range of 1 km with the 0.3% (3σ) percentile of highest noise levels.

4 PROOF-OF-CONCEPT PERFORMANCE RESULTS

4.1 Distributed Acoustic Sensing (DAS)

4.1.1 Results for Use Case 1 (short range)

Fig. 7 shows the RMS phase noise on a 25 km fiber route measured with 10 m gauge length. The definition of distance range given above is clearly fulfilled even at 15 km range where the noise level is only about 45 mrad (80 mrad 3σ) approx. 30 times (18 times) smaller than the fault detection limit. For the application in Use Case 1, the given DAS sensitivity will enable fault localization or partial discharge detection with high sensitivity along the entire cable length with low false alarm rates.

The spatial resolution is verified to be smaller than the required 10 m by the results in Fig. 8. It shows the local phase at the location of the fiber stretcher (FS) at 8 km distance. On the transition from quiet fiber to the active region on the FS, the phase signal ramp up happens in a spatial range of 9.72 m, and similarly for the down ramp. See the left and right ramps (red lines, LR and RR). The red plateau line marks the expected width with acoustic activity on the FS. The dashed horizontal line shows a threshold for valid signals of $3\times$ the rms noise (3σ) of the quiet sections around the FS. The sampling interval of this data is 0.81 m which is smaller than the required 1 m.

4.1.2 Results for Use Case 2 (long range)

The range limit of DAS with below 20 m spatial resolution is tested on the 150 km fiber route. Fig. 9 shows the rms phase noise level over distance. In this configuration 135 km distance range are achieved according to the definition given above. The stronger criterion of low ' 3σ rms noise' indicates a distance range of approx. 118 km.

Fig. 10 shows the phase signal around a FS at 124.8 km distance. The spatial resolution is below 20 m, which is the requirement in this measurement configuration with 20 m gauge length. Again, the dashed line shows the noise threshold (see explanation above) which is higher at this long distance with lower SNR of the backscatter signal. The spatial sampling interval of 2.45 m is lower than the required 5 m.

In total, the required 125 km range with below 20 m spatial resolution is achieved. Further improvement of the DAS signal quality is required for highly reliable cable fault detection at this range. We expect to achieve the required improvements during the prototype development and with more advanced Raman amplification, as described in the Conclusion & Outlook chapter below.

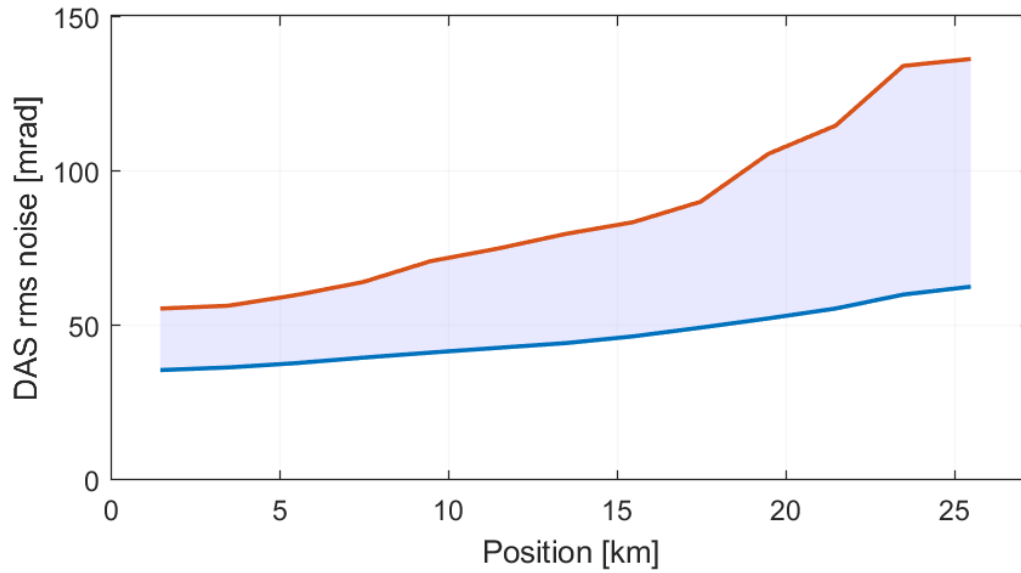


Figure 7: DAS noise level over 25 km distance. Blue: rms noise, Red: 3σ rms noise. Measured with 10 m gauge length.

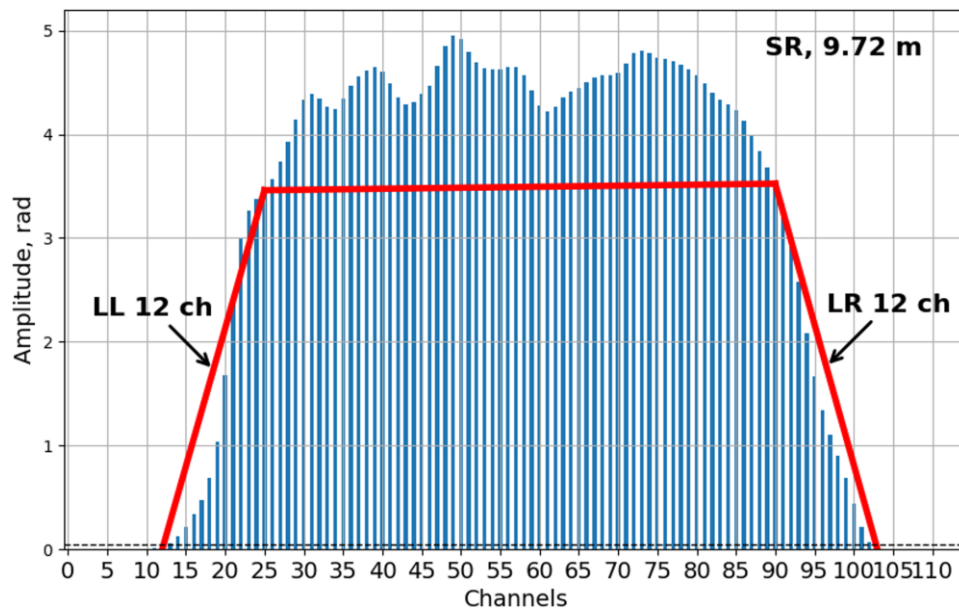


Figure 8: DAS signal level in the region of the Fiber Stretcher. Each channel represents one spatial sampling interval of 0.81 m width.

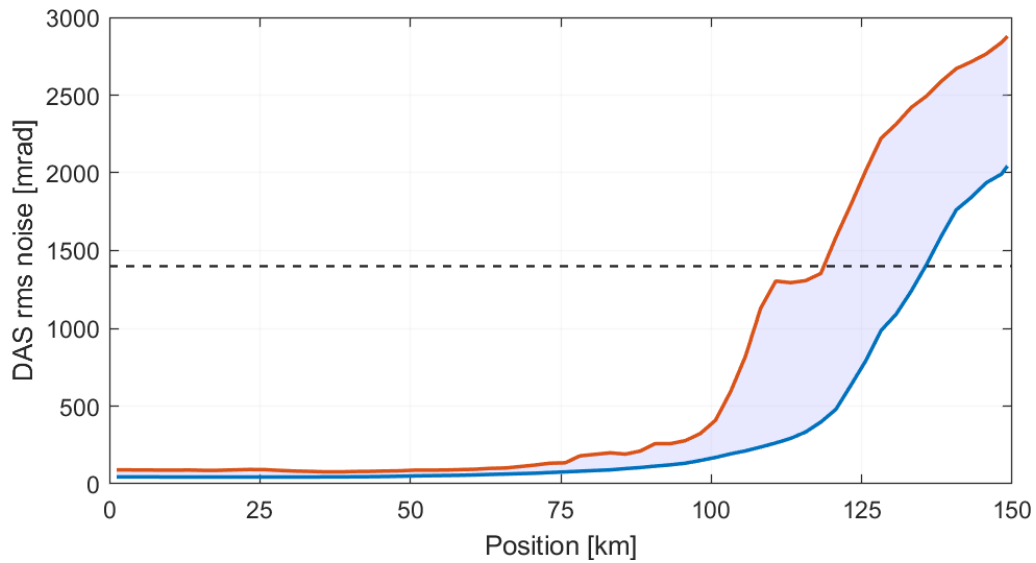


Figure 9: DAS noise level over 150 km distance. Blue: rms noise, Red: rms noise with 3σ detection probability. Black dashed line: loud event detection threshold. Measured with 20m gauge length.

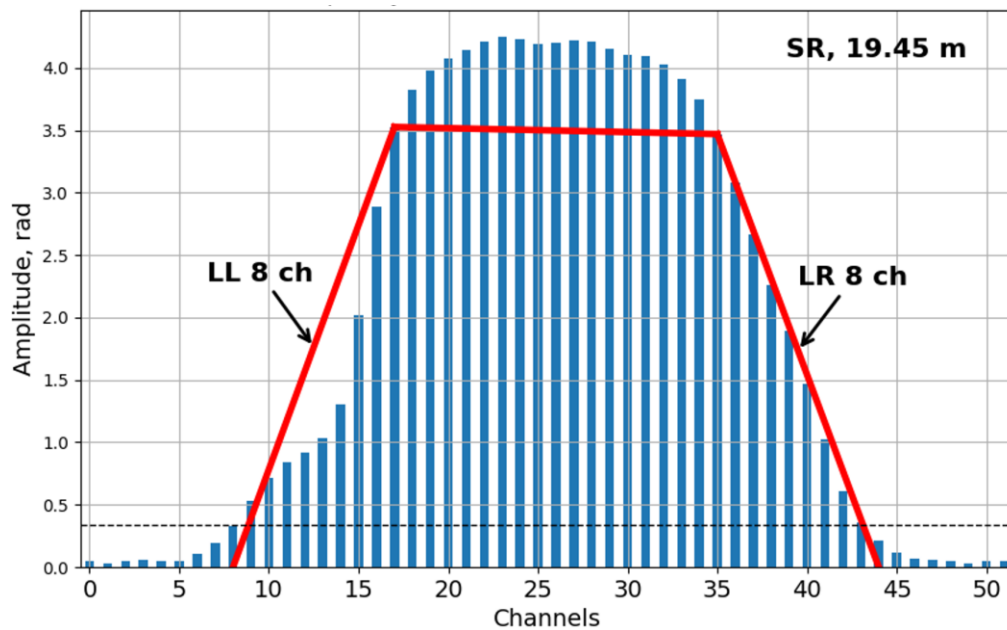


Figure 10: DAS signal level in the region of the Fiber Stretcher. Each channel represents one spatial sampling interval of 2.43m width.

4.2 Distributed Temperature Sensing (DTS)

4.2.1 Results for Use Case 1 (short range)

Fig. 11 presents the temperature resolution (represented by the temperature repeatability) for 10 min measurement time and below 2 m nominal spatial resolution (see Fig. 10). The limit of 1.5°C repeatability is well achieved up to 25 km which is much further than the required 15 km. Notably, less than 0.5 °C temperature repeatability is seen up to 15 km. The measurement time of 10 min is much shorter than the maximum allowed 30 min. With longer measurement time, the temperature repeatability could be improved, or the maximum distance range could be increased.

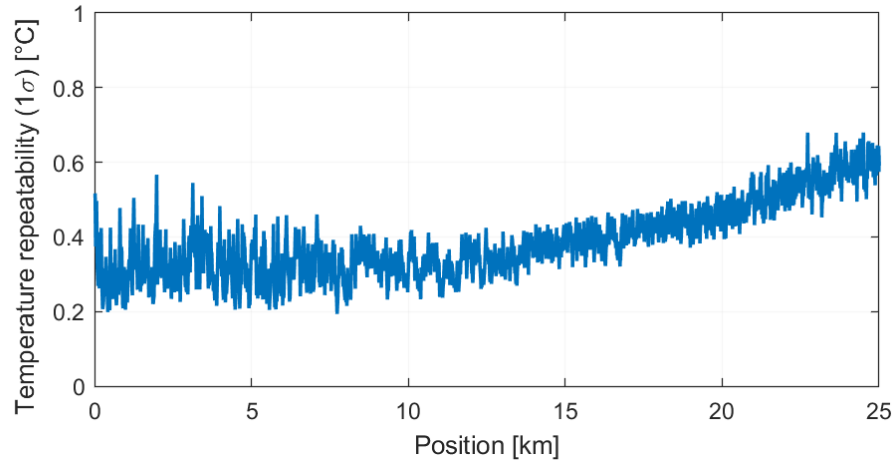


Figure 11: Temperature repeatability for 2m spatial resolution and 10 min measurement time.

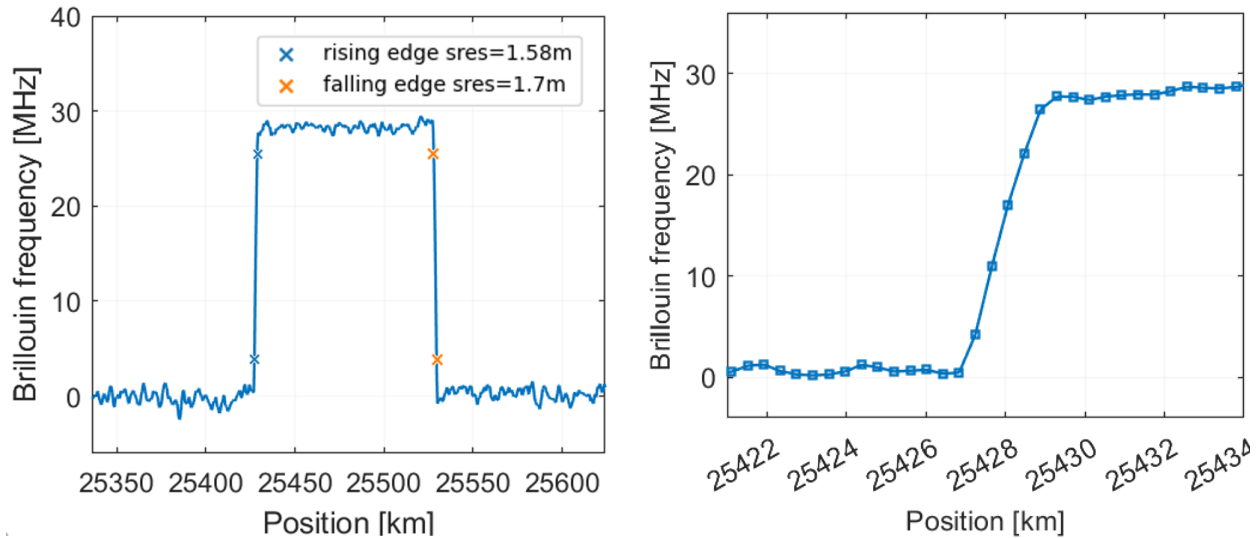


Figure 12: (a) Brillouin frequency across temperature hot spot (b) Close-up to the rising edge.

The spatial resolution is verified using the ‘hot spot’ setup at 25.4 km distance. Fig. 12(a) shows the temperature-induced Brillouin frequency shift across the transition from room temperature to a 55°C heated section. A frequency increase (decrease) of approx. 28 MHz is seen at the rising (falling) edge of the transition. More importantly, the rising and falling transition edges show a spatial resolution of 1.58 m and 1.70 m, respectively, which is below the required spatial resolution of 2 m. The sampling of the measured data in an interval of 0.4 m is illustrated in the close-up of the rising edge in Fig. 12(b) is below the required 1 m.

4.2.2 Results for Use Case 2 (long range)

The required DTS performance on 125 km fiber routes is verified by demonstrating less than 2 °C temperature repeatability, as presented in Fig. 13. Only 3 min measurement time are sufficient to cover 125 km. Up to 138 km can be monitored with the maximally allowed 20 min measurement time. The step-wise increases of repeatability behind 100 km and 125 km are caused by the decreased optical SNR due to connector losses upon spool transitions and the ‘hot spot’ setup. Note that the temperature of the first spool (first 50 km) was not stabilized and shows increased repeatability due to a temperature drift during the measurement time.

The spatial resolution and sampling interval are verified using a 75°C hot spot at 124.8 km, see Fig. 14. As per the requirements, less than 10 m spatial resolution at 2 m sampling interval are achieved.

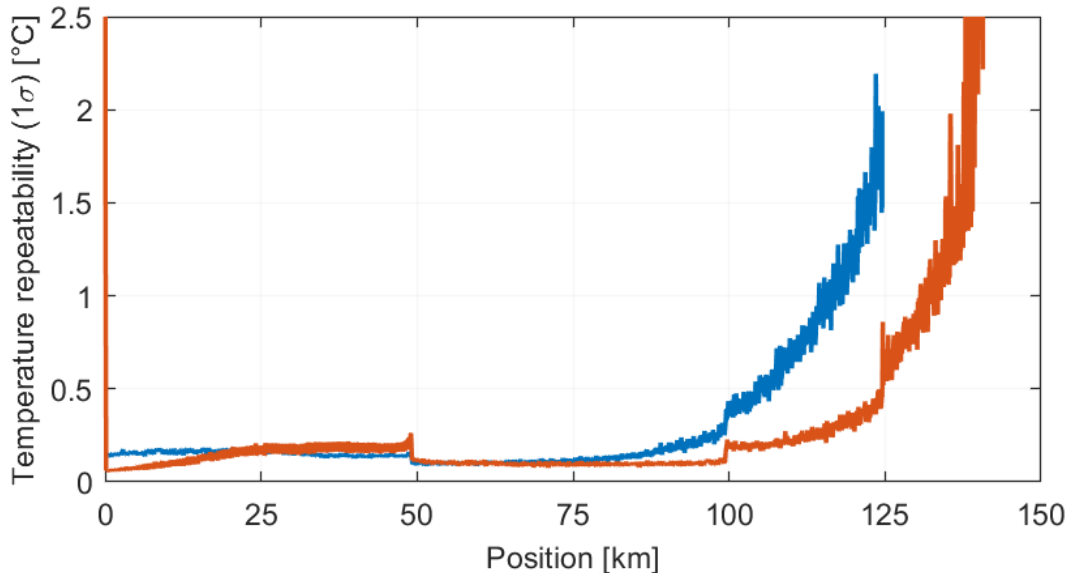


Figure 13: Temperature repeatability for 10 m spatial resolution with 3 min (blue) and 20 min measurement time (red).

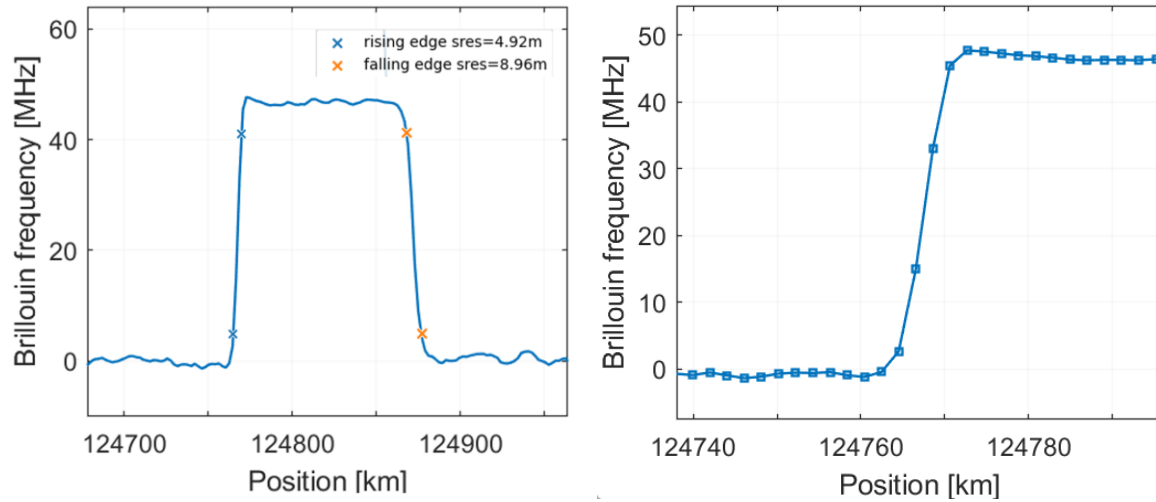


Figure 14: (a) Brillouin frequency across a temperature hot spot. (b) Close-up to the rising edge showing 2 m sampling interval.

5 CONCLUSIONS & OUTLOOK

The verification campaigns carried out confirm that the long-range DAS and DTS concept developed in Task 6.1 satisfies every performance requirement set out in D3.3. DAS measurements can resolve events over less than 10 m on a 25 km route and under 20 m on a 125 km fiber route, while the rms phase-noise stayed below the detection thresholds for cable fault. Short-range measurements show ample headroom for highly sensitive detection.

Temperature measurements reached sufficiently low repeatability levels to 25 km with below 2 m spatial resolution; and out to 125 km with below 10 m spatial resolution. All readings were obtained well within the prescribed acquisition times. Longer measurement times enable DTS at well over 135 km with only 10 m spatial resolution. The distance range can be pushed much further if higher spatial resolution or longer measurements times are acceptable.

Ultra long-range DAS and DTS measurements on over 125 km ULL fiber length will be improved further in the remainder of the project by optimizing the pulse modulation and receiver electronics in the prototype hardware development when compared to the laboratory equipment. Furthermore, continuing the work on noise reduction in raw data processing and post processing is expected to decrease noise levels for DAS (' 3σ rms noise') and improve the Brillouin frequency determination in low-SNR settings for DTS.

We expect a significant performance and range increase for both DAS and DTS to be achieved using improved Raman amplification. At the time of writing this report, the available Raman pump wavelengths and power were limited; and novel proprietary Raman amplification methods were not implemented yet. This performance boost will be reported in Deliverable D6.2.

Because the functional, accuracy and range targets were met or exceeded, the measurement concept, components choice and operating parameters were fixed for prototype interrogator development. The demonstrated performance also opens opportunities beyond HVDC-cable monitoring - in particular for long-range pipeline leak detection, railway-track surveillance, structural-health monitoring or geothermal-well supervision - where similar DAS and DTS capabilities are required.



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