Ultra-Long Reach Fiber Distributed Acoustic Sensing for Power Cable Monitoring

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ABSTRACT

This paper reports the longest reach Distributed fiber-optic Acoustic Sensing (DAS) system, without the need for inline amplification This was achieved using a DAS system specifically designed for long distance in combination with different fiber types optimized either for low loss or for high backscatter coefficient. Instrument- and fiber parameters were analysed to model the expected performance with various fiber combinations. A measurement range exceeding 112 km, and 125 km if the far end is optimized, is realized with a suitable SNR for power cable applications.

KEYWORDS

Distributed Acoustic Sensing (DAS), Distributed Fiber-Optic Sensing (DFOS), Coherent Optical Time Domain Reflectometry (C-OTDR), Fiber optics sensors, Fiber properties, Vibration analysis, Power Cable Monitoring

INTRODUCTION

Temperature monitoring of power cables using optical fiber Distributed Temperature Sensors (DTS) is a well-established and widely used technology. The optical fiber cable may either be installed near the power cable or embedded within the power cable itself. In recent years the technology to reliably carry out Distributed Acoustic Sensing has also been widely reported [1]. Distributed Acoustic Sensing (DAS) technology based on coherent Rayleigh backscatter in optical fiber resembles a vast number of "microphones" using a simple passive glass fiber as sensor over long distance and has been a subject of significant interest.

Whilst current commercial DAS systems reach up to 40 or 50 km sensor length, recent research has been presented which increases the reach past this point. Shiloh et al. [2] for example presented in 2017 a reach of 64 km whilst Martins et al. [3] reported 125 km using second-order Raman amplification along the sensor fiber and Wang et al. [4] reported greater than 175 km, utilizing a combination of Raman and Brillouin amplification along the fiber albeit with a 25m spatial resolution. This paper reports a significant advance in the field, pushing the maximum possible reach of a commercial DAS to 112 km covering the whole range or even 125 km with some performance gap along some range in between. Notably, this performance improvement is achieved without the need for amplification along the sensor fiber whilst maintaining a spatial resolution of 10 m. This result is achieved by combining a new DAS system with a sensor fiber that is optimized for DAS applications. With increasing sensor fiber length, the amount of light returning to the DAS interrogator from the far end decreases. At the same time the maximum possible rate for the light pulses launched into the fiber by the DAS interrogator reduces to match the light round-trip time to the fiber end and back to the interrogator. Both degrades the SNR and limits the maximum reach of distributed acoustic sensing (DAS). The reach depends on the DAS stimulus pulse energy E sent into the fiber, the Rayleigh backscatter coefficient B of the fiber describing the fraction of the stimulus energy elastically scattered back to the interrogator and the attenuation of the fiber per kilometer A. These parameters are in general inter-dependent, i.e. tweaking a fiber to higher backscatter may also lead to higher loss per kilometer. The maximum pulse power is limited by the onset of non-linear effects, starting to transfer energy from the stimulus pulse towards shifted frequencies by non-elastic interaction with the fiber material, e.g. by stimulated Brillouin scattering or self-phase modulation as clarified by Izumita et al. [5]. The non-linear limit of optical power at a given wavelength in general depends on the used fiber.

The task is therefore to find fibers with an optimum combination of these parameters to maximize the reach in DAS measurements. We investigated different fibers types and fiber combinations to achieve highest reach in different scenarios, i.e. for cases of single fiber type or combinations of fiber types.

DAS SYSTEM AND SENSOR FIBERS

For this investigation, a commercial DAS system model "N5200A" from AP Sensing was used. It is a phase-based DAS i.e. delivers quantitative strain data (in contrast to non-quantitative intensity-based DAS systems), based on a proprietary "2P Squared DAS" technology, and optimized for long reach measurements. It operates with an interrogation wavelength of 1550 nm, typical range of 70 km and a variable spatial resolution between 5 and 40 m.

Three types of sensing fiber were investigated, and the combination of different fiber types was optimized for extended reach DAS applications. The fiber types are: Ultra Low Loss (ULL) fibers, Enhanced Backscatter (ENHF) Fibers and standard G.652 single mode fibers (SSMF):

Ultra-Low Loss fiber (ULL): Two different very low loss and large effective area fibers, TeraWave SCUBA-125 [5] and SCUBA-150 [6] from OFS with nominal effective areas of 125 µm2 and 153 µm2, respectively were proposed. SCUBA fibers are made with a pure (i.e. Ge-free) Silica core and large effective area which allows for a low loss of 0.155 dB/km and improved nonlinear performance. The large area enables launch of significantly higher input signal power in the fiber without nonlinear penalties. The trench assisted design of the SCUBA fiber index profile makes the fibers resistant towards bending irrespective of the large effective areas. The trench also results in a reduced mode field diameter (MFD) when compared to the effective area, as $A_{eff} = 1.06\ MFD^2 * \pi/4$, promoting better splice loss performance between SCUBA and SSMF with lower effective areas. Optimized splice losses of 0.1 dB or below can be achieved between large and standard effective area fibers [8]. The low loss and large area (i.e. low NA) comes with a reduced backscatter coefficient. Both fiber types have a nominal dispersion of 22 ps/nm-km and an effective refractive index of 1.465 at 1550 nm.

Enhanced Backscatter Fiber (ENHF): The enhanced back scattering fiber, OFS Acoustisens, has an estimated loss of 0.4 dB/km. The enhanced backscatter is achieved through the inscription of a continuous grating over the entire fiber length and is nominally 15 dB over the base Rayleigh scattering level [9, 10].

Standard Single Mode Fiber (SSMF): Standard single mode fiber of ITU type G.652.D was used as "reference" DAS sensor to allow a direct comparison with the other types.

SETUP AND TEST

The fibers were coiled on standard spools with defined lengths. It would have been practically difficult to arbitrarily vary the lengths for DAS tests to approach optimum lengths and combinations of types. We therefore chose the approach to measure the DAS performance with the available fiber lengths and combinations and to derive the basic fiber parameters which impact the performance of the whole DAS system and therefore derive the DAS performance for optimized configurations. Therefore, we present results from direct measurements as well as derived performance data.

The DAS measurement performance is expressed as "DAS self-noise", defined by SEAFOM in the latest draft of their standard [11]. It expresses the average noise (over some 100 m) of DAS measurements on a vibration-free sensor fiber in equivalent fiber strain, normalized to the acoustic frequency in Hz, represented by dB_{ps}, where the decibel value refers to pico-strain per sqrt (Hz).

In parallel, for qualitative visualization, a section of about 1 m fiber was looped on a surface-loudspeaker as acoustic stimulus. The loudspeaker was driven with a frequency of 100 Hz and an amplitude causing an optical (two-way) phase shift in the order of ±1.5 rad between the light backscatter before and behind the acoustic stimulus.

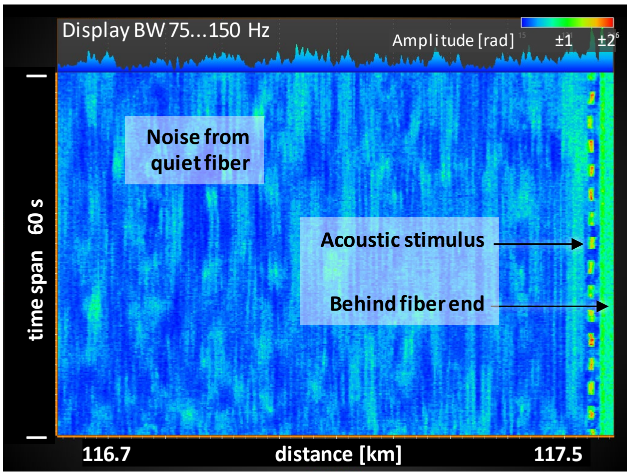
Spatial resolution, which mainly depends on the selected DAS pulse length (here 5 m) and gauge length (here 10 m), is basically constant over distance and has not been investigated here.

The maximum reach of a DAS measurement in km depends on which phase noise level is acceptable for a specific application. There is no standard to our knowledge to specify the reach of a DAS system. For this paper the maximum reach is defined as the sensor fiber length up to which the signal from a 'loud' acoustic event is at least 6 dB above the system's average self-noise level. 'Loud' refers to a broad-band acoustic event above the DAS dynamic range as defined by SEAFOM [10] where the optical phase change of the signal returning to the DAS receiver from pulse to pulse generally exceeds the interferometrically unambiguous range of $-\pi$ to $+\pi$. Practically this corresponds to slight tapping on the sensor cable or vibrations from a train reaching a buried sensor cable in several meters distance.

Weaker events like footsteps above a deeply buried cable require lower self-noise levels. Generally, the noise requirement depends on many factors, like event frequency band, event pattern in time (e.g., single burst, repetitive or continuous), cable composition, physical coupling to the environment or object, properties of the soil et cetera. Exceeding the range of $\pm\pi$ for the criteria used in this article means that the measured acoustic signal gets distorted, i.e., the appearance of an acoustic signal can be detected, but information about the spectrum (how the event "sounds") is diminished or lost.

Specifically, for the DAS system used here such a 'loud' acoustic event was found to correspond to 52 dB_{ps}. From that we define the reach limit as the fiber length where the self-noise reaches 46 dB_{ps} at the selected gauge length of 10 m and the used stimulus acoustic frequency of 100 Hz and pulse rate of 1 kHz.

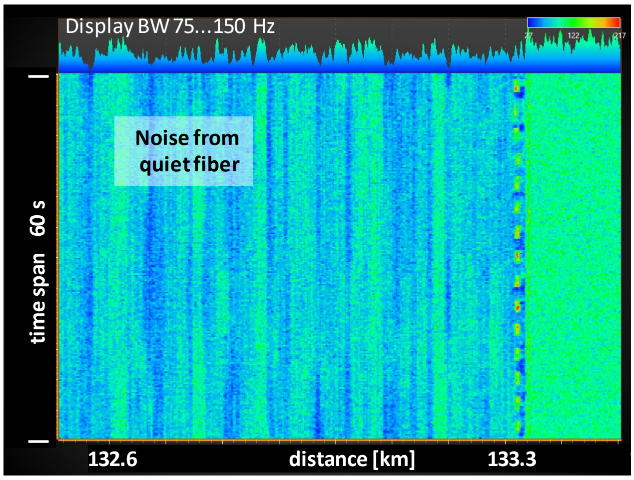
(a)



(a): Self Noise 46.6 dB_{ps} (100 km ULL + 16 km SSMF + 1 km ENHF + connectors + splices)

(b): Self Noise 50.0 dB_{ps} (100 km ULL + 32 km SMF + 1 km

(b)



ENHF + connectors + splices)

Fig. 1 Waterfall diagrams from a periodic acoustic stimulus near and beyond the Self Noise limit

Note that dB_{ps} relates acoustic powers rather than (pressure or strain) amplitudes, which means that a SNR of 6 dB in power units corresponds to 3 dB in amplitude units.

For fiber lengths up to 100 km a pulse repetition frequency of 1 kHz was selected whilst for fiber lengths over this the pulse repetition frequency was reduced to 500 Hz. The DAS system responds to any acoustic frequencies on the fiber, but due to the Nyquist sampling criteria, only acoustic frequencies up to half the pulse repetition frequency can be described correctly by the system. In this case 500 Hz and 250 Hz, respectively (constant along respective fiber).

A self-noise of 46 dB_{ps} is a level where an acoustic signal from the loudspeaker is clearly visible out of the noise, as shown in qualitative figure 1(a). It can be seen from figure 1(b) that even at higher noise levels (here 50 dB_{ps} after 133 km) acoustic signals can be identified, i.e. certain signals, like periodic signals are visible further than the reported lengths here.

RESULTS

The optimum pulse power from the DAS interrogator is defined here as the power that can be sent into the fiber where the Rayleigh backscatter from far distance (like 100 km) is maximized. When taking the maximum power for SSMF as reference (i.e. 0 dB, which is about 0.25 W), the power levels are as shown in table 1:

Table 1. Maximum pulse power at 1550 nm per fiber type

Fiber	Optimum pulse power	Uncertainty
SSMF	0 dB	(reference)
SCUBA 125 (ULL)	+1.0 dB	(±0.4 dB)
SCUBA 150 (ULL)	+2.0 dB	(±0.4 dB)

This means the ULL fibers have the advantage of allowing higher pulse powers from the DAS interrogator, as expected from the fiber design.

The fiber attenuation was determined using an OTDR, results shown in table 2:

Table 2. Attenuation at 1550 nm per fiber type

Fiber	Attenuation	Uncertainty
SSMF	0.195 dB/km	(±0.02 dB)
SCUBA 125 (ULL)	0.154 dB/km	(±0.01 dB)*
SCUBA 150 (ULL)	0.156 dB/km	(±0.01 dB)*
Acoustisens (ENHF)	0.40 dB/km	(±0.05 dB)

*incl. 2 splices over 100 km

The backscatter coefficient was measured by looking at the OTDR backscatter signal from before and behind the transition between SSMF and the respective test fiber. The connection between both fiber types was via 2 splices and 1 angled connector pair, respectively. The measurements were done in both directions i.e. transition SSMF → test fiber and test fiber → SSMF. Both showed similar absolute signal steps, but with opposite sign. From this we conclude that the average of both absolute values reflects the backscatter step with little or no impact from splice- and connector losses. Relative results versus SSMF are reported in table 3.

Table 3. Relative Rayleigh back-scatter coefficients per fiber type

Fiber	Rel. backscatter coeff.	Uncertainty
SSMF	0 dB	(reference)
SCUBA 125 (ULL)	-3.2 dB	(±¬0.8 dB)
SCUBA 150 (ULL)	-3.8 dB	(±0.8 dB)
Acoustisens (ENHF)	+ 10.0 dB	(±0.8 dB)

OTDR data generally refers to “one-way” losses, i.e. showing half of the dB backscatter signal seen by the instrument. These dB values were multiplied by 2 to get the relative backscatter signal. Backscatter in SSMF is typically in the order of 82 dB for 1 ns pulse length at 1550 nm [11]. This confirms that ULL fiber has a lower backscatter coefficient compared to standard fiber, while ENHF largely boosts the elastic backscatter.

The basic idea of combining different fiber types is to equalize the backscatter signal over distance. I.e. to compensate the decreasing backscatter power with distance by changing to a fiber with higher backscatter coefficient (at the cost of higher attenuation per meter, though) after a distance where the signal level falls below a critical limit for the intended application. In this case based on tables 1 to 3 for the used fiber types.

From DAS measurements on the different fiber types and combinations, the allowed fiber loss budget (one-way) was derived respectively, for which the noise level stays below the Self Noise limit of 46 dB_{ps}. The budget depends on the DAS system performance and the used fiber types; the initial fiber type determines the allowed interrogator pulse power avoiding non-linear effects (as long as the power level entering the following fiber type has reduced to stay below its nonlinear limit) and on the fiber type at the sensor end where the stimulus pulse power is lowest, and the backscatter coefficient determines if sufficient backscatter is available for good DAS results. The general approach is to use ULL at the beginning with the higher probing pulse power and lowest loss per km until the system noise reaches the defined limit, then change to a fiber with higher backscatter coefficient. The investigated combinations are listed in table 4.

Table 4. System loss budget (one-way) per fiber type

PP = rel. pulse power, BS = rel. backscatter

Initial fiber (Init.PP)	End fiber (End BS)	Pulse rate (SNR)	Max. loss
SSMF	SSMF	1 kHz	15.7 dB
ULL SCUBA-125 (+1 dB)	**SCUBA 125** (-3.2 dB)	1 kHz	14.6 dB
ULL SCUBA 150 (+2 dB)	**SCUBA 150** (-3.8 dB)	1 kHz	14.8 dB
ULL SCUBA 125 (+1 dB)	**SSMF**	1 kHz	16.2 dB
ULL SCUBA 150 (+2 dB)	**SSMF**	1 kHz	16.7 dB
ULL SCUBA 125 (+1 dB)	SSMF	**0.5 kHz** (-1 dB)	15.7 dB
ULL SCUBA 150 (+2 dB)	SSMF	**0.5 kHz** (-1 dB)	16.2 dB
ULL SCUBA 125 (+1 dB)	**ENHF** (+10 dB)	0.5 kHz (-1 dB)	20.7 dB
ULL SCUBA 150 (+2 dB)	**ENHF** (+10 dB)	0.5 kHz (-1 dB)	21.2 dB

Again, the loss budget varies with the different initial pulse powers and backscatter coefficients as well as different pulse rates.

Based on these optical loss budgets (table 4) and fiber parameters (tables 1, 2, 3), the reach of the different configurations are calculated and shown in figure 2. Configurations C and D start with the fiber type of lowest attenuation and end with a fiber type of high backscatter coefficient.

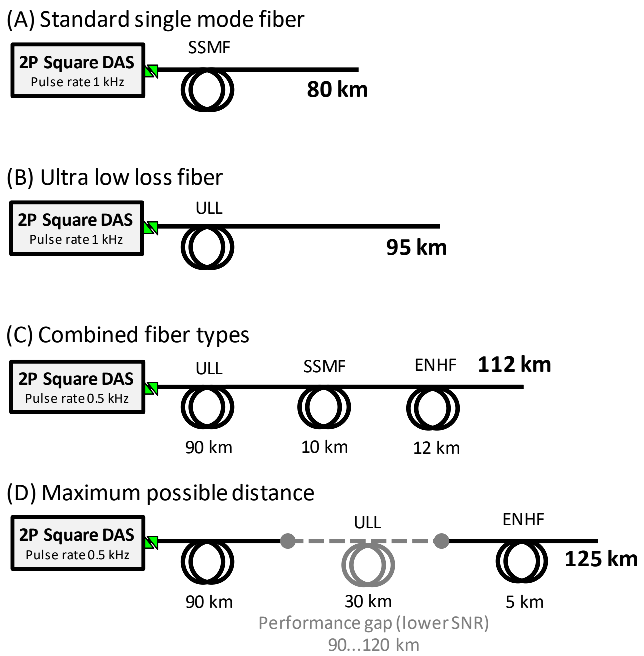


Fig. 2 Maximum reach for different fiber setups

Note: As known, the acoustic bandwidth for such time-of-flight based systems is limited by the round-trip time of light in the fiber. For sensor lengths >100 km pulse rates of <1 kHz are required, e.g. 125 km would work with a rate up to 800 Hz. In these tests the DAS pulse rates were not optimized, because of limitations in the DAS software at that time, not offering settings between 0.5 kHz and 1 kHz. In separate tests we could observe (in accordance with expectation) that higher pulse rates reduce the noise (as expressed in dBps) with a square-root law. The used DAS model will in future allow pulse rate settings in finer steps; we expect that with optimized pulse rate, the reaches will slightly increase compared to the values reported here.

CONCLUSION

We have shown the furthest reach to our knowledge of an optical DAS on a passive fiber sensor line, i.e. without optical amplification on the path, which reaches a span of 112 km for continuous coverage of the sensor fiber or a maximum distance of 125 km when looking at the last 5 sensor kilometers. This is achieved by using a commercial DAS system optimized for long reach measurements in combination with 3 fibers types, this is standard single mode fiber, ultra-low loss fiber and enhanced backscatter fiber. Such optimized fiber combination should allow to extend the reach of any DAS system. On the other hand the used DAS system has an extended reach also on solely standard fiber. The combination of both enables the reported long reach. The reach corresponds to a distance where the self-noise (according to SEAFOM) stays below 46 dBps. A qualitative result showing an acoustic stimulus at the end of 133 km demonstrates that for some applications even higher reaches are possible. For fiber lengths above 100 km a fix pulse rate of 500 Hz was set, which is lower than what the round-trip time of light in the fiber would allow. We expect further performance improvement when adapting the pulse rate to the actual fiber length.

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