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DOI
10.3997/2214-4609.2023101490

Publication date
2023

Document Version
Final published version

Citation (APA)
Chapeland, C., Verschuur, E., & Draganov, D. (2023). *Novel method for UHR streamer shape reconstruction and improved receiver positioning: a conceptual overview*. Paper presented at 84th EAGE ANNUAL Conference and Exhibition 2023, Vienna, Austria. https://doi.org/10.3997/2214-4609.2023101490

Novel method for UHR streamer shape reconstruction and improved receiver positioning: a conceptual overview

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Summary

Poor knowledge of source and receiver positions in ultra-high-resolution marine seismic data is the cause of severe damage which requires novel processing techniques to mitigate. This type of seismic data is highly relevant for ultra-shallow subsurface imaging in geo-engineering projects both offshore and in harbours. Current positioning technologies are limited partly by their accuracy but also the fact that they are only placed on head and tail buoys of the towed arrays. This leaves receiver locations on the length of the streamer cable to be interpolated. Rather than developing additional processing methods, we propose to improve the quality of the data by introducing a complimentary receiver positioning system to reconstruct the shape of the streamer cable in 4D using Fiber Optic Shape Sensing (FOSS) technology. In this abstract, we outline the key features of FOSS technology and provide a conceptual overview of our efforts to bring this technology to the field.

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Introduction

Imaging and characterisation of the shallow off-shore subsurface requires increasingly fine resolutions while remaining cost-efficient and quickly executable. The industry interest ranges from site eligibility investigation to geo-engineering project developments, long-term monitoring of man-made subsurface structures, hydrocarbon exploration and near-surface effects removal for deeper target imaging. Notably, these applications are pivotal to the energy transition and resolution, accuracy and repeatability are qualifiers that most concern these industries (Faggetter et al. 2020, MacGregor et al 2022).

To this end, high-frequency (100 Hz - 1 kHz) and ultra-high-frequency (<2.5 kHz) seismic methods are commonly commissioned. This technology is particularly competitive when characterising shallow sediments and heterogeneities as it is non-invasive and can significantly penetrate the subsurface contrary to other high-resolution methods like Ground Penetrating Radar. However, a significant drawback of employing seismics in a high-resolution context is that the clarity of the data obtained using (Ultra-)High-Resolution ((U)HR) streamers is limited by the positioning accuracy of the source and receivers in the lateral and vertical planes. The uncertainty of source and receiver positioning is particularly burdensome as the required accuracy for high-frequency, short-wavelength seismic waves approaches the operational error of the equipment positioned on the cable. To circumvent this issue, we propose a new method to reconstruct the 3D shape of the streamer cable in real time using optical fiber technology. The goal of this technology is not to replace existing positioning methods but rather to complement them to improve the quality of UHR marine seismic data to lower the costs of acquisition and reduce processing time in a manner that can be integrated with existing technology.

The literature presents complex processing schemes which require significant time, computational power and human input. This is due to the challenges presented by (U)HR data including (but no limited to) high-resolution marine statics, complex receiver ghosts and poor regularisation,which do not respond to typical processing methods due to limited far-offsets, missing low frequencies and mitigating factors during acquisition (Buryak et al. (2019), Duarte et al. (2017), Faggetter et al. (2020)). These issues are further exacerbated by the industry's transitions to full 3D (U)HR systems and could be remediated by improving the quality of the positioning data (MacGregor et al. (2022)).

Poor lateral and vertical receiver positioning along a (U)HR streamer is primarily caused by weather conditions, steering or pitch/yaw movement of the vessel and positioning equipment resolution limits. Weather has become a severe limiting factor regarding the execution of (U)HR surveys and vessel steering often prevents the survey from being continuous as data can only be recorded when the vessel is travelling at a constant speed and in a straight line). These factors may cause significant issues regarding repeatability as the exact position of the receivers may deviate with streamer models used in data processing.

According to Wardell et al. (2002) when source frequencies reach 1kHz, the positioning resolution should be <10 cm. Current high-resolution global positioning methods fall within 2 categories: satellite-based and fixed-point-based. Satellite-based positioning like Global Positioning Services (GPS) and Global Navigation Satellite System (GLONASS) provide good coverage around the globe but may suffer from lower accuracy while fixed-point-based systems like Real-Time Kinematics (RTK) provide centimeter-level accuracy but requires near-by referral stations. Positioning providers like Fugro are able to provide very high-resolution global positioning by combining these methods providing an accuracy of 3 cm and 6 cm in the horizontal and vertical planes, respectively (see the Fugro Starfix®G2+ for the accuracy reported, accessed: 11-01-2023). However, even when high-accuracy positioning systems are employed, the positioning tools are costly and usually only placed on the head and tail buoys of the streamers and sometimes the sources, leaving the length of the streamer (and thus the precise receiver positions) to be interpolated during processing (Monrigual et al. (2017)). Hydrostatic pressure sensors and gyroscopes may be used along the streamer to tackle this issue with relatively high accuracy; however, standard deviation compounds and complex post-processing corrections must be implemented, which may lead to over-smoothing of the data or loss of anomalous details. These sensors further struggle to compensate for lateral drift and wave height when the streamer is floating on the surface. Moreover, they provide discrete point measurements which contribute to increased equipment costs and load on the vessel.

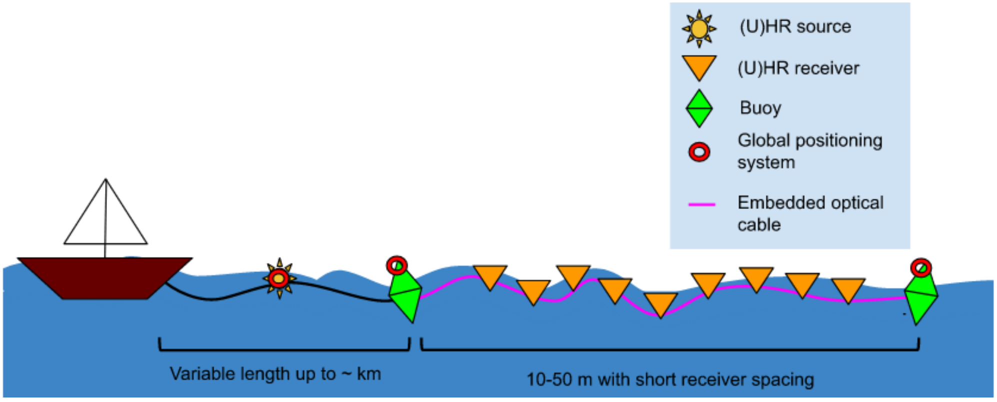

Figure 1 *Schematic diagram of FOSS technology embedded in an existing (U)HR streamer. The fiber optic cable is placed on a streamer to monitor its shape and thus the horizontal and vertical location of individual receivers.*

Concept

To estimate the precise receiver locations and receiver trim variations along a streamer we propose to use Fiber Optics Shape Sensing (FOSS) technology where strain measurements along an optical fiber cable are used to reconstruct the cable's 3D shape in time. In geophysics and seismology, fiber optics strain sensing is often synonymous with Distributed Acoustic Sensing (DAS) where the fiber is used as a sensor to detect external vibrational wavefields (Gorshkov et al. (2022), Taweesintananon et al. (2021)). However, although the hardware is similar, the aim of FOSS is to measure the strain caused by the bending of a fiber cable itself and reducing/eliminating the effects of external wavefields and environmental noise. For this application, we benefit from existing technology that was originally developed in the medical fields to monitor the path taken by a camera or needle inserted in the body and in the industrial engineering field to monitor building movement over time. (Issatayeva et al. (2021), Monsberger et al. (2021)).

We propose to embed or wrap an optical fiber (< 5 mm diameter) along an existing (U)HR streamer to monitor its shape with a high spatial and temporal resolution during the seismic survey, allowing us to model the precise 4D location of receivers within the streamers, between the global positioning systems on the head and tail buoys as shown in Figure 1. Notably, this method would use a single sensor for continuous measurements along the streamer. For a deep-towed arrays, this technology could also be set-up to float at the surface to precisely model surface wave-height above the source and receiver arrays; as Blacquiere et al. (2019) demonstrated, wave-height and rough seas can have detrimental effect on data by creating a complex ghosts "blurring effects". Our motive is that by collecting more accurate receiver locations and wave height information we will improve the quality of the data as well as reduce the limiting factors of high-frequency marine seismic acquisition execution and lower processing time and costs.

Fiber optic technology has many advantages with regards to flexibility, durability, ease of accessibility and price. Moreover, the fibers are lightweight, can perform well in water and are immune to electromagnetic interference facilitating embedding capabilities (Floris et al. (2021)). The material costs for manufacturing a multi-core optical fiber are negligible; however, creating a fiber optic cable to the specifications necessary for this application increases the costs strongly. We estimate that economies of scales would reduce these costs as currently the fiber cable must be made to order for the longer sensing length. The recording units themselves (called interrogators) present the highest expenditure; however, due to the plug-and-play nature of fiber optics, while several optical fiber cables could be permanently embedded into existing (U)HR streamers, the same interrogator can be used for all of them non-simultaneously. Our aim will be to preserve the accuracy and resolution achieved in the medical field for longer sensing lengths. Although we benefit from an established technology, our proposed application of FOSS for (U)HR streamer positioning requires extensive testing for establishing the effects of external variables during a seismic survey, increased sensing lengths and achievable maximum resolutions. Nonetheless, the expectation is that by carefully selecting the most suitable type of fiber optic strain sensor, cable path reconstruction will be minimally affected by external stimuli.

Background theory

Materials required for FOSS consist of an optical fiber containing at least 3 cores , which acts as a sensor and an interrogator unit , which acts as the emitting and recording device. When a fiberglass core is directly connected to a laser source and a pulse is emitted, the light will travel through the core. The core itself is extremely thin so a coating is added around the cladding to protect from environmental damage.

Although there are different methods used to measure a variable along an optical fiber, we focus on Distributed Optical Fiber Sensors (DOFSs) , which determine the spatial distribution of a measurand along the fiber contrary to discrete measurements, which require interpolation, like Fiber Bragg Gratings (FBGs). As the light travels along the transparent medium, it will scatter when encountering an imperfection in the atomic matrix and part of the energy will be backscattered towards the laser input where a sensor lays. Backscattered light will present a shift in wavelength, which can be detected and attributed to a specific gauge along the fiber. A gauge can refer to a fixed location of increased refractive index (like in FBGs) or to a section of the sensor where backscattering occurs in DOFs. For this application, we expect that Rayleigh backscatter strain sensing will be the most relevant. Figure 2 shows the criteria, which differentiate types of distributed strain sensing. It is important to note that these criteria are interconnected and trade-offs between accuracy and sensing lengths are intrinsic. For the application of (U)HR streamer shape reconstruction, we propose that Optical Frequency Domain Reflectometry (OFDR) is the optimum option.

Theory	Measurable (T/ε)	Sensing Range	Spatial Resolution	Strain Resolution	Temperature Resolution
Rayleigh (OTDR)	T/ε	1–2 km	0.5 m	n/a	n/a
Rayleigh (OFDR)	T/ε	70–100 m	5 mm	1	0.1
Brillouin (BOTDA)	T/ε	10 km	1.5 m	2	0.1
Brillouin (BOTDR)	T/ε	45 km	5 m	2	0.1
PPP-BOTDA	T/ε	2 km	2 cm	20	n/a
BOFDA	T/ε	9 m/11 km	3 cm/1.4 m	30	1.8
Raman	T	20 km	1–2 m	n/a	<1

Figure 2 *Comparison between different kinds of distributed fiber optic sensing systems as reported by Xu et al. (2020) and corresponding to criteria reported by Hartog (2018).*

Shape reconstruction methods

The shape sensing occurs in three stages: strain sensing along all fiber cores, computing curvature from strain and shape reconstruction using differential geometry methods. The strain ε at a given point can be directly related to the curvature K through the distance between the core i and the center of the fiber r and the angle between the core and the neutral plane β such that: $\varepsilon_i = -K_i\, r \sin(\beta)$. This expression can be adapted to take the strain contribution from multiple cores to derive the total apparent curvature. This implies that strain recorded due to other external stimuli like temperature or pressure will be common for all cores and thus will not affect the shape reconstruction accuracy. The numerical methods used to reconstruct the shape from the curvature and other similarly derived variables fall under two schools of thoughts: the Frenet-Serret frames and the multiplication matrix methods. Both methods can be extended for improved estimation of torsion thus we will be continually comparing their effectiveness for this application in future publications.

Hardware

In order to obtain the necessary small gauge length with high-resolution measurements, we use a LUNA OFDR system operated at a sampling rate of 50 Hz , which allows for a 20 m sensing length, a 5.2 mm gauge length and a 2.6 mm gauge pitch (distance between centers of consecutive gauges). The differential strain resolution is < 1με.

Outlooks

Proof-of-concept experiments are being carried out to test the capacity of the available hardware as well as to design a performant sensor. Preliminary results show a maximum shape reconstruction error of 8mm over 2 m with a simple tricore sensor for a large bending radius (from the matrix multiplication method). The bending radius is directly related to the sensitivity of the sensor to detect small deflections. If the strain caused by the deformation of the mostly straight towed (U)HF cable is too slight to be detected by the sensor or falls within the operational error of the hardware, the positioning of the receivers on the cable may be inaccurate. We are ensuring that we can mitigate the effects of temperature, pressure and environmental vibration on the strain data through a set of dedicated experiments.

Acknowledgements

We would like to thank Manos Pefkos, Pieter Doornbaal and Edvard Ahlrichs from Deltares as well as Marinus van der Hoek from van der Hoek Photonics for their continued cooperation and constructive discussions.

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