Initial results from a simplified sub-sampling approach for Distributed Acoustic Sensing

R. Ellwood, A. Godfrey and C. Minto
OptaSense Ltd, Cody Technology Park, Ively Road, Farnborough, Hampshire, GU14 0LX, United Kingdom
Robert.ellwood@optasense.com

Abstract. Recently, interest has risen in the use of Distributed Acoustic Sensing (DAS) to monitor the condition of sub-sea cables connecting off-shore windfarms. Certain failure modes of these cables develop gradually, over the course of weeks to months, in response to external environmental factors. DAS provides a wealth of information on physical processes occurring over a long linear length. A significant challenge in acquiring all this information is in managing the volume of data captured (in excess of 1TB a day). This paper presents results from an investigation into an approach to adapt the way the data is acquired and stored, whilst not inherently biasing the process. The approach combines a range of traditional techniques, as well as a simplified implementation of the already well established sparse sampling technique. This approach is applied to the collection of data from a windfarm export cable over a period of 876 hours. Analysis of this data demonstrates the systems capability to practicably capture long term trends in the data due to environmental factors.

1. Introduction

Distributed fibre optic sensing encapsulates a range of techniques for remotely monitoring a variety of physical parameters including temperature, strain, acoustic signals and magnetic fields, with new capabilities being demonstrated regularly. What separates these techniques is the fundamental optical parameter that each technique relies on to detect perturbation in the physical parameter of interest. A non-exhaustive, but inclusive, list of these techniques include distributed fibre Bragg sensing, Brillouin fibre sensing (temperature and strain), Raman sensing (temperature) and Rayleigh sensing (relative temperature and strain) [1] [2] [3].

DAS systems are based on measuring variation in the optical path length using Rayleigh backscatter and as such are extremely sensitive to strain and temperature changes on the fibre. Since these properties can be utilised to measure more than just acoustic signals, a more accurate description of this technique is Distributed Rayleigh Sensing (DRS) [4]. DRS techniques benefit from not requiring specialist fibre, only requiring powered access to one end of the fibre, and the ability to produce wideband acoustic data from comparatively small spatial measurements. DRS has developed as a key technology in monitoring long linear assets in a range of industries including pipeline, oil/gas extraction, transport networks and perimeter security.
Recently interest has risen in the use of DRS to monitor the structural health of sub-sea cables connecting off-shore windfarms as these represent significant investment in this infrastructure. Analysis of sub-sea cable failures [5] has shown that 63% of failures occur on cables over 10 years old. Of all failures, 33% are attributed to external parameters excluding third party involvement (anchor drop, trawling or excavation), examples of the types of failure modes included in this group are changed burial depth, thermal effects and lead sheath fatigue. These types of failure mechanisms accumulate gradually over the course of weeks to months and require long term measurements to observe their development. DRS produces significant amounts of data (~1 to 40 TB/day/50 km) and successfully handling and processing this amount of information over months to years represents a significant challenge. This data challenge is the main reason why slow changes in the signal have not previously been studied across long distances.

Compressed sensing is a powerful signal processing technique used for the sampling and recovery of sparse signals [6]. One application of this technique is to allow for a reduction in stored data volumes, all be it with an associated computational expense, by recovering a signal from a series of measurements below the number required by Nyquist-Shannon sampling theorem. Since its inception, compressed sensing approaches have been applied to a myriad of signal processing applications such as imaging [7], holography [8], ground penetrating radar [9] and data compression [10]. Compressed sensing has been widely used throughout the field of acoustics [11], including seismic studies [12], passive acoustic mammalian studies [13] and biomedical imaging [14], to name a few, to reduce data acquisition costs. In the field of DRS other workers [15] have employed a sparse sampling technique to increase the maximum sampling rate of a fibre.

This paper presents an implementation of a simplified sub-sampling approach to DRS data to allow sufficient fidelity without biasing the acquisition. This approach makes use of a combination of traditional acquisition methodologies as well as a simplified sub-sampling approach, and allows the storage of up to one years’ worth of data on a single commercially available hard disk (12TB). This work presents a novel application of compressed sensing to the collection of DRS data, allowing for trends that develop over the course of months to be investigated over the full length of the asset. This paper’s novel contribution is to show that observed temporal sparsity in DRS data can be exploited by a rudimentary implementation of compressed sensing to demonstrate associated trends in the acoustic data that correlate to changes in ambient conditions.

**2. Material and Method**

**2.1. Acquisition approach**

The technique discussed in this paper makes use of 2 separate data processing streams, each going to a separate hard disk. The combination of processing streams and storage media are referred to as recorders. In the following section each of the recorders is discussed. The data collection arrangement from the interrogator unit (IU) is outlined in Figure 1 (A).
Figure 1 (a) Diagram of data collection featuring 2 synchronous recordings from a data stream provided by a DRS interrogator unit. The rolling recorder captures full rate (2kHz) data and once full records over the earliest data. The sub-sampled data records 1 minute long windows starting after a random delay from the last sample based on a uniform distribution. (b) Lomb-Scargle Periodogram of window function used for data acquisition (red). The black line is a simulated 75Hz signal sampled using the sparse sampling technique, this sampling technique generates additional aliasing features.

2.1.1. Rolling recorder-
In this recorder data are acquired at full sampling rate, once the storage medium is full new data are written over earlier samples. This recorder runs as standard on an OptaSense system, at a rate defined by cable length (in this case 2kHz). This technique provides high fidelity information, with the opportunity to capture in detail specific events, for example if the cable were to break or if there was an electrical cable failure.

2.1.2. Simplified sub-sampling approach-
Analysis of DRS data acquired from 6 off-shore wind farm sites around the UK has shown that the majority of signals detected are related to 3 main sources, environmental (sea/ weather condition), local surface traffic (shipping) and electrical/ thermal signatures. Some of these signatures demonstrate acoustic bandwidths up to the full bandwidth of the DRS system. The ultimate question of this project is to determine if changes these detected sources over a long periods could inform as to the cables condition. However, storing and processing this data at full rate is prohibitively expensive. It has been observed that these signals occur semi-sporadically, with some observable periodicity in most cases. For example surface traffic movement is mostly confined to daylight hours, weather patterns are notoriously variable however there is seasonal variation. Data reduction by simple temporal decimation or regular block sampling periods risks enforcing a periodicity (and therefore bias) in the observation. The sub-sampling approach implemented here seeks to collect data without assuming a periodicity by taking samples that are randomly spaced in time. An assumption of temporal sparsity is made in the application of this sampling approach, which is valid for these signals over a sufficiently long time frame. This approach is analogous to the observation of light curves in astronomy [16] or in the study of marine mammal studies [13], where acquisitions are necessarily made irregularly due to practicalities of the measurement. As outlined in [16], care must be taken in the design of the acquisition so as to not pre-bias the acquisition of data as the structure of the window function can lead to aliasing of the signal.

Due to practical limitations in the implementation of a sub-sampling recorder, the samples are required to take the form of fixed finite length blocks of successively sampled data starting after a random duration from the end of the previous block. These blocks are acquired at the full rate of the system. In order for direct comparison to existing processing techniques (see frequency band extracted technique
below) the finite width of these blocks was selected to be one minute in duration, this allowed sufficient spectral resolution for each block. A uniform random distribution was selected for the interval between samples due to the equal likelihood of events occurring throughout the period. Due to the requirement of a years’ worth of data fitting onto a single disk it was required for one block to be recorded on average each hour, as such the uniform distribution was configured to have a maximum of 2 hours delay and minimum of 0.132 seconds.

By sampling the data in this way recoverable frequency content is a convolution of the true spectrum and the spectrum of the window function created by the sampling process [16]. The window function of the acquisition has the equivalent Lomb-Scargle periodogram seen in Figure 1 (B) (red, calculated with Plomb function MATLAB with the sample time corresponding to those acquired and the signal being 1 during the block and 0 in between blocks), a modelled signal of form $y=3 \sin(2\pi ft)$ (black, where $t$ is the time from the sampling scheme and $f=75Hz$, $f_{bin}$ width 0.1Hz) is also shown demonstrating the ability to recover the fundamental frequency. Due to the nature of the sampling process a series of spikes can also be seen caused by aliasing. The top hat function of the 1 minute block has Fourier transform of a sinc function of width 0.033Hz, which ultimately limits the resolution of the system. This is acceptable as in this deployment we are primarily concerned with the acoustic frequencies recovered and how they vary over time. This scheme represents a data compression of 1/60.

By combining these recorders, the aim is to capture all signal types with no assumed features. Potentially an implementation that takes advantage of spatial sparsity in the data could also be implemented, but this was not realised here due to practical limitations.

2.2. Deployment

A modified OptaSense ISM (Infrastructure Security and Monitoring) system was deployed to an onshore landing station for a windfarm. The only modification was the inclusion of the additional recorder discussed in the previous section. Using the OptaSense ISM system allows this approach to be fully scalable from 1 interrogator (covering 50km) to tens of units allowing this technique to be applied to 1000’s of km (to date the largest installation is 1850km). In this data collection a single interrogator unit (IU, ODHF) is used in the deployed system, capable of outputting either intensity data over a range of 50km or quantitative data over a range of 10km. The system is attached to a dark fibre on an export power cable leading to an off-shore station. The fibre length was 47.2km long (see Figure 2). Data was acquired in an intensity mode with a spatial resolution of 10.2m with a sampling rate of 2kHz. Minimal supervision of the system was required with weekly checks to confirm its operation. Data was obtained by removal of the hard disks from both recorders after a month.

![Diagram](image_url)

*Figure 2 Diagram (not to scale) of cable deployment with key features observed in DRS data highlighted with letters corresponding to regions highlighted in plots (see Figure 3)*

---

**The Anglo-French Physical Acoustics Conference (AFPAC) 2020**

**Journal of Physics: Conference Series**

**1761** (2021) 012002

doi:10.1088/1742-6596/1761/1/012002
3. Analysis and Results

Data from the initial month period of the deployment of the system is analysed. This allows a direct comparison between the existing traditional recorders and the additional sparse sampling recorder. Analysis on additional data is still on going. The output from both recorders are discussed, special attention is paid to the randomly sampled recorder due to novelty of processing the data.

3.1. Rolling recorder - Frequency Band Extracted data

This recorder shows a total of 76 hours of full rate data. A frequency band extracted (FBE) plot is shown in Figure 3, focusing on energy in the 10-30Hz band. The FBE is a technique used to visualise how energy content in different frequency bands develops both temporally and spatially. The FBE process involves taking a window (type Hanning) and a Fast Fourier Transform (fft) of 256 samples of the data set for each spatial channel. A sum of the FFT bins corresponding to the band of interest is then used to generate a pixel intensity. A 50% overlap between successive steps is utilised. During the recorded period a significant increase in the sea-state can be seen based on the acoustic energy observed. Of note is that an increase in wind-state is seen around the period that an increase in acoustic energy is observed (around the 18th September). This would indicate the change in sea state. Specific regions of the cable demonstrate significant increase in signal, indicating that these regions are more impacted by the change in conditions. Being able to track how these regions change over time would give insight into changes of the cable state.

Figure 3 Frequency band extracted (FBE, 10-30Hz) showing data from the full rate rolling recorder. Localised changes in conditions for the subsea cable can be observed over the 3 days worth of data that this recorder stores. (A) shore segment. (B) intertidal zone. (C) section where significant energy is observed periodically most likely due to increased wave action. (D) variably noisy channels. (E) substation
3.2. Sub-sampled recorder

An FBE (frequency range 10-30Hz) of the randomly sampled data is shown in Figure 4. This represents a period 11 times longer (864 hours) than the period seen in the rolling recorder. In the top section of Figure 4 (denoted by A) represents the same period of time shown in the rolling recorder data. Additionally, other spatially and temporarily distinct regions demonstrate how signals in these regions develop.

Figure 4 FBE (10-30Hz) plot of variation in signal level from sub-sampled data set from entire period (section labelled A corresponds to region associated with rolling recording). The same trends are observed in both recorders, additional earlier events are seen in the sub-sampled data.

By enforcing a known periodicity on the randomly sampled data visualisation of signals as they evolve over these set periods can be effected. A demonstration of this approach is seen by taking the FBE of each block of data (in this case 0-3Hz band) from the entire acquisition period of 864 hours, stacking each FBE within a 12 hour 25 minute block and summing. The resultant image shows the variation in the acoustic energy within the tidal period (see Figure 5(A)) and highlighting the variation in the length of the cable submerged, in this case 30m.

If the same stacking approach is applied over a period of a week to the full data set, around a segment where the fibre ran parallel to a road, the plot seen in Figure 5 (B) is generated. Taking a rolling mean filter along the FBE band shows a temporally varying trend. Periods of significant acoustic energy correlates to periods of human activity (daylight hours 06:00-00:00). Interestingly the period of significant energy corresponding to Sunday in the week is shorter than the other days. This indicates the reduced length of time there is human activity on the road on a Sunday. The ability to extract insight into environmental conditions on arbitrary timescales demonstrates the benefit of this approach.
Correlation between the observed signal and other variables can also be explored by stacking the sub-sampled data with reference to other data sources. This is demonstrated by stacking the data from frequency band 10-30 Hz against wind speed (source [17]), shown in Figure 6 (A). Here we can see that some DRS channels (500-1000) show significant increase in energy with an increase in windspeed. Other locations show a reduced sensitivity with wind speed, though at higher windspeeds (>43 km/h) all channels show increased acoustic energy. It can also be seen that different channels react to changes atmospheric pressure differently (see Figure 6 (B)). Lower atmospheric pressures tend to represent more unsettled weather. As further work it is intended to relate these changes to cable survey data (not currently available) to better understand the mechanism for these responses. It is intended to investigate the periodicity of signals using methods such as the Lomb-Scargle periodogram.

Figure 5 (A) Image of the FBE data (0-3 Hz), from the sub-sampled recorder stacked over a period of 12 hours 25 minutes produced by stacking randomly sampled data from 864 hours collection period. Change in the coverage of cable with movement of tide can be observed. This demonstrates the ability to, post-acquisition, investigate changes in the data over arbitrary periods. (B) Stacked FBE data (10-30 Hz) over a period of a week sub-sampled data (randomly sampled over a period of 864 hours) from channels close to road. An increase in activity concurrent with waking hours is observed. Of note is the reduction in length of activity corresponding to a Sunday.
3.3. Limitations of approach

Whilst this limited sub-sampling approach has demonstrated some potential for acquiring acoustic data at sufficient resolution over sufficiently long periods to investigate variations in signals occurring along a sub-sea cable, this approach is not without limitations. Firstly, care must be taken over the sampling procedure. As outlined in [16] the nature of the window function and practical sampling time limits impact the recoverable bandwidth of signals, due to the introduction of additional structure from the window function of the acquisition process. Another requirement of this approach is that samples are acquired over a sufficiently long period so as to capture sufficient proportion of the variation in signal. Recovering fundamental frequencies is also challenging in these methods due to signals not necessarily being truly sinusoidal and so exhibiting higher harmonic content.

When assessing the variation in signals due to environmental factors, without collecting data over a full cycle of climatic change, being able to compare to secondary sources of data is necessary. The combination of 2 recorders allows the system to be relatively agnostic to the type of signals detected. However, sudden step changes that don’t occur during an interval that is recorded will be missed by the random sampling. They will be captured by the first rolling recorder, provided that the system/cable is monitored with sufficient care this rolling recorder can be recovered should an event of magnitude occur (e.g. cable failure). However, if the event is below this monitoring threshold it may be missed. At which point it will only be possible to resolve any state changes to a temporal accuracy of the duration the gap between recordings, as such the signals caused by the event will be aliased.

4. Conclusion

Data from a DRS system provides a wealth of information about changes in the environment and the structure of off-shore cables. It is apparent that changes of concern to these cables can occur over long time periods. Storing, processing and evaluating full rate acoustic data over this period is an intractable problem. This paper has presented a novel approach to acquiring reduced data with sufficient fidelity without biasing the acquisition. A combination of two recorders are used to compare different signals over different periods. While the application of this technique allows for distinct correlations to be determined it is limited by the collection scheme selected in terms of recoverable bandwidth. Other sources of data (such as meteorology) are vital to be able to fully understand some of these trends. There are potential state changes that could be missed by the combined recorder system. However in this paper
it has been demonstrated that even with these limitations, using a simplified sub-sampling approach months of high frequency acoustic data can be practically investigated.

5. Acknowledgements
Data for this work was collected by EDS HV group as part of a Horizon 2020-Sentry (768328) project.

References

[1] L. Schenato, "A Review of Distributed Fibre Optic Sensors for Geo-Hydrological Applications," *Applied Science*, vol. 7, no. 9, p. 896, 2017.

[2] Chen, B. Xiaoyi and Liang, "Recent Progress in Distributed Fiber Optic Sensors," *Sensors*, vol. 12, no. 7, pp. 8601-8639, 2012.

[3] C. Baldwin, "Fiber Optic Sensors in the Oil and Gas Industry: Current and Future Application," in *Opto-Mechanical Fiber Optic Sensors Research, Technology, and Applications in Mechanical Sensing*, Oxford, Butterworth-Heinemann, 2019, pp. 211-236.

[4] R. Crickmore, A. Godfrey and C. Minto, "Strain monitoring using distributed Rayleigh sensing," in *Proc. SPIE 11199, Seventh European Workshop on Optical Fibre Sensors, 111991U*, https://doi.org/10.1117/12.2539661, (28 August 2019).

[5] R. Rosevear, M. Choquette, M. Fairhurst, R. Garcia, H. Jorgensen, J.E.Larsen, B. Mampaey, R. Mosier, A. Rakowska, H. Shigetsugu, S. Tricoli and V. Waschk, "WG B1.10 UPDATE OF SERVICE EXPERIENCE OF HV UNDERGROUND AND SUBMARINE CABLE SYSTEMS," CIGRE, 2009.

[6] D. L. Donoho, "Compressed Sensing," *IEEE TRANSACTIONS ON INFORMATION THEORY*, vol. 52, no. 4, pp. 1289-1306, 2006.

[7] G. M. Gibson, S. D. Johnson and M. J. Padgett, "Single-pixel imaging 12 years on: a review," *Opt. Express*, vol. 28, no. 19, pp. 28190-28208, 2020.

[8] C. Schretter, S. Bettens, D. Blinder, B. Pesquet-Popescu, M. Cagnazzo, F. Dufaux and P. Schelkens, "Compressed digital holoography: from micro towards macro," in *Proc. SPIE 9971, Applications of Digital Image Processing XXXIX*, San-Francisco, 2016.

[9] E. Cristofani, M. Becquaert, S. Lambot, M. Vandewal, J. H. Stiens and N. Deligiannis, "Random Subsampling and Data Preconditioning for Ground Penetrating Radars," *IEEE Access.*, vol. 6, pp. 26866-26880, 2018.

[10] M. Salloum, N. D. Fabian, D. M. Hensinger, J. Lee, E. M. Allendorf, A. Bhagatwala, M. L. Blaylock, J. H. Chen, J. A. Templeton and I. Tezaur, "Reconstruction of Unstructured Mesh Datasets," *Data Sci. Eng.*, vol. 3, p. 1-23, (2018).

[11] P. Gerstoft, C. F. Mecklenbräuker, W. Seong and M. Bianco, "Introduction to compressive sensing in acoustics," *The Journal of the Acoustical Society of America*, vol. 143, no. 6, pp. 3731-6, 2018.

[12] F. J. Herrmann, M. P. Friedlander and O. Yilmaz, "Fighting the Curse of Dimensionality: Compressive Sensing in Exploration Seismology," *IEEE Signal Processing Magazine*, vol. 29, no. 3, pp. 88-100, 2012.

[13] K. Thomisch, O. Boebel, D. P. Zitterbart, F. Samaran, S. V. Parijs and I. V. Opzeeland, "Effects of subsampling of passive acoustic recordings on acoustic metrics," *The Journal of the Acoustical Society of America*, vol. 138, no. 6, pp. 267-278, 2015.

[14] N. Huynh, F. Lucka, E. Z. Zhang, M. M. Betcke, S. R. Arridge, P. C. Beard and B. T. Cox, "Single-pixel camera photoacoustic tomography," *Journal of Biomedical Optics*, vol. 24, no. 12, p. 121907, 2019.

[15] J. Zhang, H. Zheng, T. Zhu, G. Yin, M. Liu, Y. Bai, D. Qu, F. Qiu and X. and Huang, "Distributed fiber sparse-wideband vibration sensing by sub-Nyquist additive random sampling," *Optics Letters*, vol. 43, no. 9, pp. 2022-2025, 2018.

[16] J. T. VanderPlas, "Understanding the Lomb–Scargle Periodogram," *The Astrophysical Journal Supplement Series*, vol. 236, no. 16, p. 28pp, 2018.

[17] "Time and date," 10 05 2020. [Online]. Available: https://www.timeanddate.com/weather/@2644642/historic?month=8&year=2019. [Accessed 10 05 2020].