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Field test regarding application of fiber optic measurement technology in boreholes at Forsmark

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Abstract

The use of fibre optic-based measurement technologies has increased significantly during the last decades. This is due to the advances of the instrumentation, fibre sensor design and availability of a diverse number of cable designs. New monitoring applications have demonstrated how effectively optical fibre sensors can be used to complement and provide additional information to conventional techniques, such as experienced within the SKB GAP-project. This was discussed at a SKB seminar in June 2017, to which HydroResearch and Silixa were invited. As a result of the interest shown by SKB, HydroResearch and Silixa were asked to set-up and perform a one-day field-demonstration to present the state-of-the-art of both optical fibre distributed and point sensors at the SKB site of Forsmark, where about 30 persons attended.

Optical fibre sensors can be divided in two distinct types: Distributed sensors, that enable continuous, real-time measurements along the entire length of a fibre optic cable, and Point sensors, where the optical fibre is used as guide of the optical signal to the sensing element. These two types of sensors have been deployed in two boreholes (KFM16 and KFM24), and the following measurements have been performed:

1. Pressure and temperature measurements in KFM24 using Opsens point sensors
2. Distributed temperature measurements in both KFM16 and KFM24 using two Silixa's monitoring units (one of which specifically conceived for field deployment)
3. Distributed active temperature (active-DTS, or A-DTS) measurements in KFM16 for evaluation of water flow and thermal properties of the bedrock
4. Distributed acoustic measurements in both KFM16 and KFM24 for seismic evaluation to detect changes of mechanical properties of the bedrock (in comparison to geophone/hydrophone installation).

The demonstration aimed mainly towards a hands-on experience trial to comprehend the potential of such technologies. Preliminary results are presented to demonstrate the applicability of the technology; however, extensive geotechnical and hydrogeological analyses were not carried out due to the relatively limited scope of the demonstration.

The intention with the demonstration of these optical based methods was to see what could be given just from these methods. Data was given about the geometry of the boreholes. But no information about the result from e.g. the drillings or further testing was provided to the team, neither before nor after the tests. Evaluations and interpretations presented in this report are based only on data collected during the field tests. No comparison with other information is therefore made in this report.

The quality and readiness of the fibre-optic data shown during the demonstrations, combined with the large variety of applications presented, received interest from different groups of SKB, Uppsala University, and Vattenfall. A lot of potential applications were mentioned and briefly discussed on the demo day, such as:

- Rock mechanics applications
- Thermal applications
- Hydrogeological applications
- Seismological applications
- Ecological application

Silixa and HydroResearch are truly motivated and looking forward to further discussions with SKB and their partners. By working together, we see great possibilities to further develop methods in order to provide the best solutions for the specific needs of nuclear waste management.

Sammanfattning

Mätning baserad på fiberoptik har ökat markant under de senaste decennierna. Detta beror på utveckling av nya tekniker, bättre mätinstrument, nya fibersensorer, samt större utbud av bättre anpassade kablar som är optimerade för specifika mätändamål. De nya applikationer som då framkommit har visat hur effektivt optiska fibersensorer kan användas. Mätningarna kan ge ytterligare information till konventionella tekniker, eller i vissa fall helt ersätta konventionell mätning, vilket exempelvis visats inom SKB GAP-projektet. Dessa möjligheter diskuterades vid ett SKB-seminarium i juni 2017, dit HydroResearch och Silixa var inbjudna. Som ett resultat av det intresse som SKB visat, ombads HydroResearch och Silixa att genomföra en endags fältdemonstration för att presentera det senaste inom både distribuerade fiberoptiska mätningar och punktsensorer. Detta gjordes i oktober 2017 i Forsmark, där ett 30-tal personer deltog.

Optiska fibersensorer kan delas in i två huvudtyper typer: distribuerade sensorer som möjliggör kontinuerliga realtidsmätningar längs hela längden av en fiberoptisk kabel, och punktsensorer, där den optiska fibern används för överföring av den optiska signalen till avläsningssensorn. Dessa två typer av sensorer installerades i två borrhål (KFM16 och KFM24), i vilka följande mätningar utfördes:

1. Tryck- och temperaturmätningar i KFM24 med Opsens punktsensorer
2. Distribuerade temperaturmätningar i både KFM16 och KFM24 med två olika mätinstrument från Silixa (varav ett speciellt utformad för fältutplacering)
3. Distribuerade aktiva temperaturmätningar (active-DTS, eller A-DTS) i KFM16 för utvärdering av grundvattenflöde och termiska egenskaper
4. Distribuerade akustiska mätningar i både KFM16 och KFM24 för seismisk utvärdering för att detektera förändringar av berggrundens mekaniska egenskaper (i jämförelse med geofon/hydrofoninstallation).

Demonstrationen gjordes primärt som ett fältförsök för att förstå potentialen hos tekniken. Ambitionsnivån och omfattningen var därför lägre och inte i nivå med det som görs vid normala mätningar. Preliminära resultat presenterades för att visa teknikens tillämpbarhet, men några jämförande geotekniska och hydrogeologiska analyser genomfördes inte baserat på dessa mätningar av demonstrationskaraktär.

Avsikten med demonstrationen av dessa optiskt baserade metoder var snarare att se vad som kunde utföras enbart från dessa metoder. Data erhölls om borrhålens geometri, men ingen ytterligare information om resultatet från exempelvis borrningar eller ytterligare tester lämnades till teamet, varken före eller efter testerna. Utvärderingar och tolkningar som presenteras i denna rapport baseras endast på data som samlats in under fälttesterna.

Kvaliteten på de fiberoptiska mätningarna som visades under demonstrationerna, i kombination med den stora variationen av applikationer som presenterades, väckte intresse från olika grupper inom SKB, Uppsala universitet och Vattenfall. Många potentiella applikationer nämndes och diskuterades kort på demodagen, exempelvis:

- Bergmekaniska applikationer
- Termiska tillämpningar
- Hydrogeologiska tillämpningar
- Seismologiska tillämpningar
- Ekologisk tillämpning

Silixa och HydroResearch har sedan länge fascinerats av vad tekniken kan erbjuda både idag och i framtiden och ser fram emot ytterligare diskussioner med SKB och deras partners. Genom att arbeta tillsammans ser vi stora möjligheter att vidareutveckla metoderna för att ge de bästa lösningarna för de specifika behoven av kärnavfallshantering.

Content

1 Introduction and background

The use of fibre optic-based measurement technologies has increased significantly during the last decades. This is due to the advances of the instrumentation, fibre sensor design and availability of a diverse number of cable designs. There is an increasing number of publications and development programs in place indicating a multitude of potential applications across several fields.

Optical fibre sensors can be divided in two distinct types:

- Distributed sensors, that enable continuous, real-time measurements along the entire length of a fibre optic cable.
- Point sensors, where the optical fibre is used as guide of the optical signal to the sensing element.

The optical fibre sensors are passive in nature, allowing their deployment in harsh environments for monitoring large infrastructures in oil and gas exploration, pipelines, security, nuclear, mines etc. Advances in optical fibre sensors have been mainly supported by the increasing demand of improving efficiency along the energy sectors, providing integrity measures, and have been part of a monitoring scheme under a low carbon economy. Silixa Ltd, UK (distributed sensors) and Opsens, Canada (point sensors) have been amongst the world-leading manufacturers of such emerging technologies.

HydroResearch was one of the early adopters applying distributed temperature measurements for leakage detection in embankment dams (Johansson and Farhadiroushan 1999). Nearly 20 years later, over 100 hydropower or tailings dams are now equipped with optical fibre cables in Sweden. The technology has also been adopted for other geotechnical and geophysical applications, with a considerable number of deployments for both the study of groundwater-surface water interactions and characterization of flow in boreholes. The high spatial density of measurements achievable over long distances/large areas, with high temporal and temperature resolutions has propelled distributed sensing technology due to the unique ability to provide insight into transient processes not readily captured by point sensing techniques.

SKB adopted distributed temperature sensing to carry out thermal profiling in a relative deep borehole under the Greenland Analogue Project (GAP), to identify the depth of the permafrost. Regular measurement campaigns have been carried out since 2011, where the distributed temperature data was used in combination with other monitoring systems (pressure, temperature, electrical conductivity) by HydroResearch and Geosigma, demonstrating how effectively optical fibre sensors can be used to complement and provide additional information to conventional techniques.

The achieved results and the awareness of the potential of the optical fibre sensing has led SKB to identify several applications on both short and long-term where such technologies could provide critical information for their scopes. Therefore, HydroResearch and Silixa have set-up and performed a one-day field-demonstration to present the state-of-the-art of both optical fibre distributed and point sensors on the 26th of October 2017 at the SKB site of Forsmark. The demonstration was a follow up from a SKB seminar where both HydroResearch and Silixa had been invited to give an introductory talk.

Optical fibre cables and fibre point sensors have been deployed in two boreholes (KFM16 and KFM24), and the following measurements have been performed:

1. Pressure and temperature measurements in KFM24 using Opsens point sensors
2. Distributed temperature measurements in both KFM16 and KFM24 using two Silixa's monitoring units (one of which specifically conceived for field deployment)
3. Distributed active temperature (active-DTS, or A-DTS) measurements in KFM16 for evaluation of water flow and thermal properties of the bedrock
4. Distributed acoustic measurements in both KFM16 and KFM24 for seismic evaluation to detect changes of mechanical properties of the bedrock (in comparison to geophone/hydrophone installation).

The demonstration aimed mainly towards a hands-on experience trial to comprehend the potential of such technologies. Preliminary results are presented to demonstrate the applicability of the technology; however, extensive geotechnical and hydrogeological analyses were not carried out due to the relatively limited scope of the demonstration.

The intention was to run the demonstration as a blind test, presenting results obtained exclusively from the optical based methods installed. Neither cross comparisons with other techniques nor integration of data with previously available measurements were performed and therefore included in this report. Data was provided to the project team about the geometry of the boreholes, but nothing about any previous tests run by SKB in the boreholes.

Result from the different measurements is summarized in:

- Excel-file containing result from Opsens, DTS in KFM16 and Active DTS in KFM24, sent to SKB
- iDAS data for passive and active seismic (.SEGY-format), sent to SKB and Uppsala University

About 30 persons attended the field demonstration, which was preceded by Silixa's and HydroResearch's presentations of fibre optic-based monitoring applications including future advances.

2 Site description

The boreholes instrumented were KFM24 and KFM16. Basic documentation regarding the drilling were provided by SKB, by the report by Nilsson (2017).

The two boreholes, KFM16 and KFM24 are located southeast of the cooling water channel as shown in Figure 2-1 . KFM24 is the deepest drilled from a concrete slab that still surrounds the surface around the top of the borehole (Figure 2-2). KFM16 is shallower than KFM24 and was drilled without a concrete slab.

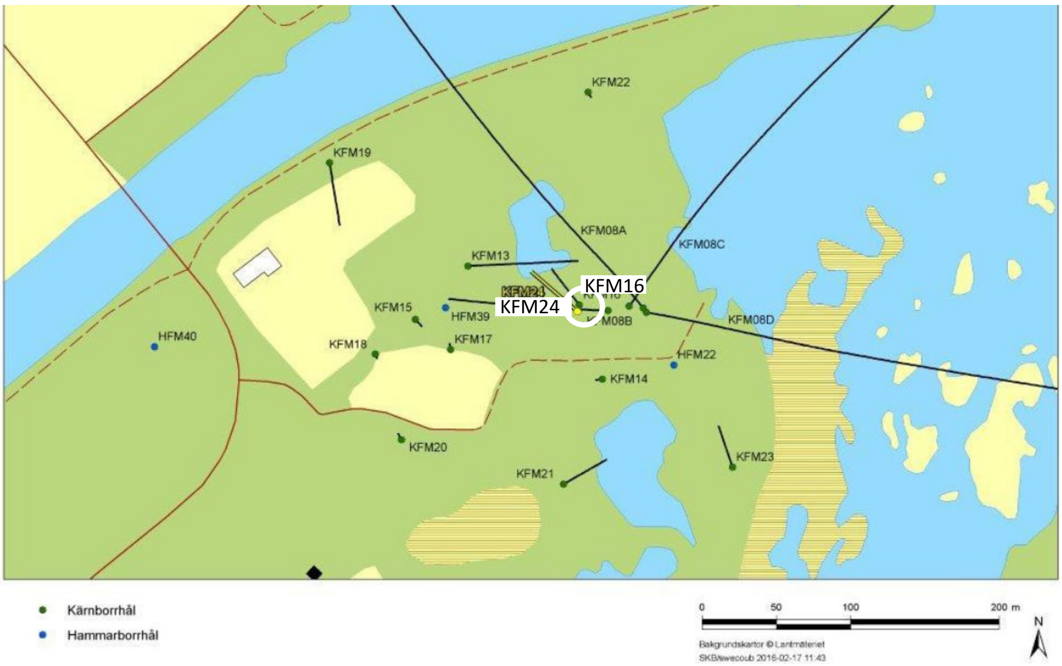


Figure 2-1. Map showing the location of the core boreholes KFM24 and KFM16 used in the field test.

Figure 2-2. Photo of the boreholes.

Borehole KFM24 has a length of 550 m and an inclination of 84° (Figure 2-3). The upper 35.6 m have a diameter of 200 mm or larger, while the diameter below 35.6 m is 76 mm. Casing goes down to 35 m. The top of casing (TOC) is about 0.3 m from the soil surface. More details are shown in the completion diagram in Figure 2-3.

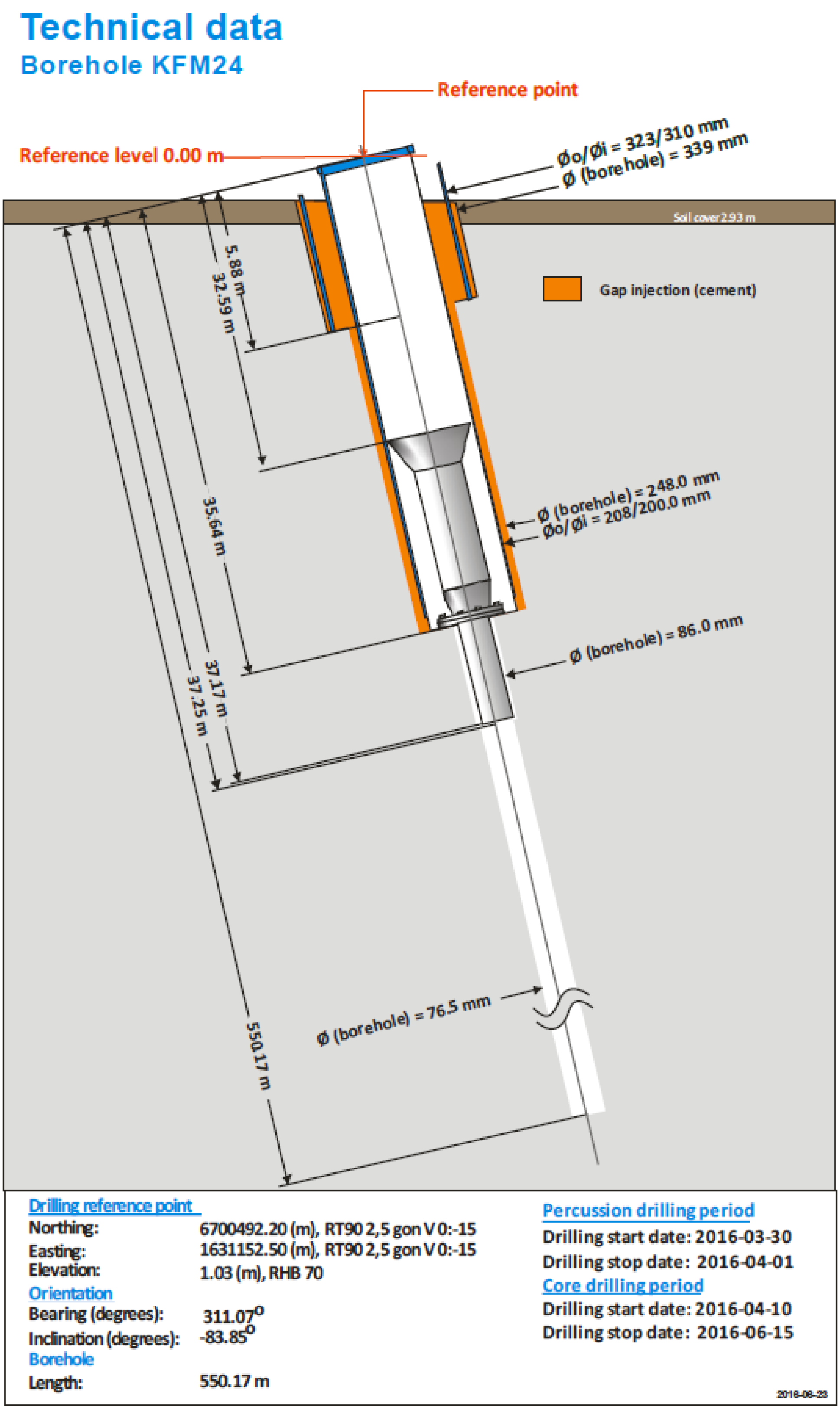


Figure 2-3. *Technical data for KFM24.*

Borehole KFM16 has a length of 60 m and an inclination of 59°. The hole has a diameter of 76 mm, along its entire depth as shown in Figure 2-4. Casing is down 4.42 m with TOC located about 0.5 m above the soil surface, before extension during the test.

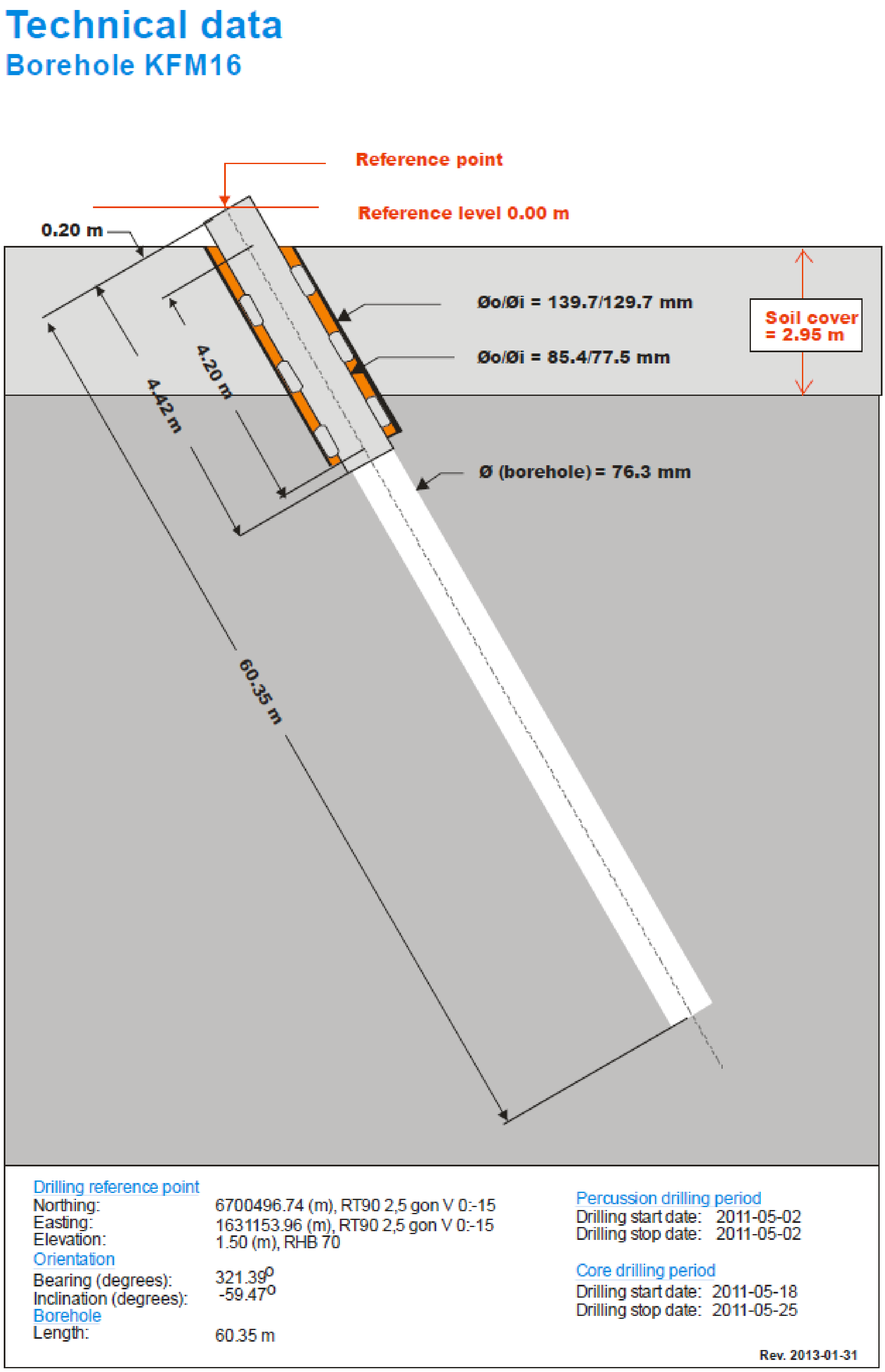


Figure 2-4. *Technical data for KFM16.*

3 Activity plan

SKB, Silixa and HydroResearch visited Forsmark on Oct 4th, 2017 to perform a site inspection and discussed the deployment plan for the field demonstration. Based on this information an Action Plan was carried out (SKB AP SFK-17-028). The roles for persons involved were defined as shown in Figure 3-1.

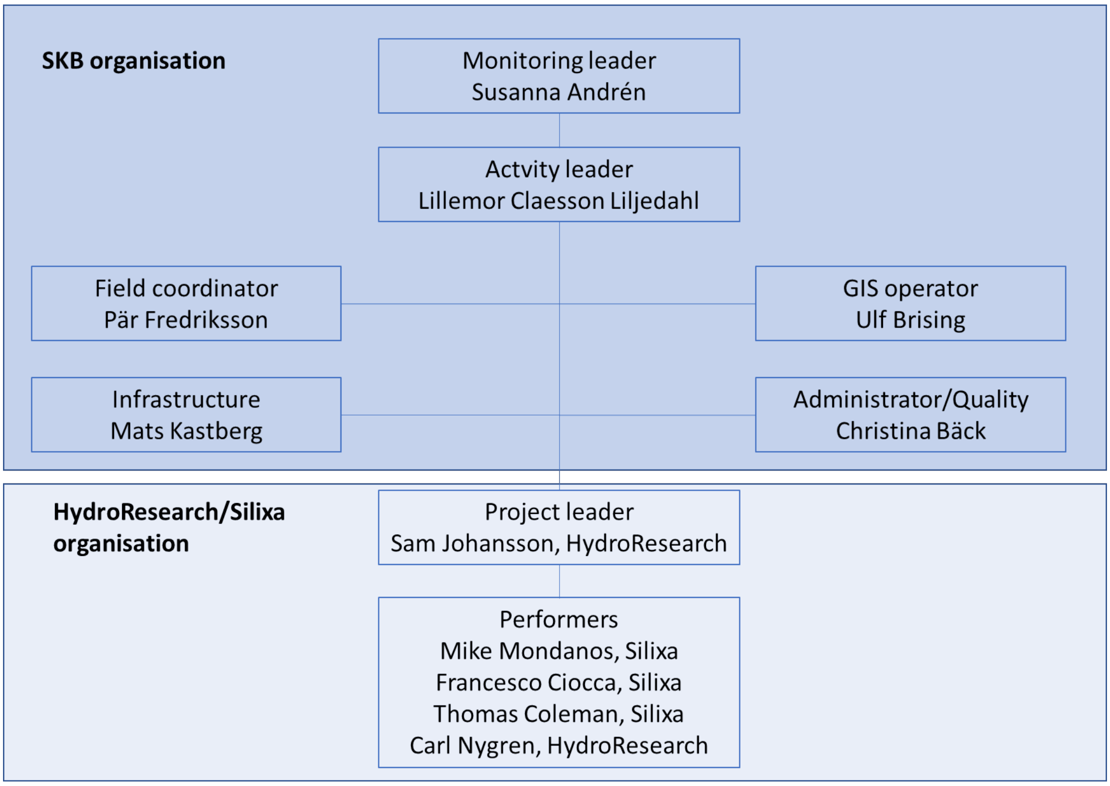


Figure 3-1. *Organisation scheme.*

SKB provided the test location, one container and one trailer to install the equipment, logistics, on-site support, accommodation near the site and a site H&S orientation over a period of 6 days in October. Below is a summary of the activities performed;

Sunday 22nd - Travels and final preparations:

- Arrival on site, and final preparation of monitoring components.

Monday 23td - beginning of installation:

- Site introduction, FLUTe liner installation in KFM16, cable installation in KFM16 and KFM24. Deployment of Opsens sensors in KFM24. Start of distributed and point measurements.

Tuesday 24th – end of installations:

- Testing of iDAS measurements, connect Active-DTS heat pulse system and start of a six hour long heating test on KFM16.

Wednesday 25th – final test and special demo:

- Field demo for visitors from Uppsala University and Vattenfall Research and Development, with specific focus on acoustic applications.

Thursday 26th – Field demo day:

- Presentation and introduction of the methods showed in the field and initial result, followed by demonstration of the different monitoring devices in field; decommissioning.

Friday 26th – Final packing and travel:

- Removal and packing of all used material. The equipment directly bought within this project (the 60 m liner made for KFM16) belongs to SKB and was transferred to SKB after removal from the borehole.

The equipment deployment is shown in the schematic in Figure 3-2.

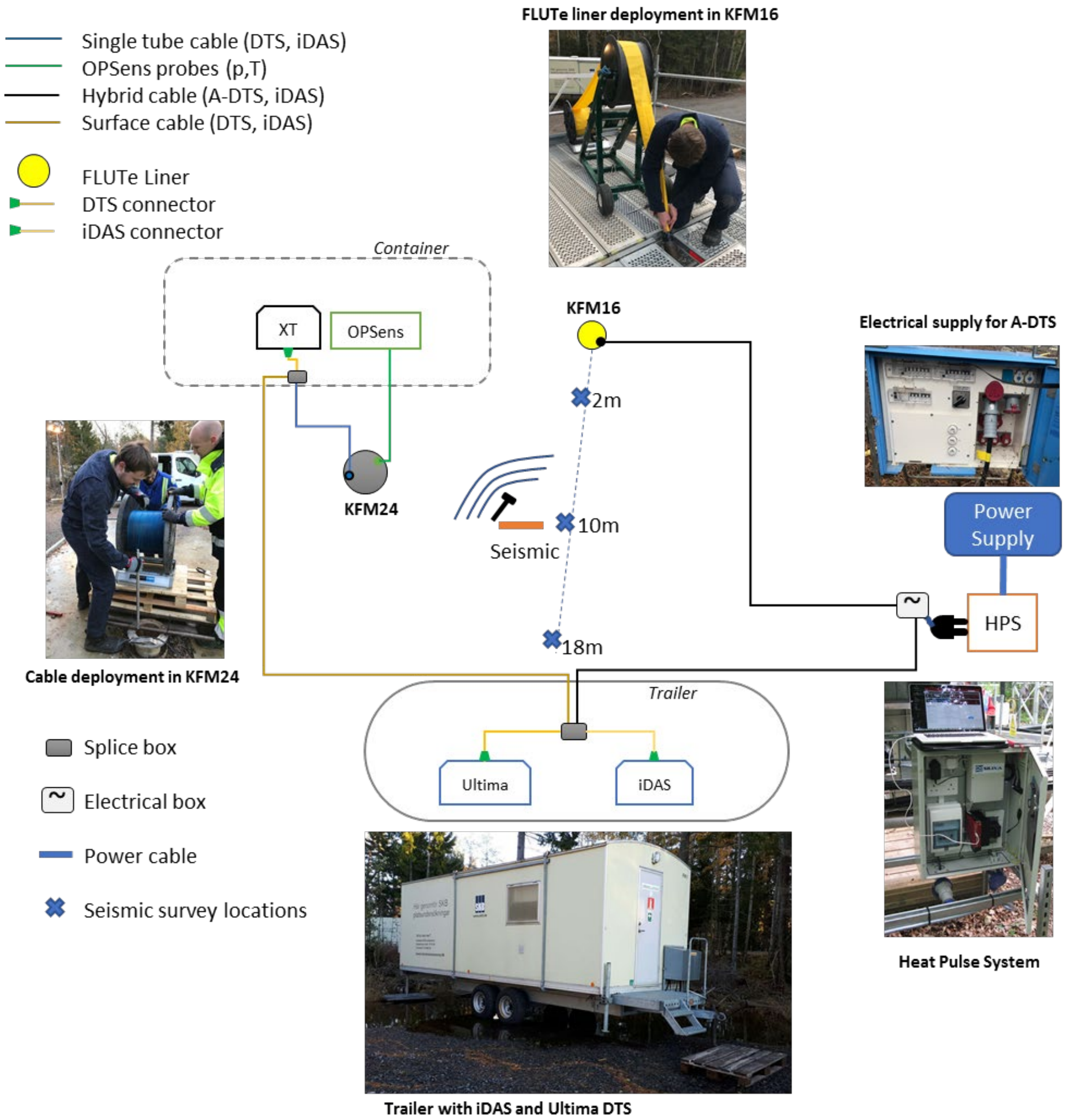


Figure 3-2. *Installation set-up for the demonstration.*

4 Distributed temperature measurements

4.1 Objective

Demonstration of distributed temperature sensing (DTS) with fibre optic cable to measure temperature profiles in KFM16 and KFM24.

4.2 Monitoring method and unit

Distributed temperature sensing is performed using a DTS monitoring unit and a cable with standard optical fibres. The technique is based on Raman backscatter (Dakin et al. 1985, Tyler et al. 2009). Similar technology was used on the deployment by SKB under the GAP-project.

Resolution performance is dependent on multiple factors, but recent advances in instrumentation have allowed for temperature and spatial resolutions as fine as 0.01 °C and 30 cm, respectively. To achieve this spatial resolution a finer sampling resolution is needed. Experiences from several installations can be found in Johansson and Farhadiroushan (1999) and Johansson and Sjödahl (2017).

A cable based on a polymer encapsulated steel tube containing optical fibre, known as a fibre in metal tube (FIMT) was installed in KFM24. The datasheet can be found in Appendix 2. At the bottom of the cable the pairs of optical fibres were spliced in a u-bend configuration (duplexed) within Silixa's engineered downhole termination (Figure 4-1). The downhole termination protects the fibres from mechanical damage and water ingress while providing a return path. Duplexed fibres provide a great deal of flexibility enabling robust temperature calibration methods to be utilized while also allowing for cables in multiple boreholes to be connected and monitored simultaneously using a single DTS or iDAS unit. A double-ended configuration utilizes looped or duplexed fibres, enabling autocorrection of changes in optical signal attenuation along the fibre length of the two wavelengths of backscattered light used in Raman DTS (variable differential attenuation). In such configuration there are potential improvements to the temperature accuracy of the fibre measurements (e.g. van de Giesen et al. 2012). The termination also helps with the deployment as the additional weight keeps the cable under tension during the installation which is especially important in inclined boreholes.

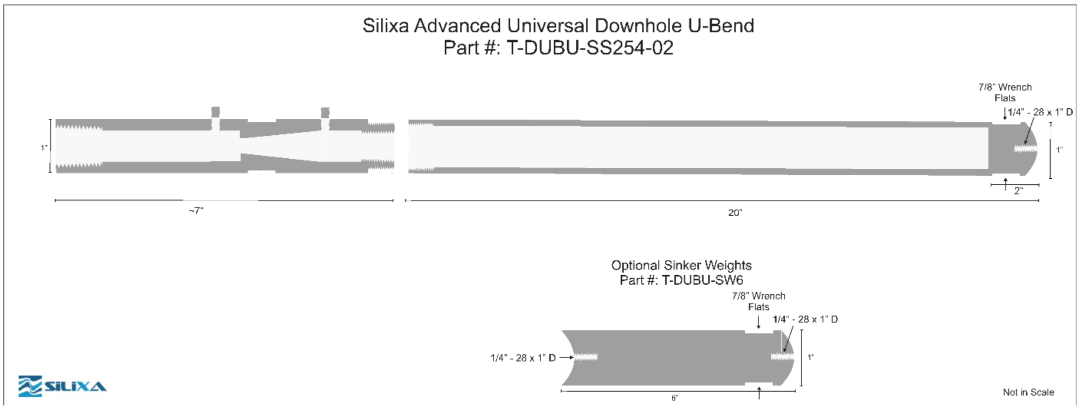


***Figure 4-1.** Downhole termination and cable used for KFM16 and KFM24.*

Two different DTS units were used for the temperature measurements on site; Silixa Ultima-S for KFM16 and Silixa XT-DTS for KFM24 (Figure 4-2). Ultima-S is a rack mounted unit and has the finest spatial resolution available on the market.

The XT-DTS is designed for remote and harsh environments, with coarser spatial resolution than the Ultima-S but with an optimised performance over selected range lengths. Specifications can be found in Appendix 3 and Appendix 4, respectively. Measurements in KFM24 started on October 23rd and stopped on October 26th.

Figure 4-2. *Silixa Ultima (top) and Silixa XT-DTS (bottom).*

4.3 Results

The temperature profile of KFM24 is shown in Figure 4-3. Between 100 and 550 m a temperature gradient of 10 °C/km can be seen. The temperature remained stable within the borehole during these measurements, allowing the data to be used as a demonstration of the instrumentation's field performance. The calculated standard deviation was <0.02 °C and Tmax-Tmin was ≈0.1 °C at all depths. Both measurements are a good indicator of the resolution and stability performance of Silixa XT-DTS.

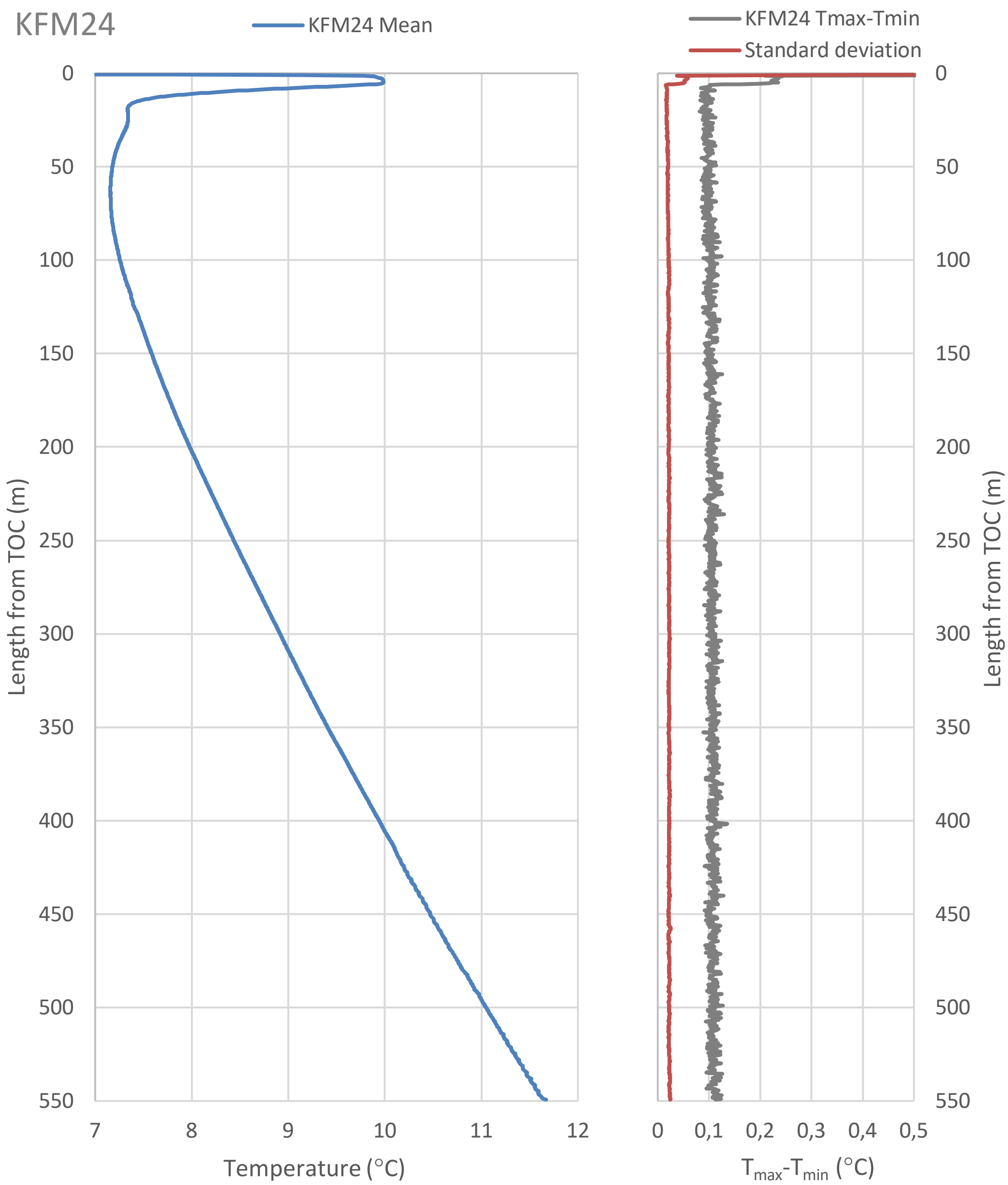


Figure 4-3. *Mean temperature profile (left) for KFM24, and max-min temperature and standard deviation (right) during the measurement period 20171023 19:02 to 20171026 15:26. 0-point is TOC.*

5 Active-Distributed Temperature Measurements

5.1 Objective

Silixa demonstrated thermal response measurements using an Active-DTS (A-DTS) technique to infer a distributed profile of apparent thermal conductivity of the formation at sub-meter resolution. The apparent thermal conductivity is a powerful variable that can provide key indications of changes in the lithology of the formation as well as identify the presence of active fractures with groundwater flow (Coleman et al. 2015, Bense et al. 2016).

5.2 Monitoring method, application and unit

The principle relies on the generation of an artificial increase in fibre optic cable temperature (i.e. the heat pulse). Active heating is achieved by creating an electrical heating circuit using metal conductors embedded into special optical cables, often known as hybrid or composite because of their structure. The Joule effect causes a homogeneous power output and heat dissipation along the cable, with the temperature response governed by the thermal properties of the formation surrounding the cable. The cable locally exchanges heat with the formation through conduction, differently according to the thermal conductivity of the medium in contact with the cable. The presence of groundwater flow (such as in active fractures) enhances heat transport through thermal advection. By monitoring the thermal response at all points along the cable during heating and/or cooling, an apparent thermal conductivity profile can be calculated at sub-meter vertical resolution. In a qualitative sense, the smaller the temperature increase during the heating, the more thermally conductive is the medium surrounding the cable.

A description of the hybrid optical cable used for the demonstration is in Appendix 1.

The cable was terminated at the far end using the same type of steel downhole termination applied to the single steel tube cable deployed in KFM24 (Figure 4-1). The fibres were spliced in pairs and in this case the termination also included the connection of the electrical copper conductors, to form a closed electrical circuit for cable heating.

60 meters of hybrid cable were deployed in KFM16 on October 23rd. After the cable installation, a flexible borehole liner (FLUTe) was installed. The FLUTe liner is a fabric “inflatable sock” that has the function to seal the borehole and to prevent any cross-connected flow that could bias measurements of the natural gradient groundwater flow system. The liner also presses the optical fibre cable against the borehole wall, significantly improving the contact (i.e. coupling) between the cable and the formation. This improved installation/coupling method in most cases removes the potential effect of installation variability on the thermal response while improving sensitivity to changes in apparent thermal conductivity. The liner also improves the efficiency of ground motion/strain transfer from the formation to optical fibre, thus improving the distributed acoustic sensing response.

To enable installation and keep the liner inflated, a positive pressure differential between the water inside the liner and formation of about 3 meters of water head was maintained. SKB made this possible by kindly providing a platform with a water reservoir and an above-the-ground extension of the KFM16 casing. The platform, as well as the water reservoir at higher level, allowed to perform the descent of the liner in ideal conditions (Figure 5-1). The 1.5 m extension of the KFM16 casing gives a new TOC, which is used in the data presentation below.

Figure 5-1. FLUTe installation (left) and KFM16 head extension with the platform (right).

A 6-hour heat pulse was applied before the demonstration (on October 24th afternoon) to the 60 m of cable deployed in KFM16, at a heating power rate of 7.5 W/m. The power rate was selected and kept stable using Silixa's Heat Pulse System (HPS) as shown in Figure 3-2. The HPS uses AC current from an electrical source (mains in this specific case) and delivers constant power even in presence of variations of the cable electrical resistance with increasing temperature. This is a critical benefit as the A-DTS application relies on the assumption of a constant power supply. A description of the HPS is provided in Appendix 6.

The Silixa Ultima-S DTS (refer to Appendix 4 for the technical specifications) was used to monitor the temperature every 0.126 m along the cable, at time intervals of 30 seconds, in double ended configuration.

5.3 Results

The supplied power rate of 7.5 W/m was sufficient to generate temperature increases > 8 °C at the top 3 meters of cable installed in the well head extension (surrounded by air, a good thermal insulator), and between 4 °C and 8 °C below the surface, where the cable is in contact with the highly thermally conductive saturated rock formation (Figure 5-2).The temperature change ΔT, was calculated by subtracting the ambient background temperature at each DTS spatial sample depth in KFM16 from all subsequent measurements after the heating cycle has commenced (Figure 5-3, left). Variations of ΔT with depth may indicate variations in the lithology (the cable is in contact with rock presenting varying mineralogy, porosity, and associated thermal conductivity) as well as the presence of fractures with water flow removing heat by advection. For the demonstration, the temporal evolution of ΔT during the heating phase was analysed per each DTS spatial sample along KFM16, to extract a distributed profile of apparent thermal conductivity (Figure 5-3, right).

The vertical ambient temperature profile (Figure 5-3 left) was measured after installation of the cable and the FLUTe liner using water from the tank, which was not at the same temperature as the water into KFM24. The lack of thermal equilibrium in KFM16 at the time of the measurements therefore explains the different temperature profiles with depth, compared to KFM24 (Figure 4-3).

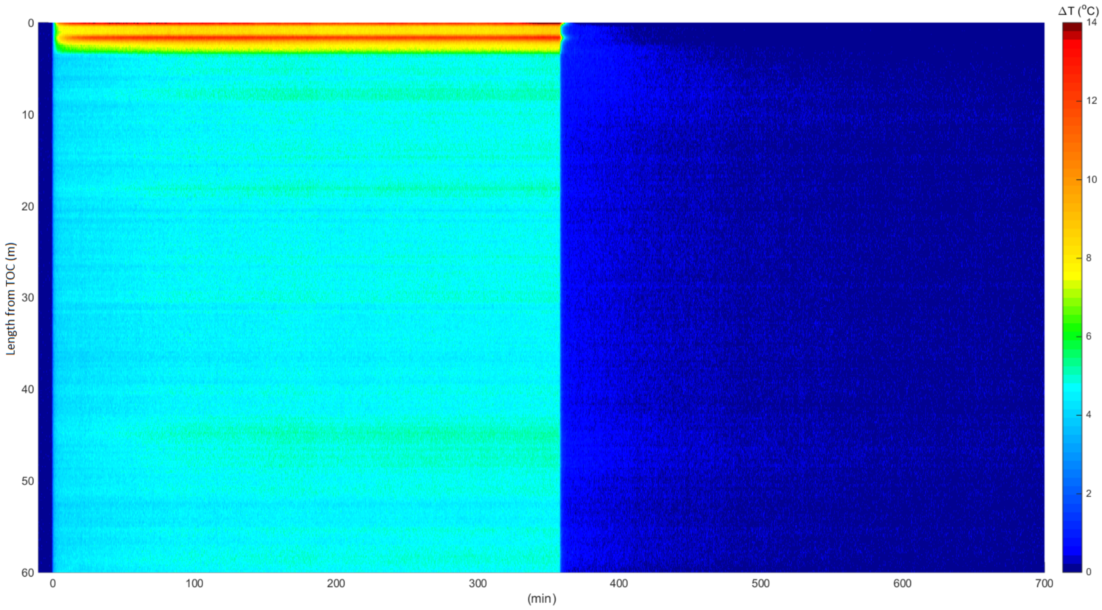


Figure 5-2. *Thermal plot of the A-DTS test performed in October 24th, with temperature colour scale as shown on the left. The x-axis is time in minutes, after heating started. The y-axis is the borehole depth (meter below the top of the casing, TOC).*

Calculated apparent thermal conductivity with depth (Figure 5-3) are in the range [2-5 W/mK], which is typical for saturated rocks. Typical values for granites are about 3.4 W/mK, with a variation between 2.1-4.1 W/mK (Sundberg 1988). The higher values of apparent thermal conductivity [4-5 W/mK] are likely representative of locations with groundwater flow in fractures.

Further refinement of the absolute accuracy of the apparent thermal conductivity profile can be achieved through calibration with a few core samples from unfractured locations without flow. The obtained result could then be combined with detailed lithological profiles previously extracted by SKB with both direct and indirect methods, and allow to:

i) provide reference values of thermal conductivity for the different bedrock layers

ii) associate anomalously high values of calibrated thermal conductivities to presence of features such as fractures with flow and

iii) monitor the evolution of the features at high space-time resolution, providing valuable data for flow quantification and hydrothermal modelling of the formation.

A gentle increase in the profile is visible below 10 m below TOC (mbTOC), followed by another much sharper at 20 mbTOC, which might indicate a sensible change in the rock thermal properties. Another feature of interest is the "M" shape of the profile between 20 m and 25 m depth, and the decrease between 45 mbTOC and 50 mbTOC.

Localized areas presenting departures from the expected values might indicate the presence of localized flow in fractures. Repeated measurements can provide more information and possibly, thanks to recent improvements in the data treatment, quantitative information about volumetric groundwater flow. Numerical modelling of A-DTS measurements in the hydrogeological context of the site can greatly expand the utility of the apparent thermal profile by enabling the estimation of flow in individual fractures.

A-DTS data are provided to SKB along with the report in .xlsx format, to allow the comparison with the lithology around KFM16.

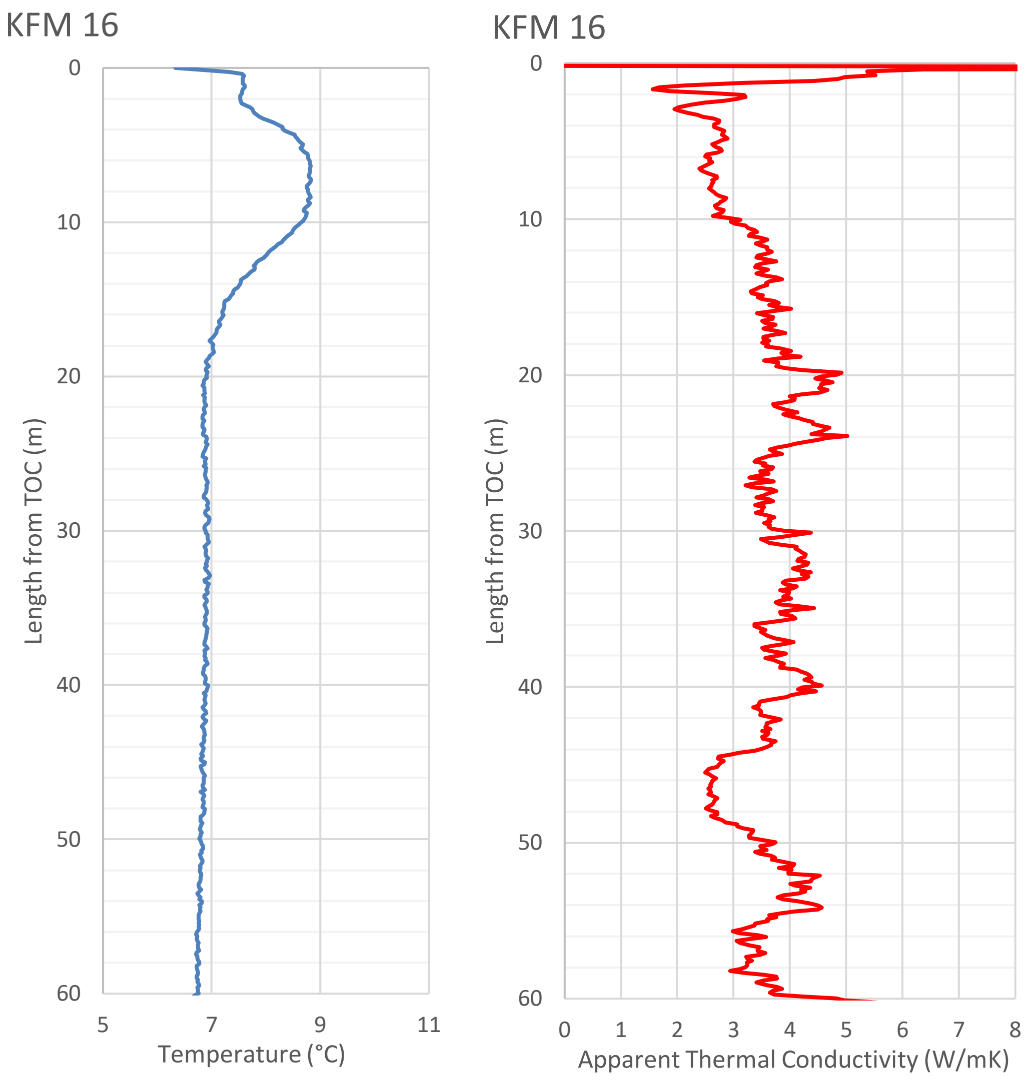


Figure 5-3. *Vertical ambient temperature profile (left) before the A-DTS test and resulting apparent thermal conductivity profile (right). TOC used in the figure refers to the extended pipe used during the test, i.e. not the same TOC as per KFM24.*

6 Intelligent Distributed Acoustic Sensor, iDAS

6.1 Objective

Silixa aimed at demonstrating the capability of its intelligent Distributed Acoustic Sensor (iDAS) to detect and record the arrival and propagation of seismic waves (Parker et al. 2014) along the formation using optical fibre. Seismic waves were actively generated in proximity of KFM16 and KFM24 using a seismic source. Qualitative information using 2D space-time plots is provided. The scale of this survey was intended to provide an introduction to distributed acoustic sensing for seismic applications. Results are scalable to the scope of the investigation, with the measurement technique being especially suitable for large scale 4D (3 spatial dimensions plus time) investigations due to the inherent measurement efficiency advantage of a permanently installed high resolution receiver array. Low frequency strain applications and monitoring techniques were beyond the scope of the demonstration.

6.2 Monitoring method and unit

A metal plate (60 cm x 20 cm x 2 cm) was laid at the soil surface at different offsets (2 m, 10 m, 18 m) in the southern direction with respect to the head of KFM16, along the orientation of the borehole (Figure 3-2). A 3 kg sledgehammer was used as a seismic source. The sledgehammer was manually driven to hit the top of the metal plate. This generates mostly seismic pressure waves (P-waves), to which the optical fibres are particularly sensitive to in this installation geometry because compressions and expansions are especially induced in the longitudinal direction of the fibre.

On October 23rd the optical fibres of different cables were spliced to allow the simultaneous acoustic monitoring of KFM16 and KFM24 (Figure 6-1). A as the fibres were spliced in the downhole terminations, both boreholes were measured twice in opposite directions, increasing the total length of fibre sensed to about 1,600 m.

KFM16 was first in the series, located between optical fibre distances of 40 m and 160 m in Figure 6-1, while KFM24 was located from 350 m to 1450 m along the measurement fibre

An accelerometer connected to a GPS antenna was used to trigger the acquisition in order to capture the wave time arrivals. This facilitates the stacking of multiple shots to improve the signal-to-noise ratio. 15 shots per each offset were recorded during the demonstration, on October 26th. An iDAS with a gauge length of 10 m and sampling resolution of 0.25 m was used. The sampling frequency was 5 kHz. The shots were then low pass filtered at 500 Hz and stacked to remove high-frequency noise.

6.3 Results

iDAS provided a clear response to the generated seismic perturbation (Figure 6-1). The high magnitude zones indicate either vibrations of the cable laying on the surface or coiled on the drum close to the head of KFM24, or tube waves attributed to the vibration of the casing and/or grout. Tube waves were mostly visible in the top 5 m for KFM16 (Figure 6-2, left) and 30 m for KFM24 (Figure 6-2 right), Deeper, the arrival of the P-wave was detected in both boreholes. In KFM16 the signal was much stronger than in KFM24 because of the presence of the FLUTe liner that increased the signal coupling efficiency between the formation and cable. In KFM24, despite the lack of liner for coupling and the weak seismic source adopted, it was still possible to distinguish the first arrival of P-waves up to 300 m depth and therefore calculate its velocity. The application of a FLUTe liner in KFM24 would have improved the measured response while also allowing monitoring the entire depth, allowing more seismic wave reflections and subsequent arrivals to be detected.

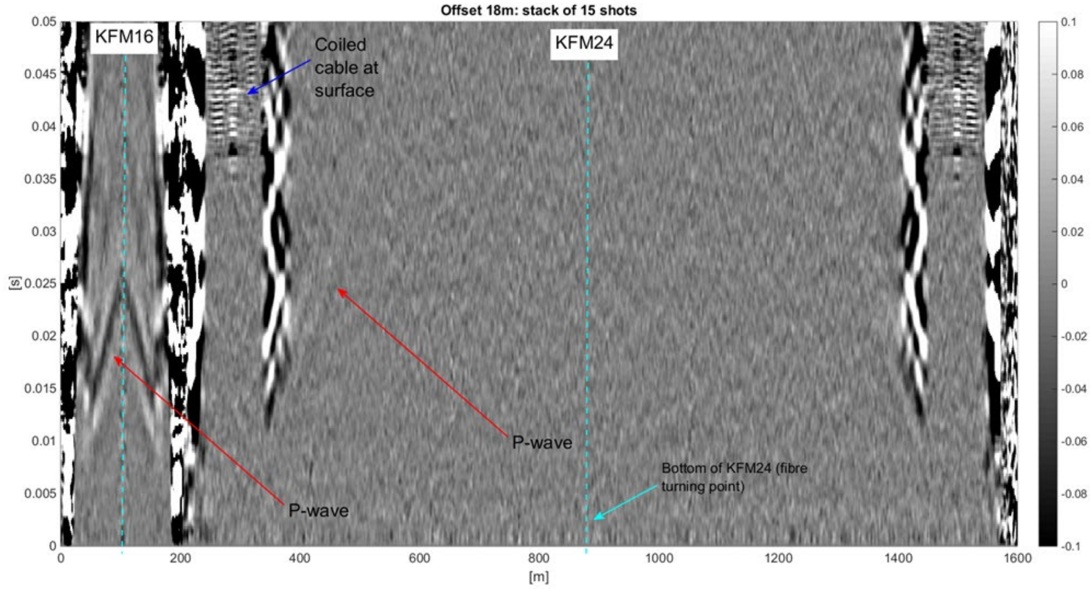


Figure 6-1. *iDAS response to seismic perturbation in KFM16 and KFM24.*

Calculated velocity of the P-waves in KFM16 was 4,200 m/s, whereas in KFM24 was 6,000 m/s (Figure 6-2, left and right panel, respectively). 4,200 m/s is a fairly low value for granite; this could possibly be an indicator that the formation is more fractured near the surface (as generally expected) compared to the deeper layers and should be checked against the lithological profile of the site later. The lack of good contact between the optical fibre cable and the formation due to the absence of a FLUTe liner in KFM24, resulted in intense tube waves that masqueraded the P-waves in the shallow layer and did not allow to compare the velocities in the top 60 m between the two boreholes.

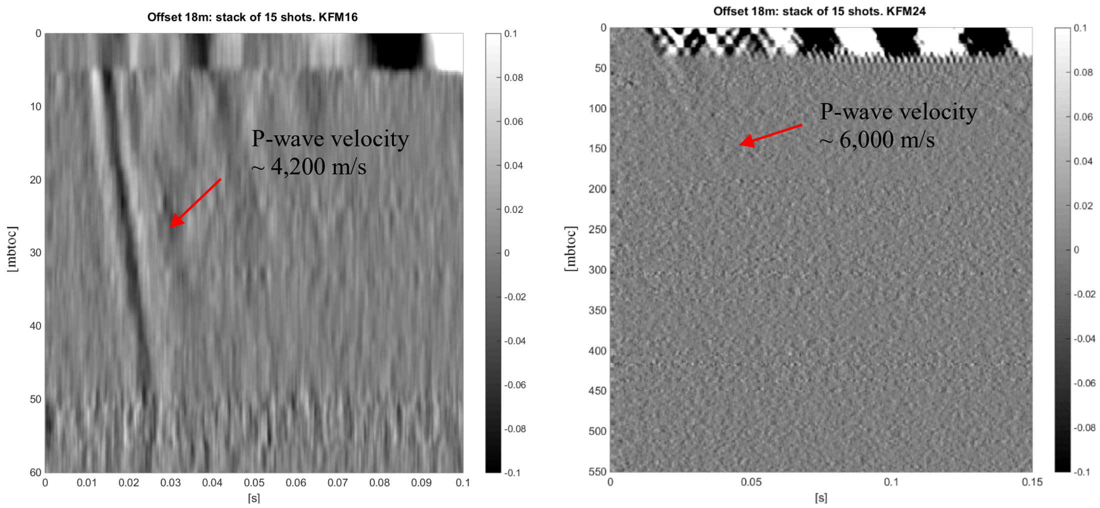


Figure 6-2. *P-waves detected in KFM16 (left) and KFM24 (right).*

Several hours of iDAS measurements were also performed without active seismic source during the FLUTe liner installation on Monday October 23rd, only in KFM24. Data are not presented here but after the field demonstration, the recorded data have been converted into the most commonly used format (.SEGY) and provided to SKB and the seismologists of the University of Uppsala for microseismic events detection and analysis. Being able to characterize first and then monitor in real-time the microseismicity of the site during all stages of the repository construction is a potential application of a permanent iDAS installation that has significant relevance to the site. As for the active seismic, the presence of a FLUTe liner would have significantly enhanced the sensitivity of the iDAS to the microseismic activity.

6.4 Discussion

The reason why the iDAS mostly recorded P-waves lies in the nature of the distributed acoustic measurements along optical fibre. The optical fibre is particularly sensitive to stretching and compression phenomena acting parallel to the fibre itself, such as vertical compressional waves. In these cases, iDAS performs as well as a single-component geophone (Figure 6-3), with the unique advantage of having a dense array of geophones recording simultaneously.

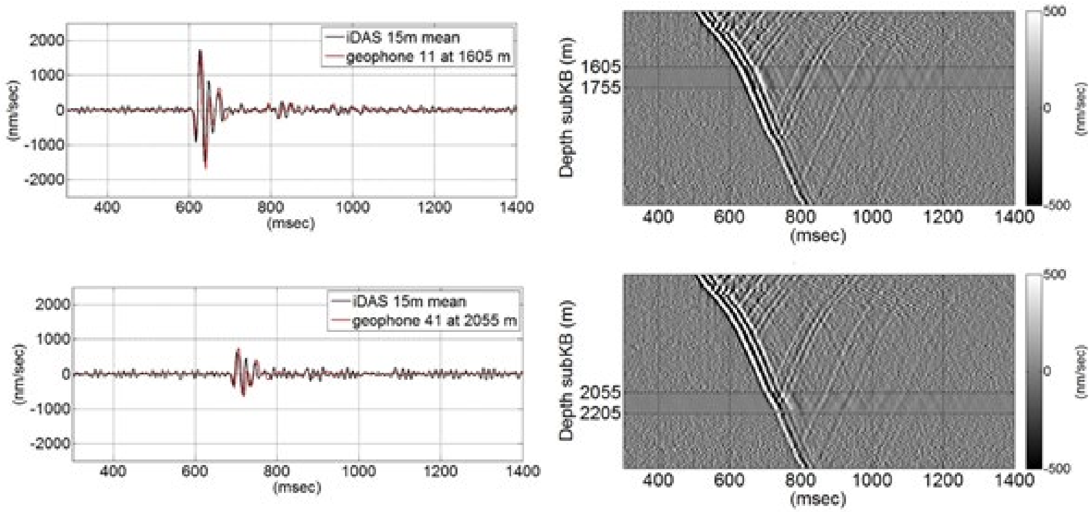


Figure 6-3. *Examples of collected signal using iDAS and geophones.*

The sensitivity to shear waves or compressional waves not parallel to the fibre is limited over a linearly deployed fibre. However, new solutions to increase the sensitivity to seismic waves coming from a broader angle of incidence are arising. One example is the helical cable, where the fibres are helically inserted into the cable structure.

The technology is still under development and further improvements can be expected both regarding monitoring equipment and cables/fibres. Today iDAS has a dynamic range of 120dB, which increases up to 160dB for Carina system (new iDAS + Constellation fibre). The sampling frequency can be as high as 100kHz for 1km of fibre and lowers at increasing fibre length. Therefore, seismic events, usually occurring at sub kHz frequencies, can be reliable detected over multiple kilometres of fibres.

7 Fibre optic-based point sensors - Opsens

7.1 Objective

Demonstration of fibre optic point sensors for pressure and temperature measurements. The sensors are developed for demanding environments with high demands on reliability and accuracy. Since the monitoring technology for the sensors is based on optical fibres it will not be subject to interference from electromagnetic influence, vibration, and lightning. The length between the sensor and read-out unit can be up to 3 km. These properties may be of interest for some applications for SKB. Further information is found in Appendix 7.

7.2 Monitoring method and unit

The optical sensors are enclosed in stainless steel (Figure 7-1). The sensor is located at the endpoint of the optical fibre. Each sensor requires one fibre unlike the distributed measurement where the actual fibre acts as the sensor. A description of the technology of the sensors can be seen in Figure 7-2.

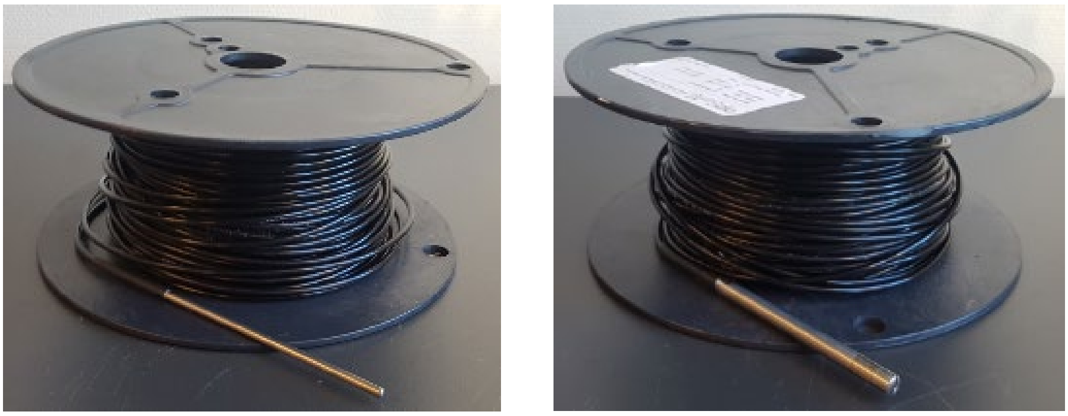


Figure 7-1. *Temperature sensor (left) and pressure sensor (right).*

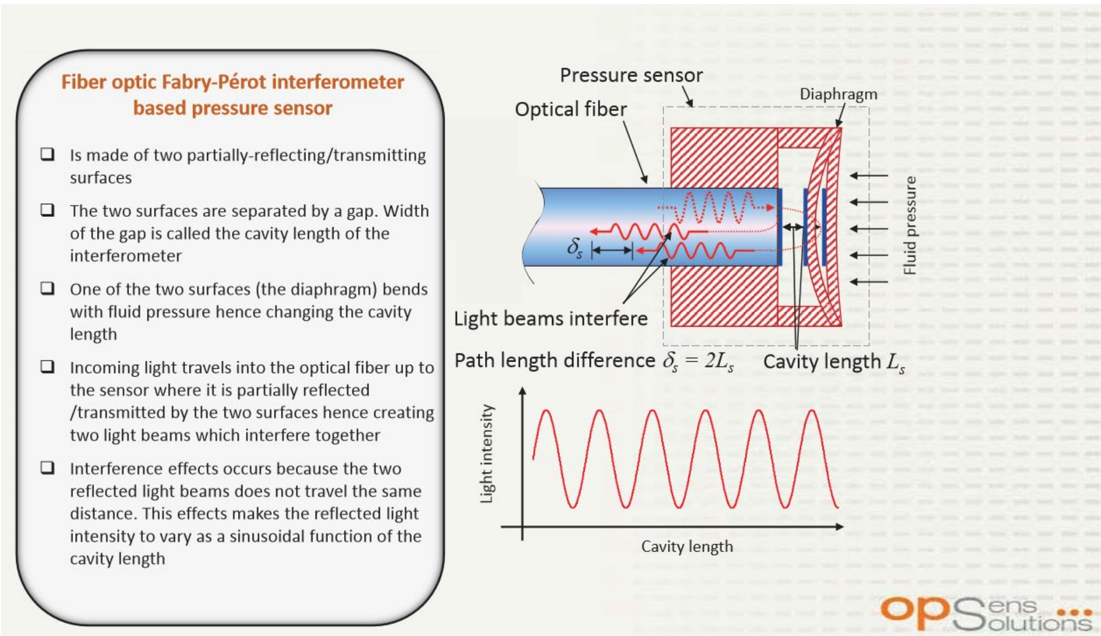


Figure 7-2. *Explanation of the Opsens sensor technique.*

The resolution and precision are dependent on the measuring range of the sensors which can be adapted to the needs of the installation. The measuring range for the used sensors is -25 °C to 50 °C for the temperature sensor and 25 psi (172 kPa) for the pressure sensor. For this range the temperature sensor has a resolution of 0.01 °C and a precision of ±0.3 °C. The pressure sensor has a resolution of <0.02 % full scale and a precision of ±0.1 % of full scale. For more details see Appendix 7.

The two sensors were installed in KFM24 on October 23rd at the same level as the conventional pressure sensor installed by SKB. The readout unit (Figure 7-3) was placed in the blue adjacent container (Figure 6).

Figure 7-3. *CoreSens Read-out unit front (left) and back (right). The data export can be made using Ethernet 10/100 Base T-interface or analogue output (0-5V, ±5V, 0-10 V, 0-20mA or 4-20mA) as seen in the right photo.*

Data were logged until Oct 26, with some interruptions for data transfer and tests of data collection frequency etc. A Mini-Diver for pressure and temperature measurements (van Essen) was installed later approx. 10 cm above the Opsens sensors on October 25th and removed on October 26th.

7.3 Results and discussion

Hands-on evaluation of the Opsens technology is in the preliminary stages, with the first testing of the Opsens equipment conducted just three days before the deployment at Forsmark. Thus, the first days, different settings were used, and tests were made to gain knowledge of the equipment during field application. Data below are therefore presented from October 25th to 26th and should be considered preliminary as further optimization of the technology may be possible.

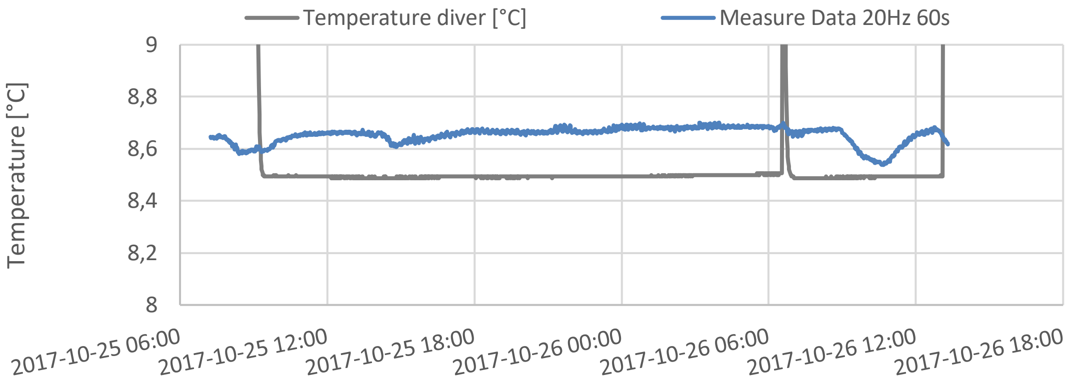
The temperature measurements from the diver are nearly constant during the period, as expected at this depth. The temperature from the Opsens sensor varies from 8.5 °C to 8.7 °C during the measurement period (Figure 7-4a). Three anomalies occur. The pressure from the Opsens sensor follows the pressure from the diver with an offset of approx. 1.1 kPa. The pressure measurements show also three anomalies (Figure 7-4b) at similar time as the temperature traces.

The temperature in the container was measured with a van Essen Baro close to the Opsens readout unit. Three periods with cold temperature can be seen ((Figure 7-4c). These coincide with the time for the anomalies in pressure and temperature measurements by Opsens, which lead to suspect that the performance of the readout unit from Opsens is dependent on the surrounding temperature.

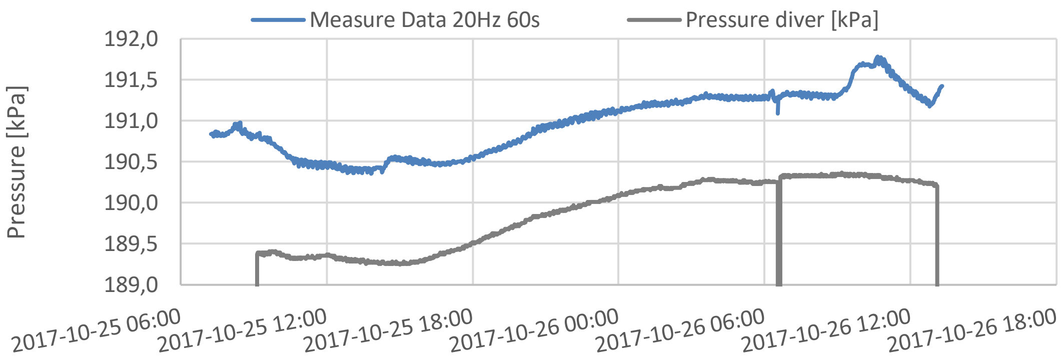
The CoreSens (read-out unit) can be ordered in different versions. The most common version is rack mounted which can have up to 13 modules (26 channels). The version used for this demonstration is a standalone unit with one module (2 channels). Each module has an embedded temperature sensor to compensate for ambient temperature variations. As we see impact from the ambient temperature variations it seems like the compensation is not optimized for this standalone chassis. This was later confirmed by Opsens when testing the unit. An improved temperature compensation is now built in the unit.

The result from the field measurements is just outside the specifications. A clear temperature influence is seen, caused by the ambient temperature variations. With a better temperature compensation, the accuracy would be improved. Ideally, the readout units should be placed in a temperature-controlled environment to obtain the best accuracy. During times where the ambient temperature is stable, the sensor readings have about 0.05 kPa and 0.02 °C variation at most.

a)



b)



c)

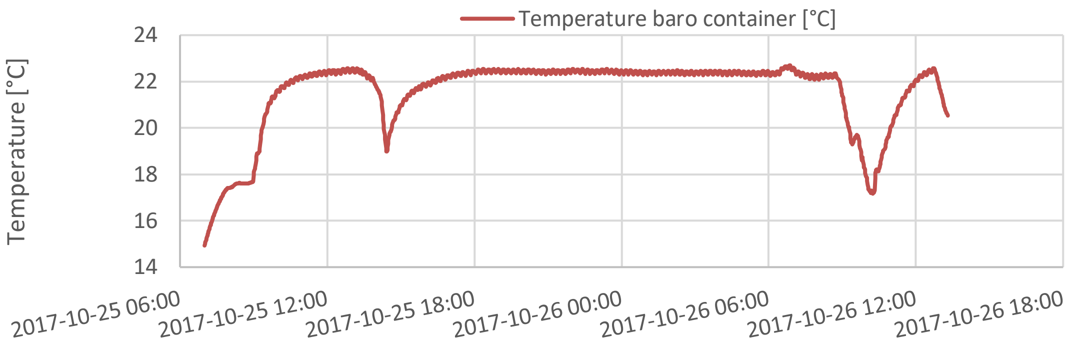


Figure 7-4. *a) Temperature (grey and blue) at approx. 9 m from surface in KFM24. b) Pressure (grey and blue) at approx. 9 m from surface in KFM24. c) Temperature close to Opsens readout unit inside container. The large peaks at start, morning Oct 26th and end in the diver temperature corresponds to installation, data collection and removal of the diver.*

8 Conclusions and recommendations for future work

Silixa and HydroResearch demonstrated the advantages of optical fibre sensors. The density of measurements enables to capture information at close intervals over very short times. Temperature, acoustic signals, and pressure can be monitored with high precision and frequency with almost no post-processing.

Beside the numerous advantages offered over many traditional techniques, optical fibres can be permanently deployed over infrastructures and allow repeated measurements without intervention.

The development of fibre monitoring systems has been driven by the demand of continuous measurements within the energy sectors. New geophysical applications have been developed that can be used for subsurface characterization of natural conditions and dynamic processes. Seismic applications are being used today for the monitoring of underground constructions and reservoirs to the extent of being able to track gas plumes and oil reserves. Based on our experience and response of the participants during the demonstration there are extensive potential applications. Data handling, online evaluation, and integration with existing instrumentation techniques and platforms are factors that must be considered when planning long term and large-scale monitoring.

Multilevel monitoring wells (MLSs) are one of the most useful hydrogeologic tools for both measuring head profiles, conducting hydraulic tests, and for chemical sampling. Incorporating fibre optic-based sensing systems into MLSs allows for the creation of a next generation, advanced monitoring platform that can be used to:

- Measure hydraulic head profiles through time
- Conduct hydraulic tests at multiple depths
- Conduct regular chemical sampling at all sample ports
- Monitor passive temperature profiles to identify changes in the flow system, seasonal temperature changes, groundwater recharge events
- Conduct active-DTS tests to characterize the apparent thermal conductivity at all depths to identify flow system changes
- Monitor seismic events passively to detect microseismic events, earthquakes
- Carry out active seismic surveys for characterizing rock formations and changes through time
- Monitor distributed strain and the associated hydromechanical response in the formation that may take place during repository construction activities
- Additional applications (currently being developed and refined by researchers worldwide)

Fibre-optic distributed and point sensors can be incorporated into traditional packer or backfill based MLS designs, or into FLUTe flexible liner MLSs that enable the fibre optic cable to be coupled to the formation at all depths (Figure 8-1). Design engineering and an advanced MLS with fibre test installation are recommended. To date, optical fibre distributed, and point sensors have not been commercially incorporated into MLS installations, offering an opportunity for SKB-HydroResearch-Silixa to continue to advance the leading edge of monitoring instrumentation design and implementation. SKB's requirements for advanced characterization and monitoring to assess the natural hydrogeologic environment as well as potential effects of repository construction and operational activities to ensure the long-term safety of the public and environment are well suited to the implementation of next generation techniques. The resolution, quality, and quantity of data that can be captured by optical fibre enabled MLS systems have the potential to be transformative steps in hydrogeological monitoring through efficient borehole utilization.

In addition to integration with MLSs, fibre optic cable can be readily grouted into existing boreholes as they are sealed to allow a sealed borehole to be transformed into a permanent, high resolution, and depth discrete monitoring system.

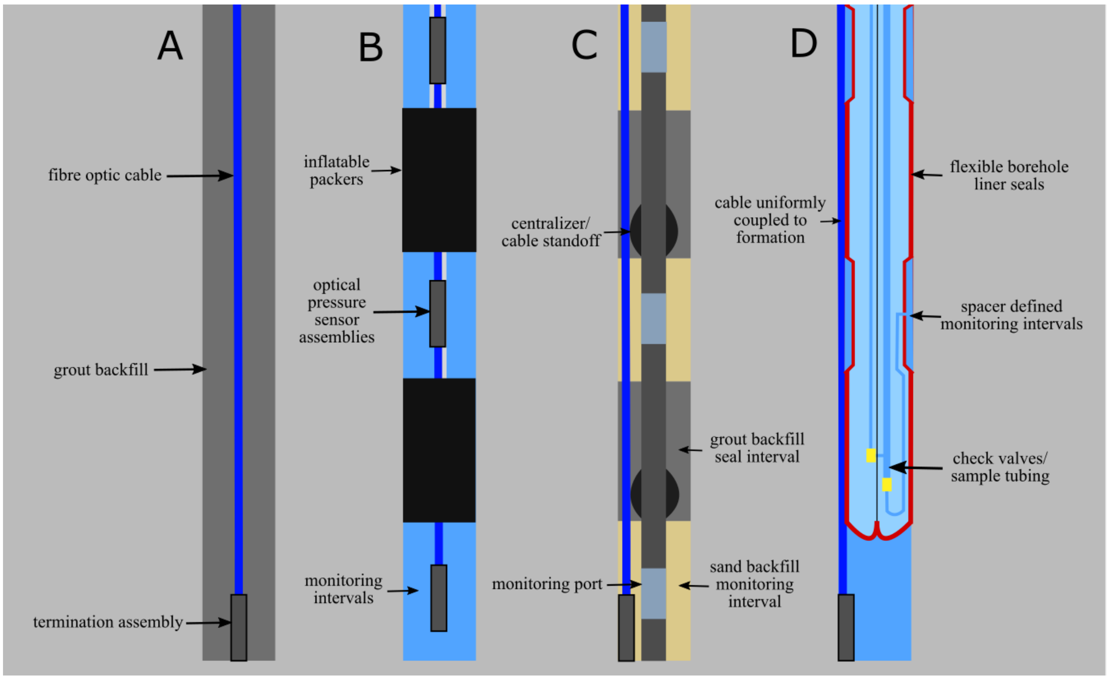


Figure 8-1. *Conceptual advanced MLS designs. a) fibre optic cable installed in backfill. b) integrated into packer-based systems. c) integrated into backfill based Waterloo or G360 MLS systems. d) installed behind blank liner or Water FLUTe MLS.*

Fibre optic cables can be adapted to a wide range of installation environments. In addition to the downhole applications, fibre optic cables can be easily deployed horizontally in the shallow soil to provide a high space-time resolution monitoring of key variables such as soil temperature, soil moisture and thermal conductivity (using active-DTS) and can be used to run surface seismic surveys. Third party intrusions (e.g., vehicles moving on the surface) can be identified and localized by means of the iDAS. Above ground and atmospheric deployments of fibre-optic sensors can provide air temperatures as well as detection and localization of environmental applications of interest (for instance the sound of the frogs).

Research and development of fibre optic sensors is ongoing with both continued refinement and step changes in sensor performance occurring. A recent step change in performance is the introduction of Silixa's CarinaTM distributed acoustic sensing system that provides a greater than 100x improvement (20 dB noise reduction) when compared to traditional distributed acoustic sensing. This performance improvement is achieved using engineered ConstellationTM fibres. Carina provides a new opportunity to elucidate complex problems by providing high fidelity distributed acoustic data. Continued developments in fibre optic sensing systems are likely to refine existing methods and enable novel techniques utilizing existing and future fibre infrastructure.

Finally, the high density of spatial and temporal data that fibre-optic sensors provides can be easily used to implement, improve, calibrate and validate numerical models of the complex thermo-hydro-mechanical dynamics for the full life cycle of the repository.

The genuine interest from the SKB staff regarding the use of fibre optic measurements, and their technical skills paved the way for a successful test installation of the new technology. All preparation work was made as planned, and the remaining monitoring installation went smoothly thanks to the good preparation work.

The quality and readiness of the fibre-optic data shown during the demonstrations, combined with the large variety of applications presented by Silixa and HydroResearch, received interest from different groups of SKB, Uppsala University, and Vattenfall. A lot of potential applications were mentioned and briefly discussed on the demo day, and both problems and potential solutions were identified for different monitoring needs. Silixa and HydroResearch are truly motivated and looking forward to further discussions with SKB and their partners. By working together, we see great possibilities to further develop methods in order to provide the best solutions for the specific needs of nuclear waste management.

Discussed potential applications included:

- *Rock mechanics applications:*
    - Monitoring of rock deformation with potential for a laboratory and field trials with both iDAS for slow strain monitoring and A-DTS for real-time monitoring of rock stability during drilling and construction phase of the deep repository.
- *Thermal applications:*
    - Characterization of thermal properties in rock.
- *Hydrogeological applications:*
    - Use of the FLUTe liner with multi-level pressure and chemical sampling ports that could be readily integrated with fibre optic cable.
    - Installing cables when boreholes are grouted and for incorporating fibre optic cable into existing packer-based multilevel monitoring well designs. There is significant potential for instrumenting new boreholes in preparation for repository construction.
    - Characterization of hydraulic properties in rock and water flow.
    - Ground water/surface water interaction.
- *Seismological applications:*
    - iDAS based local seismology network on site.
    - Downhole and surface cable for passive seismic continuous monitoring by Uppsala University.
- *Ecological applications:*
    - Detection and localization of sounds from frogs and other significant ecological indicators.

The potential use for fibre optic point sensors is the same as for the sensors used based on electrical components. The optical sensors should be seen as complement at special applications where their high performance, reliability, and small physical size may be of interest.

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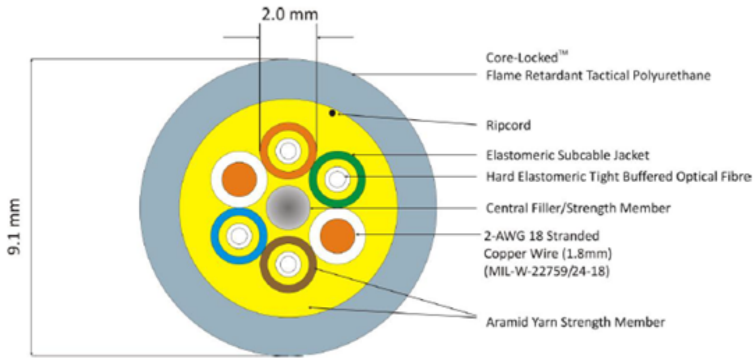
Appendix 1 Hybrid Optical Cable

Spec Sheet
HS-2S2M2C-1PU091-01-B
Composite Fibre Optic Cable



* Drawing not to scale

Typical characteristics

Fibre Code/Type	OM2/Multimode			ITU-T G.652.A /Singlemode,
Fibre Count	2			2
Core Diameter	50 µm			9 µm
Cladding Diameter	125 µm			125 µm
Primary Coating Diameter (UV cured acrylate)	500 µm			500 µm
Secondary Buffer Diameter (hard elastomeric)	900 µm			900 µm
Numerical Aperture	0.20			--
Proof Test Level	100 kpsi			100 kpsi
Wavelength	850 nm	1310 nm	1310 nm	1550 nm
Maximum Attenuation	3.5 db/km	1.5 dB/Km	0.5 dB/Km	0.5 dB/Km
Bandwidth	500 MHz-Km	500 MHz-Km	-	-
Nominal Zero Dispersion Slope			0.092 ps/(nm^{2}Km)	

Mechanical Properties

Cable Diameter	9.1 mm (0.36 in)
Total Cable Weight	83 kg/km (56 lbs/1000')
Installation:	
Max. Tensile Load	1,600.0 N (360 lbs)
Min. Bend Radius	18.2 cm (7.2 in)
Operating:	
Max Tensile Load	400 N (90 lbs)
Min Bend Radius	10.0 cm (3.9 in)
Operating Temperature	-55ºC to +85ºC
Storage Temperature	-70ºC to +85ºC

Note: Cable is designed for use with United States National Electrical Code(NEC) Class 2 power sources. The individual copper conductors are rated for use at 600V AC and these same copper conductors in the finished cable were further tested for open & short circuit insulation at 600V and AC dielectric breakdown at 600V . However the overall finished cable is not UL listed and has not been certified to any applicable electrical or safety standards.

The customer is responsible for ensuring the compliance with all applicable local and national safety codes during use.

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ISOQAR UKAS 9032QM8001
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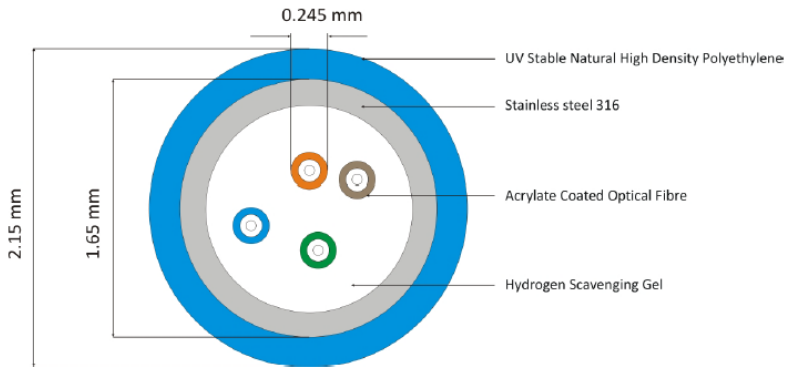
Appendix 2 Downhole Optical Cable

Spec Sheet
DH-2S2M-2HDPE022-01-BL
Single Steel Wall Tube Fibre Optic Cable



*** Drawing not to scale**

Typical characteristics

Fibre Type	Multimode		Singlemode	
Fibre Count	2		2	
Core Diameter	50 µm		9 µm	
Cladding Diameter	125 µm		125 µm	
Wavelength	**850 nm**	**1300 nm**	**1310 nm**	**1550 nm**
Maximum Attenuation	2.7 db/km	0.90 dB/Km	0.37 dB/Km	0.22 dB/Km

Mechanical Properties

	ENTIRE ARMOURED CABLE
Nominal overall Diameter	2.15 mm (0.085 in)
Approximate Weight	9.9 kg/km (6.6 lbs/kft)
Approximate Weight in Seawater	6.2 kg/km (4.1 lbs/kft)
Tensile Strength	838 N (188.5 lbs)
Yield Strength	706 N (158.8lbs)
Strain at Yield	0.429%
Coefficient of thermal expansion	1.82E-05 m/m°C (1.01E-05 in/in°F)
Hydrostatic Pressure	5.9 MPa (859 psi)
Working Pressure	4.8 MPa (695 psi)
Dynamic Bend Radius	165 mm (6.5 in)
Static Bend Radius	41mm (1.6 in)
Temperature rating	-40°C to +85°C
	STEEL TUBING
Material	Stainless steel 316
Thickness inner tubing	0.2mm

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Appendix 3 Silixa XT™ DTS

High Performance Ruggedised
Distributed Temperature Sensor

XT-DTS™

DATASHEET

The XT-DTS is the highest performance ruggedised distributed temperature sensor currently on the market. Designed for remote and hostile environments, the unit has a class-leading operating temperature range of -40°C to +65°C. The XT-DTS can operate on solar or wind power without compromising the superior accuracy and reliability. It can be configured and controlled remotely via a wireless or satellite link enabling remote data collection, which allows for effective asset optimization and environmental risk management even in previously unreachable locations. The unit can be optimised for 2 km, 5 km and 10 km ranges.

Product Specifications

Sensing Capabilities

Range	Channels	Resolution		Measurement Time	Fibre Type	Referencing
		Sampling	Temperature			
0 - 10km	4	25cm	0.01°C	≥5 sec	50/125μm multimode	x2 PT-100 probes

Power Supply Requirements

40W @ Room Temperature
45W @ -40°C
43W @ +65°C

Capacity to reduce power consumption for standby operation (Idle power requirements: about 13W)

Communication Options

2 x Ethernet
Internal SSD [64GB]

Physical Dimensions

Height	Width	Depth	Weight
165mm	365mm	470mm	12kg

Operating Environment

Temperature: -40°C to +65°C
Humidity: 5-95%RH

Operating System

Windows XP (32bit)
Windows 7 (64bit)

Certification & Compliance

Safety	EMC	FCC	CE Mark
Class 1 Laser Product • IEC 60825-1: Edition-2:2007 • CFR 21 Parts 1040.10 & 1040.11 • EN 61010-1:2010	• EN61326-1:2013	CFR 47:2008 Part 15 Sub Part B	• 2014/35/EU (safety) • 2014/30/EU (EMC)

Data Monitoring

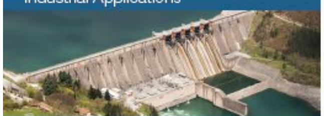
XT Viewer
XT Client

Well Services

Metering

Pipeline Surveillance

Industrial Applications



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Appendix 4 Silixa Ultima™ DTS

experts in distributed sensing

SILIXA

ULTIMA™ DTS DATASHEET

The ULTIMA-DTS range is the world's highest performing family of Distributed Temperature Sensors. The ULTIMA offers the finest temperature resolution and spatial resolutions, from 0.01˚C and 25cm, over a wide operating temperature range. It is a standalone unit with an on-board PC and a user-friendly software interface. The ULTIMA is available with either 4 or 8 optical channels. The units are optimised for spatial and temperature resolution for the following ranges: 5, 10, 20 and 35km. The system can be configured to produce both single-ended and double-ended measurements. Minimum measurement time is 1 second.

Product Specifications

Sensing Capabilities

Range	Channels	Resolution	
		Temperature	Sampling
0 - 5km*	4 / 8	0.01°C	0.125m
0 - 10km	4 / 8	0.01°C	0.25m
0 - 20km	4 / 8	0.02°C	0.5m
0 - 35km	4 / 8	0.03°C	1m

*The unit is also available with a 0-2km range with an optimised temperature resolution.

Power Supply Requirements

AC Power	Maximum Power
100-240V, 50-60Hz	145W

Communication Options

Ethernet	USB
DVI	Internal HD

Physical Dimensions [19in rack compatible]

Height	Width	Depth	Weight
6.97in / 177.1mm	18.30in / 464.8mm	18.40in / 467.4mm	16.9kg / 37.3lb

Certification & Compliance

Safety	EMC	FCC	CE Mark
Class 1 Laser Product • IEC/EN 60825-1:2007	• EN 61326-1:2006	FCC CFR 47:Part 15: B:2008	• 2006/95/EC (safety) • 2004/108/EC (EMC)

Data Monitoring

ULTIMA DAQ
ULTIMA Viewer
Enhanced Viewer

Oil & Gas

Flow Metering

Pipeline Surveillance

Distributed Sensing

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Appendix 5 Silixa iDAS™

experts in distributed sensing

iDAS™ — iDAS DATASHEET

The world's finest distributed acoustic sensor, the iDAS, has a novel optoelectronics architecture that allows for digital recording of acoustic fields at every location along a singlemode or multimode optical fibre. Amplitude, frequency and phase fidelity allows for numerous advanced applications.

Benefits of iDAS

- Finest Sampling Resolution = 25cm
- Sampling Frequency = 1kHz-100kHz
- Range = up to 40km
- Easily deployed in remote and hostile environments
- Finest Spatial Resolution = 1m
- Frequency Range = 0.01Hz to 50kHz
- Dynamic Range = >120dB
- Compatible with standard singlemode and multimode optical fibre

Product Specifications

Sensing Capabilities

Range	Channels	Frequency		Resolution	
		Range	Sample	Sampling	Spatial
0 - 40km	1	0.01Hz - 50kHz	1kHz*	down to 25cm*	down to 1m*

* Range dependent

Power Supply Requirements

AC Power
100 - 240V, 50 - 60Hz

Communication Options

Ethernet	USB
DVI	Internal HD

Physical Dimensions [19in rack compatible]

Height	Width	Depth	Weight
6.97in / 177.1mm	18.30in / 464.8mm	18.40in / 467.4mm	16.9kg / 37.3lb

Certification & Compliance

Safety	EMC	FCC	CE Mark
Class 1M Laser Product	• EN 61000-6-2:2005 • EN 61000-6-4:2007 • EN 61000-3-2:2006 • EN 61000-3-3:2008	FCC CFR 47:Part 15: B:2009	2004/108/EC (EMC)

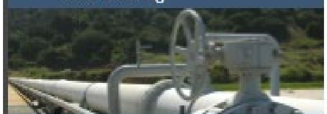
Data Monitoring

iDAS Viewer	iDAS DAQ

Designed and manufactured by Silixa's technical team, the iDAS is unique in the world. Its specifications offer a major technological leap forward compared to disturbance sensors.

Oil & Gas

Flow Metering



Pipeline Surveillance

Distributed Sensing

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Achilles JQS Qualified

ISOQAR UKAS

Appendix 6 Silixa Heat Pulse System™

experts in distributed sensing

HEAT PULSE CONTROL UNIT SPECIFICATION SHEET

HEAT PULSE CONTROL UNIT

ACTIVE DISTRIBUTED TEMPERATURE SENSING

DTS

In monitoring applications active distributed temperature measurements can provide crucial information both on fluid transport and static thermal properties in environments offering limited natural temperature gradients.

Silixa's Heat Pulse Control Unit (HPCU) allows variable power and time controlled heat pulses to propagate along an optical cable. It operates with an electric power supply and an optical fibre cable with embedded heating elements (hybrid configuration). HPCU can be combined with any Silixa distributed temperature sensor to provide a complete monitoring solution. Both units are controlled by a shared interface. The total measurement time, frequency and intensity of the heating cycles can be set to meet the resolution requirements of the installation.

Specifications:

Typical deployment example

Output power	Heated length	Cable resistance	Power rate	Temperature increase*
18 kW	1 km	42 Ω/km	17 W/m	5° C

*Example based on a standard hybrid cable with 2X18AWG twisted copper conductor as heating elements. The copper conductors are wired in series at the far end of the cable.

Power

- inlet: 220 - 600VAC, up to 32Amps
- outlet: 0 - 600VAC, up to 30Amps (max power :18kW)

Communication options

- 2 x ethernet port

Physical dimensions, IP66 enclosure

Height	Width	Depth	Weight
600 mm	500 mm	250 mm	12 kg

Operating environment

- Temperature: 0°C - 50°C
- Humidity: 20% - 90% RH non-condensing

Panel PC

- Rated IP65
- OS: Windows7 (64bit)

Certification & Compliance

Safety	EMC	FCC	CE Mark
CFR 21 Parts 1040.10 & 1040.11 EN 61010-1:2010	EN61326-1:2006	CFR 47:2008 Part 15 Sub Part B	2006/95/EC (safety) 2004/108/EC (EMC)

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Achilles JQS Qualified

ISOQAR UKAS 0026

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Appendix 7 Opsens™

SIGNAL CONDITIONER

DESIGNED FOR THE MOST DEMANDING APPLICATIONS REQUIRING SYNCHRONISED HIGH SPEED MEASUREMENT

RACKMOUNT CONFIGURATION

Inputs Outputs Analog

Two channels per module

KEY FEATURES

- 2 channels per module
- Available in Rackmount or Stand-alone configuration
- High linearity, precision and resolution
- Stackable for a larger quantity of measuring channels
- EtherCAT® capability (available in 2017)
- Ethernet interface and analog outputs
- Embedded web application

STAND-ALONE CONFIGURATION

CORESENS

Compatible with Opsens Solutions' WLPI fiber optic sensors: pressure, temperature, strain, displacement

DESCRIPTION

The CoreSens is a versatile, scalable system that includes a control unit, modular signal conditioner unit (WLX-2 modules) supporting a **variety of fiber optic sensors.** Each WLX-2 modules have **two channels** to optimized number of sensors per chassis.

The CoreSens is designed for the most demanding applications requiring synchronised **high speed measurement.**

At the heart of the CoreSens is the Opsens Solutions' White Light Polarization Interferometry (WLPI) technology (Patent #7,259,862) which provides a means for making **accurate and reliable measurements** of physical parameters such as **temperature, strain, pressure and displacement.**

Through its EtherCAT® capability (available in 2017), the system offers a larger quantity of measuring channels working simultaneously at speed up to 1 kHz. The CoreSens unit chassis can be easily stackable for applications involving hundreds of measuring points.

In its chassis configuration, an embedded web application allows **control** of the CoreSens. The Rackmount module also offers a SDHC memory capabilities to store data locally.

EtherCAT® is registered trademark and patented technology, licensed by Beckhoff Automation GmbH, Germany.

APPLICATIONS

- ✓ Simultaneous measurements of temperature, pressure, strain and displacement
- ✓ Synchronized monitoring for multiple measuring points
- ✓ Military and aerospace applications
- ✓ Dynamic surveillance of civil engineering and geotechnical infrastructures
- ✓ Structural health monitoring

opSens Solutions

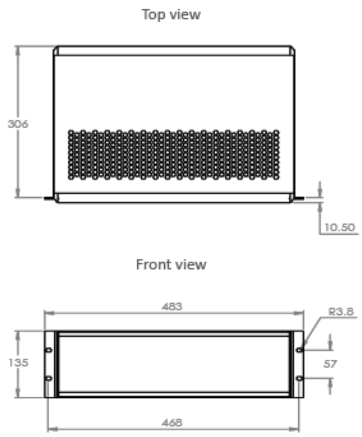
Enlightenment through smart measurements

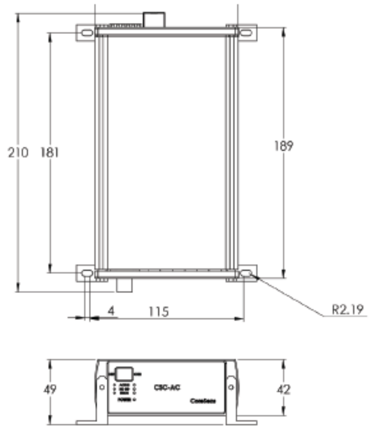
CORESENS
SIGNAL CONDITIONER

SPECIFICATIONS

CONFIGURATION	RACKMOUNT	STAND-ALONE

MECHANICAL DRAWINGS
(in mm)





NUMBER OF CHANNEL	**26 channels** 13 WLX-2 modules with 2 channels per module	**2 channels**
SAMPLING RATE	WLX-2 modules (500 Hz) WLX-2S (1 kHz available in 2017)	WLX-2 modules (500 Hz) WLX-2S (1 kHz available in 2017)
I/O INTERFACES	Ethernet 10/100 Base-T interface, EtherCAT® capability (available in 2017)	Ethernet 10/100 Base-T interface
ANALOG OUTPUTS RANGE	0-5 V, ±5 V, 0-10 V, 0-20mA, 4-20 mA	0-5 V, ±5 V, 0-10 V, 0-20mA, 4-20 mA
INPUT POWER	90 to 260 VAC	8 to 32 VDC
DIMENSION	19" Rack Mount, 3U	210mm x 115mm x 42mm
WEIGHT	Full: 9.4 Kg (0.35 Kg per WLX-2 module)	0.68 Kg
POWER CONSUMPTION	Full: 70W (5W per WLX-2 module)	5W
STORAGE TEMPERATURES	- 30°C to 65°C	- 30°C to 65°C
OPERATING TEMPERATURES	0°C to 45 °C	0°C to 45 °C
HUMIDITY	95% non condensing	95% non condensing
WEB APPLICATION	Yes	NA
LOCAL DATA STORAGE	SDHC (32Gb)	NA

Opsens Solutions reserves the right to make any changes in the specifications without prior notice.
IMP0160 En CoreSens Rev2.1 | *Printed in Canada*

OpSens Solutions • • • ISO 9001 Certification
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FIBER OPTIC PRESSURE SENSOR

MEMS-BASED FIBER OPTIC PRESSURE SENSOR AND PIEZOMETER FOR THE HARSHEST ENVIRONMENTS

KEY FEATURES

- Maintenance free
- No drift over time, reliable results during years
- Intrinsically safe
- Robust design
- Can be located 3 km from the readout unit
- Immune to EMI, lightning

OPP-C Reliable - Robust - Easy to install

DESCRIPTION

The OPP-C pressure sensor is compatible with all Opsens Solutions' WLPI (Patent #7,259,862) signal conditioners. This compact and very robust probe can be customized to specific customer requirements. The fiber optic extension cable can be a maximum length of 3 kilometers.

Opsens Solutions' OPP-C, MEMS-based fiber-optic pressure sensor, is perfectly tailored to meet the challenges of pressure monitoring Applications **in submerged and/or harsh environments.**

The OPP-C sensor delivers **long term accuracy, durability and high fidelity pressure measurements** with a pressure operating range of **up to 70 bar.**

It's the prefect piezometer: Completely sealed, with a stainless steel body and diaphragm, the OPP-C is designed to work in adverse conditions of temperature, pressure, and toxic or corrosive atmospheres. It can be grounted in place if needed.

With the inherent advantages of fiber optic, it is **not subject to interference** from electromagnetic interference, vibrations and lightning that may be present in the sensing environment.

APPLICATIONS

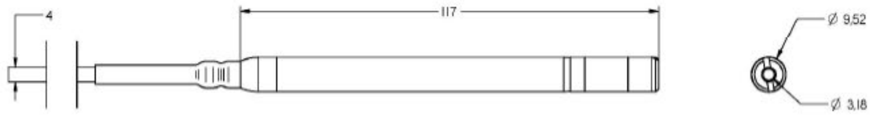
- Geotechnical applications
- In-situ pressure monitoring for food processing
- Harsh subsurface monitoring equipment
- Hydrostatic pressure measurements with corrosive chemicals.
- Groundwater elevation surveillance in wells and streams
- Pressure monitoring in pumping stations
- Hazardous and nuclear environments
- Offshore platform and refineries

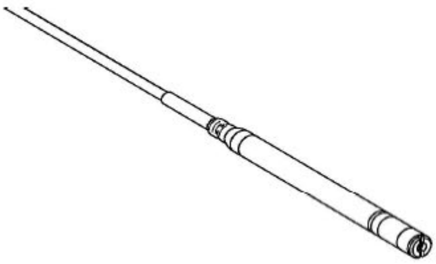
opSens Solutions

Enlightenment through smart measurements

OPP-C

MEMS-BASED FIBER OPTIC PRESSURE SENSOR AND PIEZOMETER





SPECIFICATIONS

MEASURING RANGE (other ranges available on request)	25 PSI (172 kPa)	50 PSI (345 kPa)	100 PSI (690 kPa)	500 PSI (3500 kPa)	1 000 PSI (7000 kPa)
RESOLUTION	< 0.02 % F.S. (Range dependant)				
PRECISION	±0.1 % F.S. (Excluding thermal effect)				
THERMAL COEFFICIENT OF ZERO	< 0.03 % F.S / °C				
PROOF PRESSURE	200 % F.S.				
TEMPERATURE OPERATING RANGE	-20°C to +85°C (other temperatures available upon request)				
EMI/RFI LIGHTNING	Complete immunity				
HOUSING	Stainless steel (117 mm x 9.5 mm)				
MASS	0.06 Kg				
CABLE LENGTH	Up to 3 km (Sampling rate dependent, consult factory for more details)				
OPTICAL CONNECTOR	SCA (Standard), SC (Standard), other connector available on request				
CABLE SHEATHING	From ruggedized flexible outdoor cable to robust stainless steel cable				
SIGNAL CONDITIONER COMPATIBILITY	All Opsens Solutions' WLPI signal conditioners				

Opsens Solutions Inc. reserves the right to make any changes to the above specifications without prior notice.
IMP0091 En OPP-C Rev3 | Printed in Canada

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WLPI BASED FIBER OPTIC TEMPERATURE SENSOR FOR DEMANDING APPLICATIONS AND ROUGH HANDLING USAGE

Use with any of Opsens' WLPI series of signal conditioners

Key Features

- Robust design
- Good accuracy
- Outstanding repeatability
- Low drift and low hysteresis
- EMI/RFI and microwave immune
- Intrinsically safe

Applications

- EM, RF and microwave environments
- High voltage environments
- Nuclear and hazardous environments
- Sterilization applications
- In-situ process control
- RF and microwave drying applications
- Civil engineering and geotechnical applications

Description

Opsens' OTP-P fiber optic temperature sensor offers the highest performances in the industry. The OTP-P sensor uses the temperature-dependent birefringence of specially selected crystal as the temperature transduction mechanism. Because of the pure monocrystalline material used, the OTP-P does not shows thermal creeping or aging as with other fiber optic sensors based on the thermal dilatation of glass optical fibers.

Combined with Opsens' WLPI signal conditioning technology (patent # 7, 259, 862) and with the inherent advantages of fiber optics, the OTP-P delivers unprecedented repeatability and reliability in the most adverse conditions such as high level of EM, RF, MR and microwave fields environments as well as with high voltage and rapid temperature cycling conditions.

The standard operating range of the OTP-P is from -40 °C to +250 °C.

The OTP-P is compatible with all Opsens' WLPI signal conditioners. This robust fiber optic temperature sensor, available in different cables and sheath options,is customizable according to customer specific applications or for OEM-type applications.

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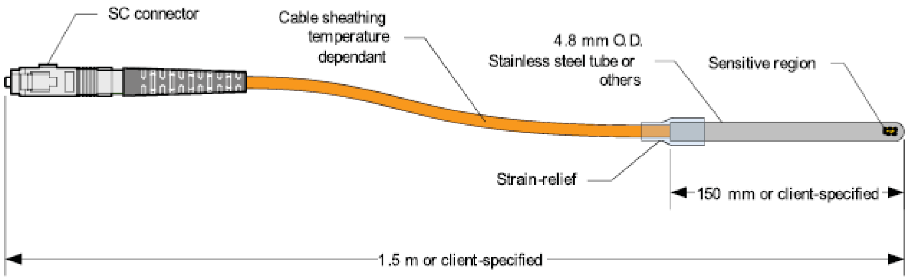

Specifications

Temperature operating and calibrated range	-40 °C to +250 °C
Resolution	0.1 °C
Accuracy	±1.0 °C @ ±3.3 sigma limit (99.9% confidence level)
Operating humidity range	0-100 %
EMI/RFI susceptibility	Complete immunity
Calibration	NIST traceable
Cable length	1.5 meters standard (other lengths available)
Optical connector	SC standard
Cable sheathing	Operating temperature range dependant (contact factory)
Thermowell material	Stainless steel (Ceramis or other materials available as option)
Signal conditioner compatibility	All Opsens WLPI signal conditioners

All specifications are subject to change without prior notifications

IMP0083 OTP-P REV1.5 Printed in Canada