光ファイバ分布計測の孔井観測における トレンド

ニューブレクス株式会社　岸田 欣増

2023年12月

Kishida@neubrex.com

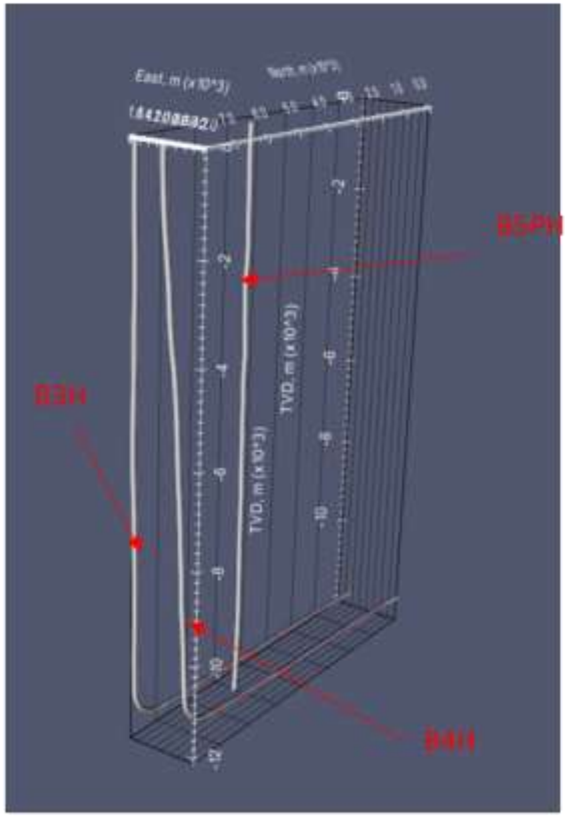
Contents

- Neubrex/RFS reputation established at UrTech 2022 HFTS-2
- DFOS計測の技術流れ（How many interrogators?）
- 光センシングケーブルの最新動向
  - Downhole Optic Sensing Cable at harsh environment
  - Helical Surface Seismic of 2C and 3C
- DFOSの最新動向
  - RFAS – slow and fast
  - 超音波DAS　3MHz/30Km
  - 強地震対応型DAS
- DFOS from option to necessary

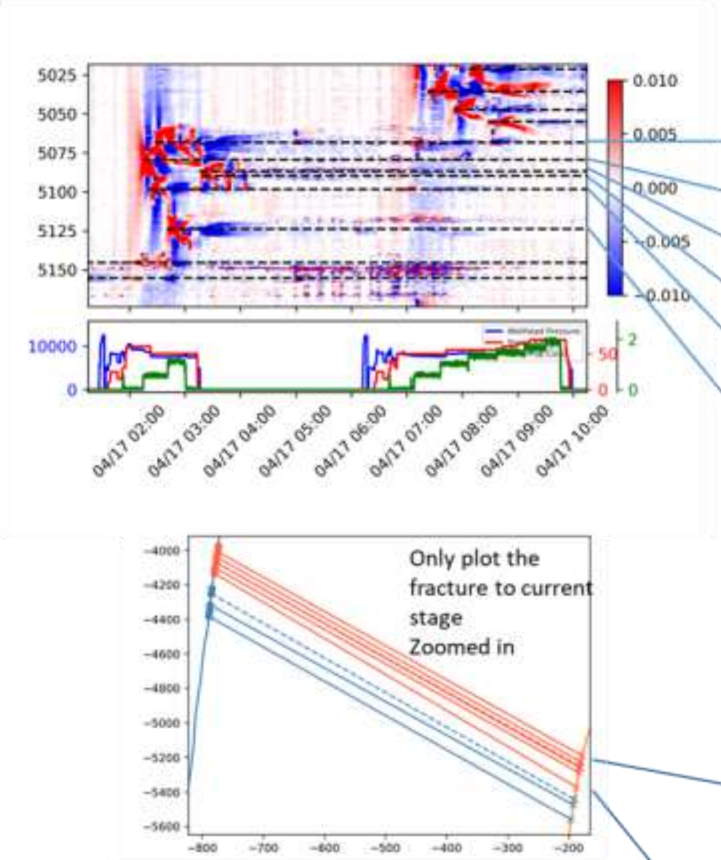
Neubrex/RFS reputation established at UrTech 2022 HFTS-2

日本はDFOSの発祥地にも関わらず長い間に応用学術界に注目されていなかった。現在は海外から押しつけられてDASのブームになっている最中であるが、DASの認識は味わいであり、ひずみやほかの計測にほぼ知られていない。米国の国プロHFTS-2での成果と影響を紹介する。

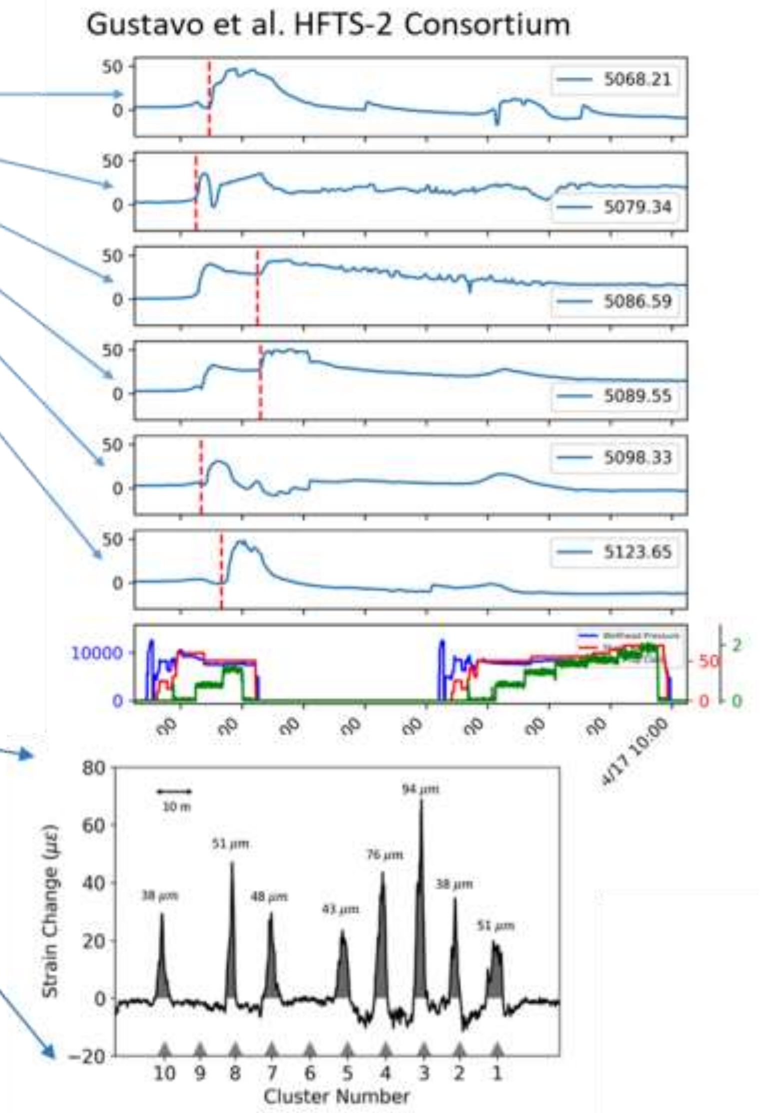
DFOS Reputation established on frac in HFTS-2, 2022



Wells

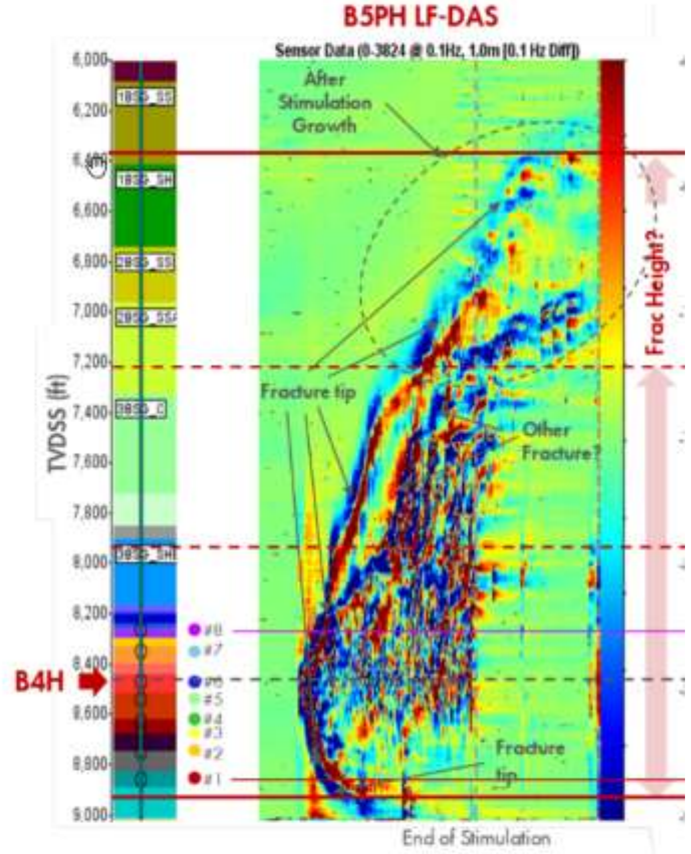


Strain measured of 2 stages

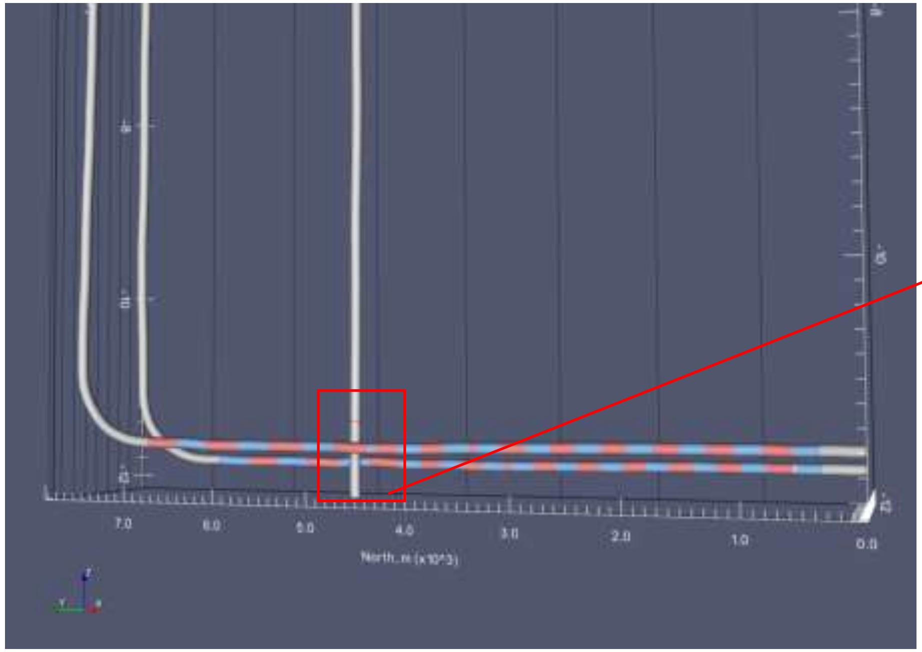


Application of DFOS shale oil field. The direction, speed and size of each frac are measured quantitatively

Illustration of SRV and DRV

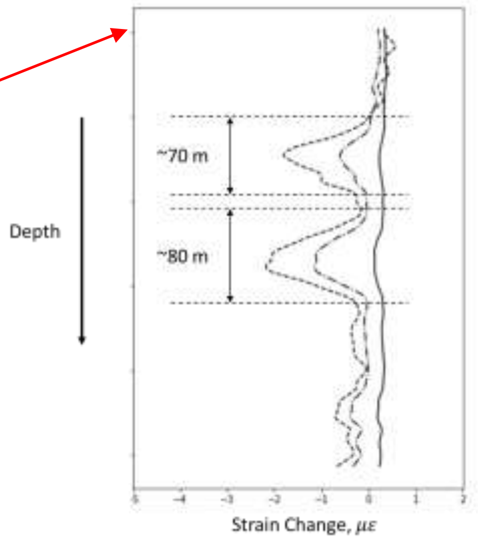


Microseismic events
Gustavo et al, UrTec, 2021



SRV observed by microseimic has big misleading to DRV. Whiles strain monitoring is reasonable.

DRV(Drainage Rock volume)



Strain at vertical well

Planar frac and crack swamps

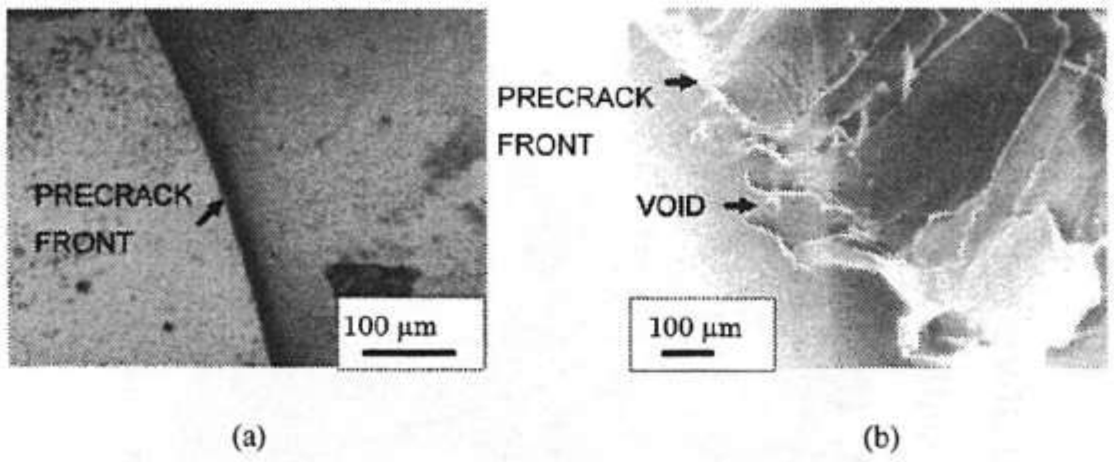


FIG. 2. Fracture surface in the striker impact and the laser loading experiments; (a) SP111 loaded by HPB one point impact, (b) SP007 loaded by laser shock waves. The arrows indicate voids that initiated cracks.

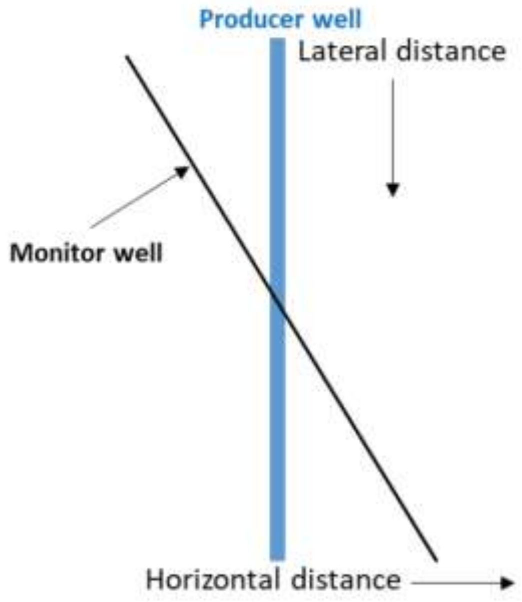
Xin-zen Li, et al, 1998

Table 1: Compare of fracture toughness of shale, glass and steel

Fracture toughness	Shale	Soda-lime glass	Pyrex glass	Steel
$MPa.m^{-1/2}$	0.98~1.8	1.0	2.0	62

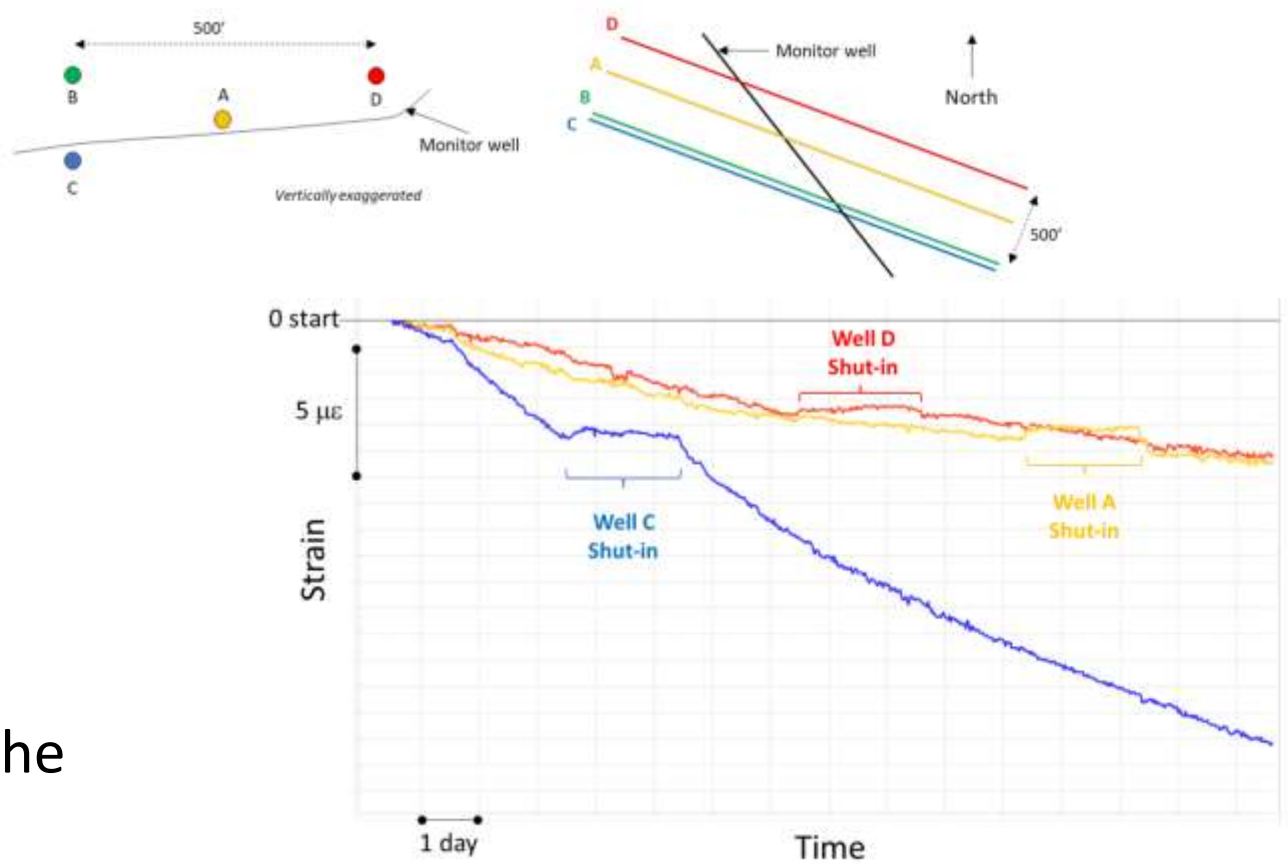
The main view, in the past, was ‘crack swarms’ which was supported by DAS observation of frac noise. However, observation of strain ended the argument and ‘Single planar frac’ with limited DRV is finally accepted.

DRV is small portion of frac



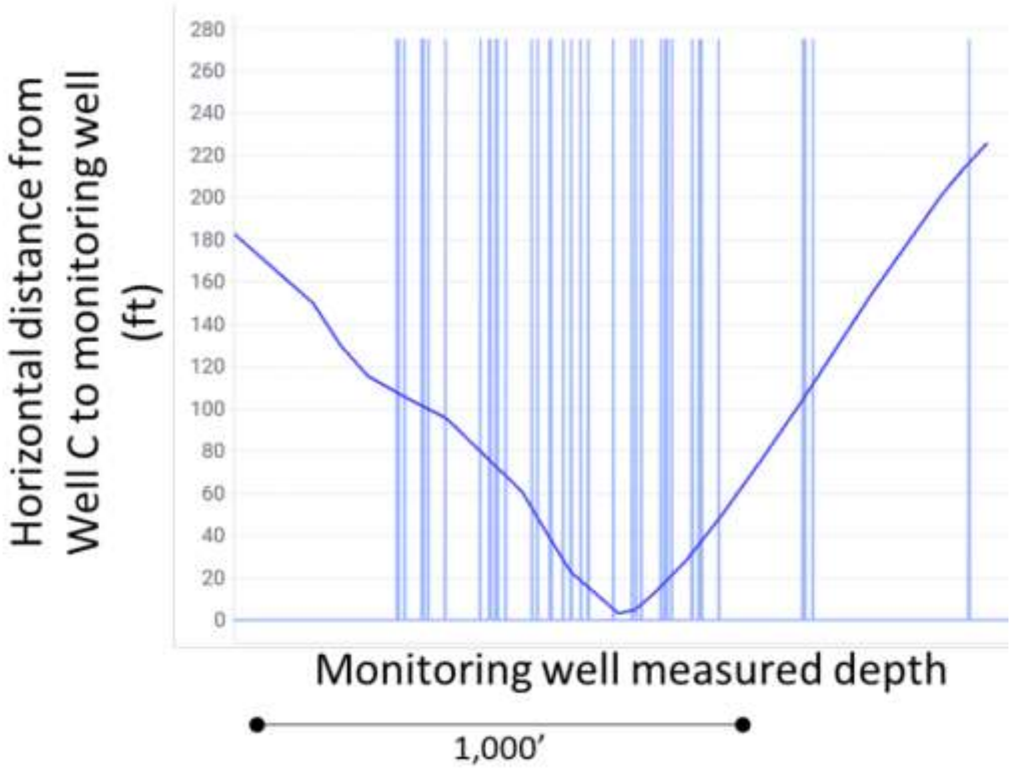
Monitor well by strain (RFS, Neubrex) observation exam the DRV performance of nonconventional well.

Dhuldhoya et al, 2022



Strain vs time at 3 discrete monitoring well depths depicting effective fracture connections to specific wells

DRV is small portion of frac



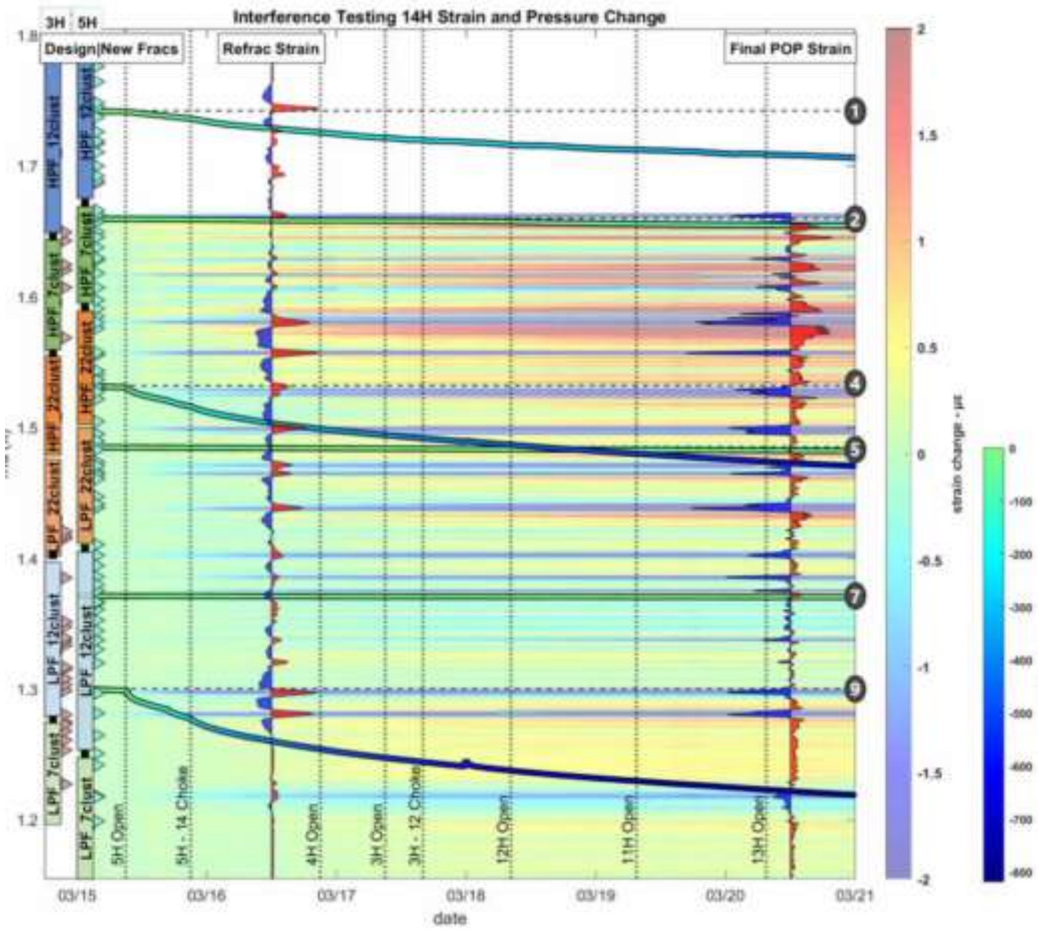
Dhuldhoya et al, 2022

- Recent studies (Raterman et al., 2017, 2019, Karan et al, Li et al, 2022) have demonstrated that proppant can only propagate in very short distance along the hydraulic fractures compared with entire hydraulic fracture length.

DRV ~ 10% of SRV

- The present recovery rates from the unconventional reservoirs are low, i.e. around 16% ~26% !

E and P? now stress more on P (production)



For tight rock, strain is more effective than pressure

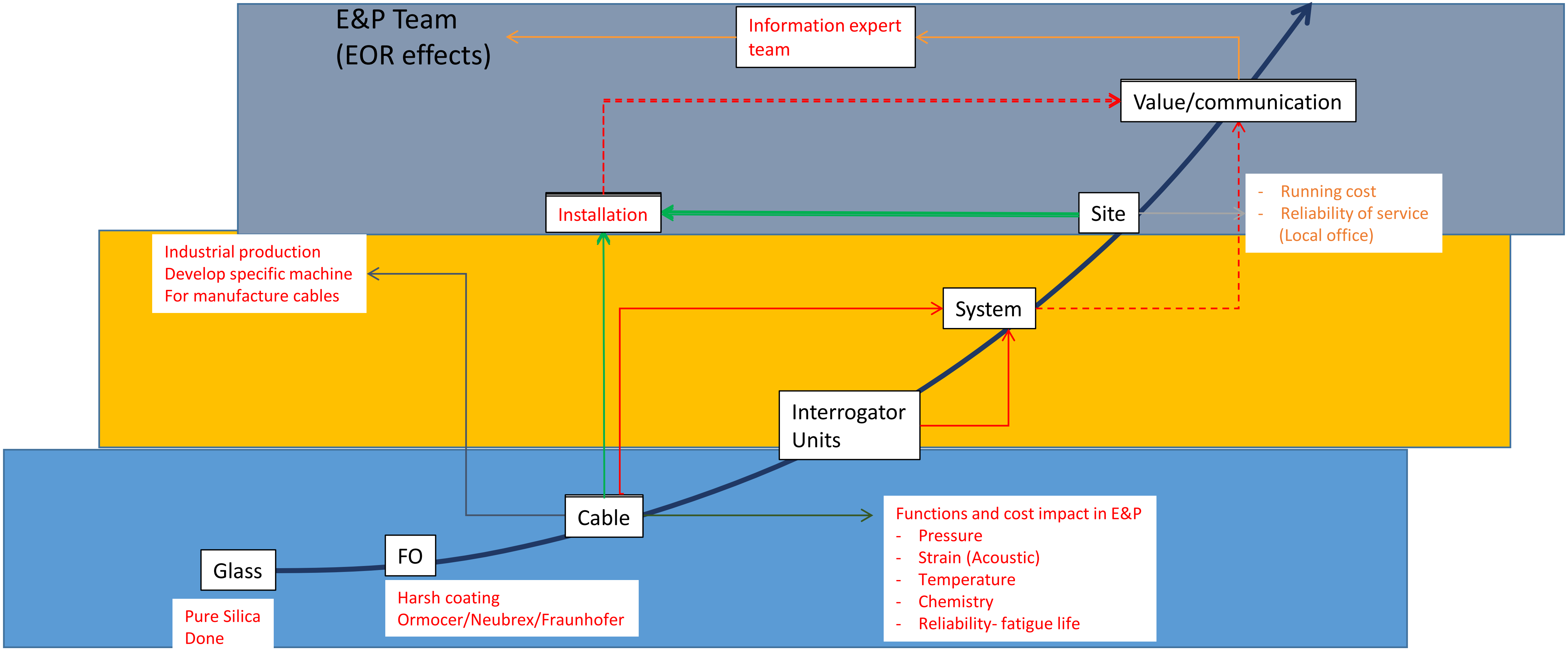
RFS-DSS strain change waterfall plot during the initial interference testing. Each external gauge is placed at its measured depth as a dashed line. As the gauges are drawn down, a colored line will deviate from the gauge location. Vertical dashed lines represent when individual wells were put on production or had choke changes. The left edge of the Figure shows triangles representing cross well strain intersections during the 5H and 3H refrac and the wells respective completion designs. Two logs are overlain on the data, the DAS strain change during the 5H and 3H refrac (left log) and the final strain change at the end of the interference test (right log).

Haustveit et al, 2023

DFOS計測の技術流れ

ラーマンはMMFファイバにほぼ限定され様々な問題がありながら普及されていた。ブリルアンはほぼ日本限定で日本独自な技術。最近十年はレイリー散乱で注目され、RFS（TW-COTDR）とDASは2大分野となり、Neubrex社は常にリーディング位置であった。

Value Chain and Architecture



世界最先端の要素技術と事業モデル

必要な4つの要素技術とサービスを全て自社開発・提供する最先端の事業モデル

計測機技術 → 光ケーブル技術 → 情報解析技術 → データサービス

Neubrexの保有技術・サービス

計測機技術	光ケーブル技術	情報解析技術	データサービス
DTS / RFS / DTSS-B / DAS	石油向けHPHT / 土木・変位 / 放射線環境	減肉 / 3D変位 / 油井流れ圧力 / 3D地震波	専用商品群 / 日米欧の3拠点に専門技術者を配置
独自技術 (RFS) / 最高性能 (DTSS-B, DAS)	独自技術・最高性能	20年間の解析ノウハウ蓄積	海外で9年間のサービス提供実績

競合他社技術の状況

計測機技術	光ケーブル技術	情報解析技術	データサービス
Silixa（英） / 横河電機 (DTS); Silixa（英） / Opta Sense(米) / Sintela（英） / Apsensing（独） (DAS)	Prysmian(伊) / Solifos（スイス）	pipeLine LYTT（英）	LYTT（英）

光センシングケーブルの最新動向　(1)

Downhole Optic Sensing Cable at harsh environment

（計測機＋ケーブル）は計測システムである。光計測ケーブルはシステム成敗の大半が握っている、通信用のケーブルと全く異なる哲学であり、ここでHPHT（高温高圧）坑内ケーブルを簡要に紹介する。

DFOS from single FO to composite of FOs

DFOS = T, ε, A

By single optic fiber

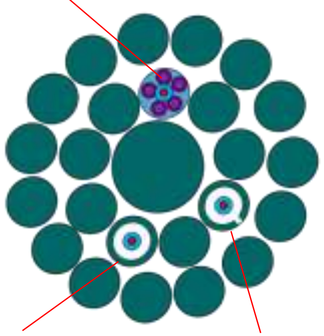
- **DTS** – dominated by Raman
  Need MMF for precision
- **DSS** – Brillouin like PPP-BOTDA
  or single end PSP-BOTDR
- **DSS** – RFS (Rayleigh Intensity
  Pattern)
- **DAS** – Rayleigh phase shift

DFOS = P (HPHT downhole)

need multi-FO in one cable but still is a line information

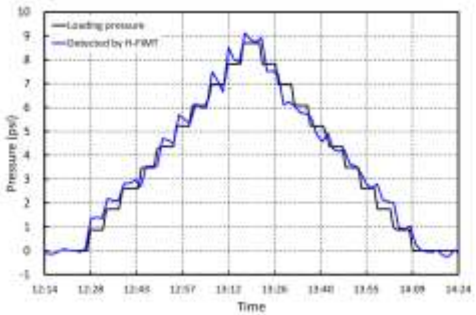
- DPATS have 3 optic fibers
  - ‘loose FO’ in FIMT for temperature
  - SK wires for absolute strain,
  - H-FIMT pressure cells in space of designed span at precision of 1 psi.

Strain-Fiber



T-Fiber

P-Fiber cell
Hole as pressure channel



Pressure precision better than 1 psi!

Lessen learnt in the past 15 years

What was wrong?	What can we do next?
regard DFOS as a large scale commodity *= lower unit price x large quantity*	DFOS is a small scale but high-tech business *- high unit price x small number x high reliability*
Need many companies on tec and cost competition *= many kinds of products, cost reduced by expand of number*	Few companies, now the uni-pole of Neubrex is the fact *- stable price x reliable selected products x data processing. interpretation fit operator's needs*
Grow market *= No expectation for big growth in predictable future. Both operators and service majors are expecting sustainable, not expand*	Limited market and exceeded *- stable price x reliable selected products x data processing. interpretation fit operator's needs*

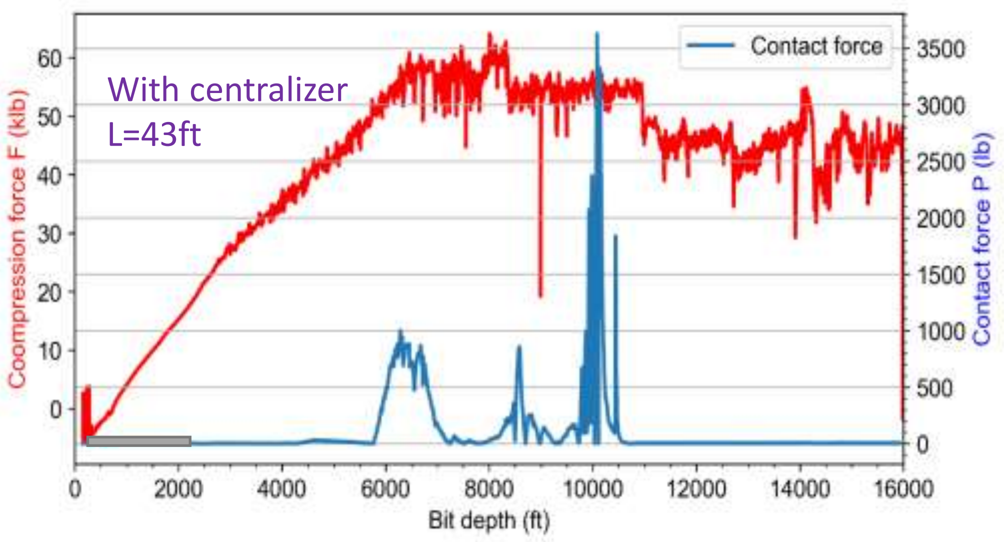
The close cooperation between operator and service sides is needed to make a 'domestic' solution.

Risk No.1: Tough installation request

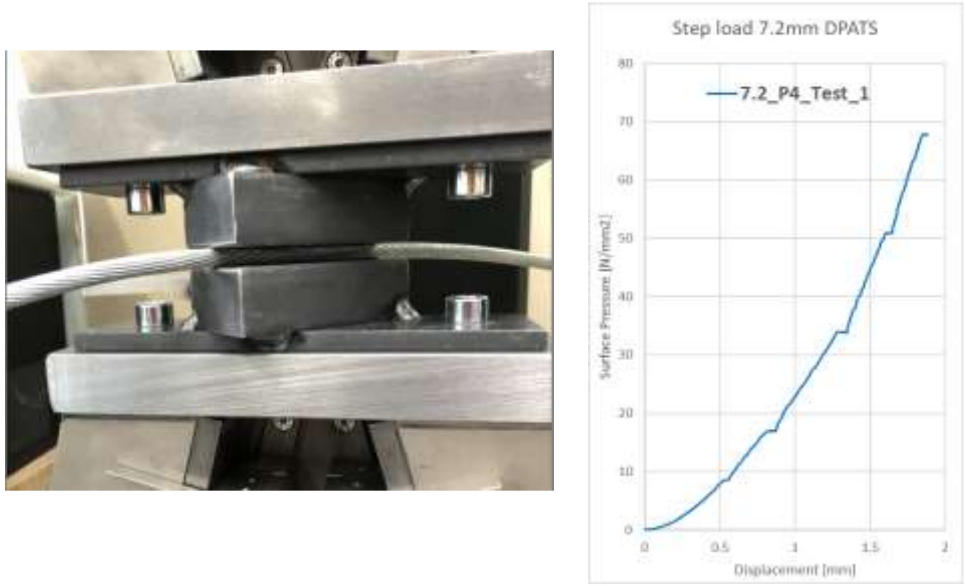
- Load request during cable installation in horizontal well.

Safety method established

- Downhole cable strength quantitatively certificated by Fiber Optic sensing criteria.

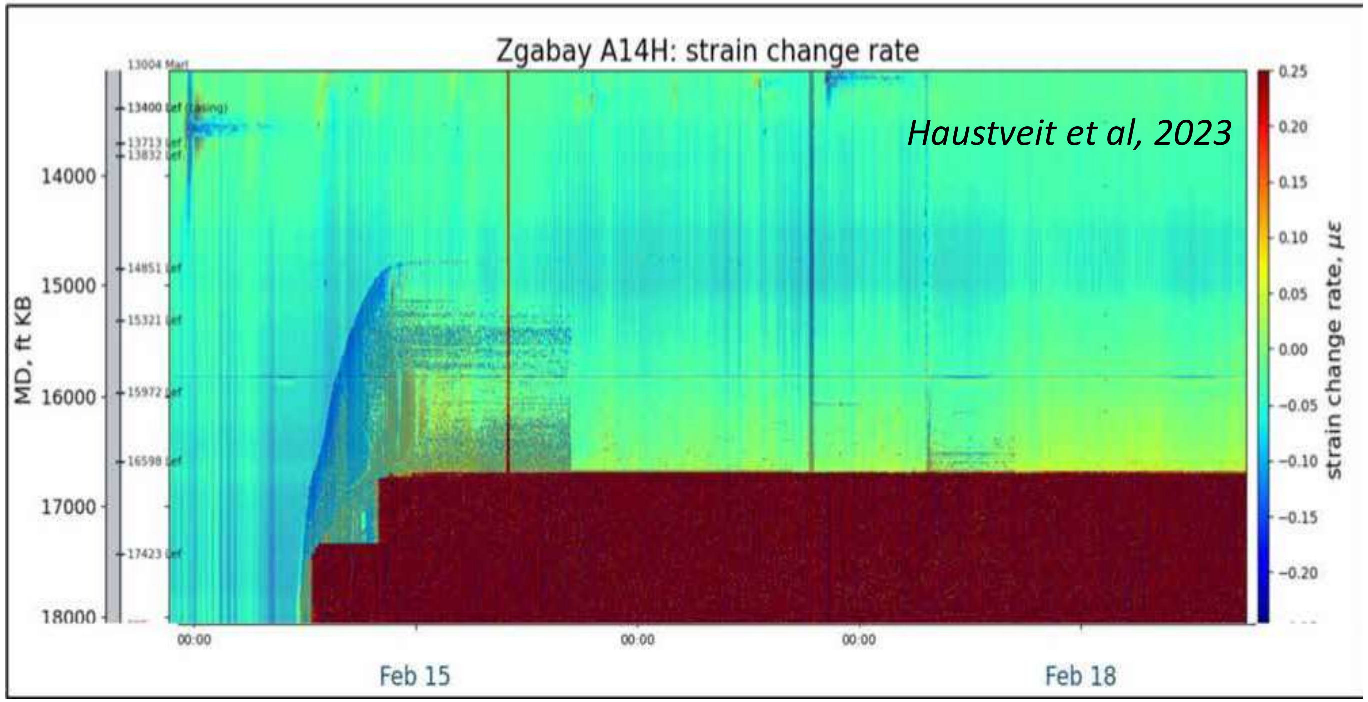


Results of cable load during installation



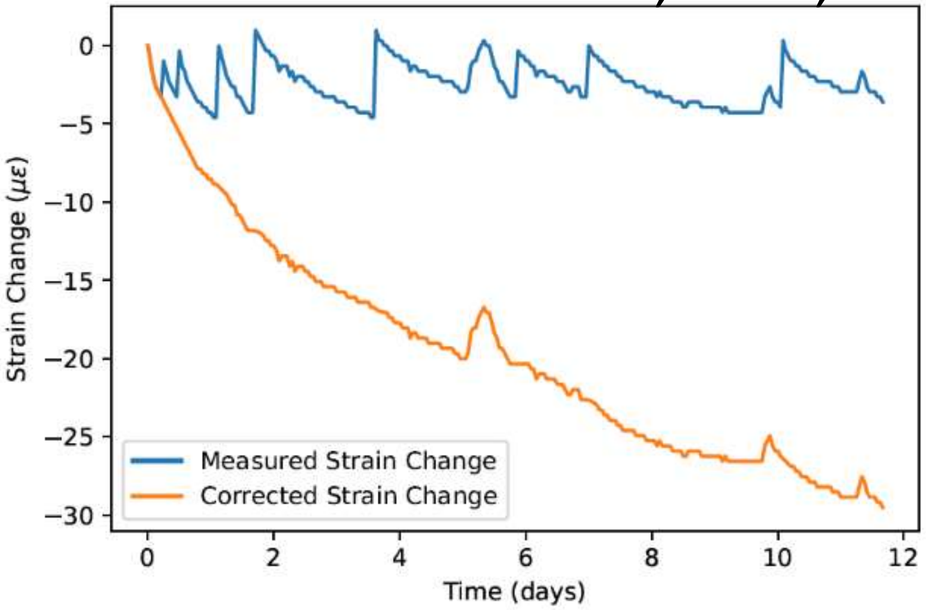
Method and results of cable strength test in plant

Cost and Failure rate are still high



Risk No.2: Terminal failure

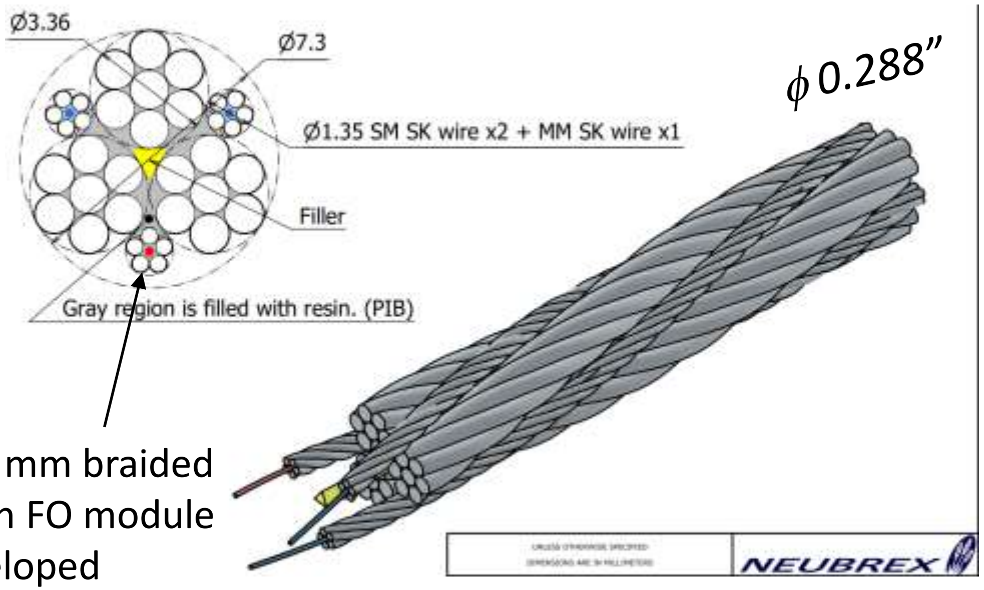
Jin et al, 2023,



Problem No.1: Slippage of loose tube

Neubrex Armored DTSS Improvements over Traditional Cables

- The cable size is 0.288”. Fit the proven Cannon clamp which is possible to fix 2 other ‘conventional’ cables or control lines.
- Proven centralizer and cable protector installation procedures.
- Fits through casing/tubing hangers and conventional well heads that keep the strength and reliability of the fibers in the cable.
- Standard size and installation hardware reduces the installation ops and provides cost control.
- FO is fully embedded inside silicon resin thus are chemically protected against acid and other downhole fluids and gases that may darken fibers.
- Conventional metal is GIP. However, user can choose stainless for high corrosion fluids such as Carbonic Acid with is crucial in CCUS.

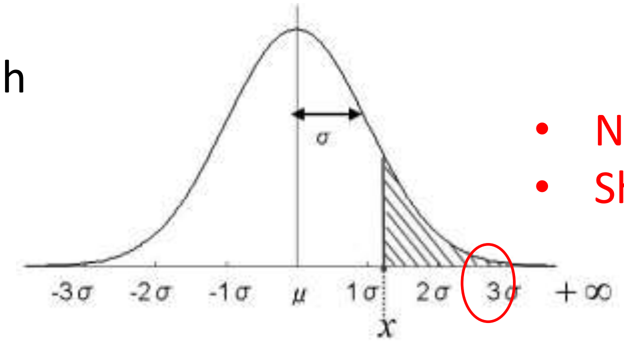


1.35 mm braided strain FO module developed

Quantitative Strength Analysis on Fibers In DSS Cable

Strength of FO module (N/mm)	Safety factor (failure rate)	Installation results in horizontal well
P-fiber: 580	2 (5%)	1 break near peak load in horizontal 10,000ft
T-Fiber: >1720	6 (4/Million)	No break
Convention: >2000	6 (4/Million)	No break
New cable > 1200	5 (0.000057%)	Should be survived during installation

How to link safety factor with failure rate



- Number in circle is safety factor.
- Shadow area is the failure rate

Field Installation on 12,500 Vertical Well. Successful Installation

↓Same tools which were used in other installation were used here and proven

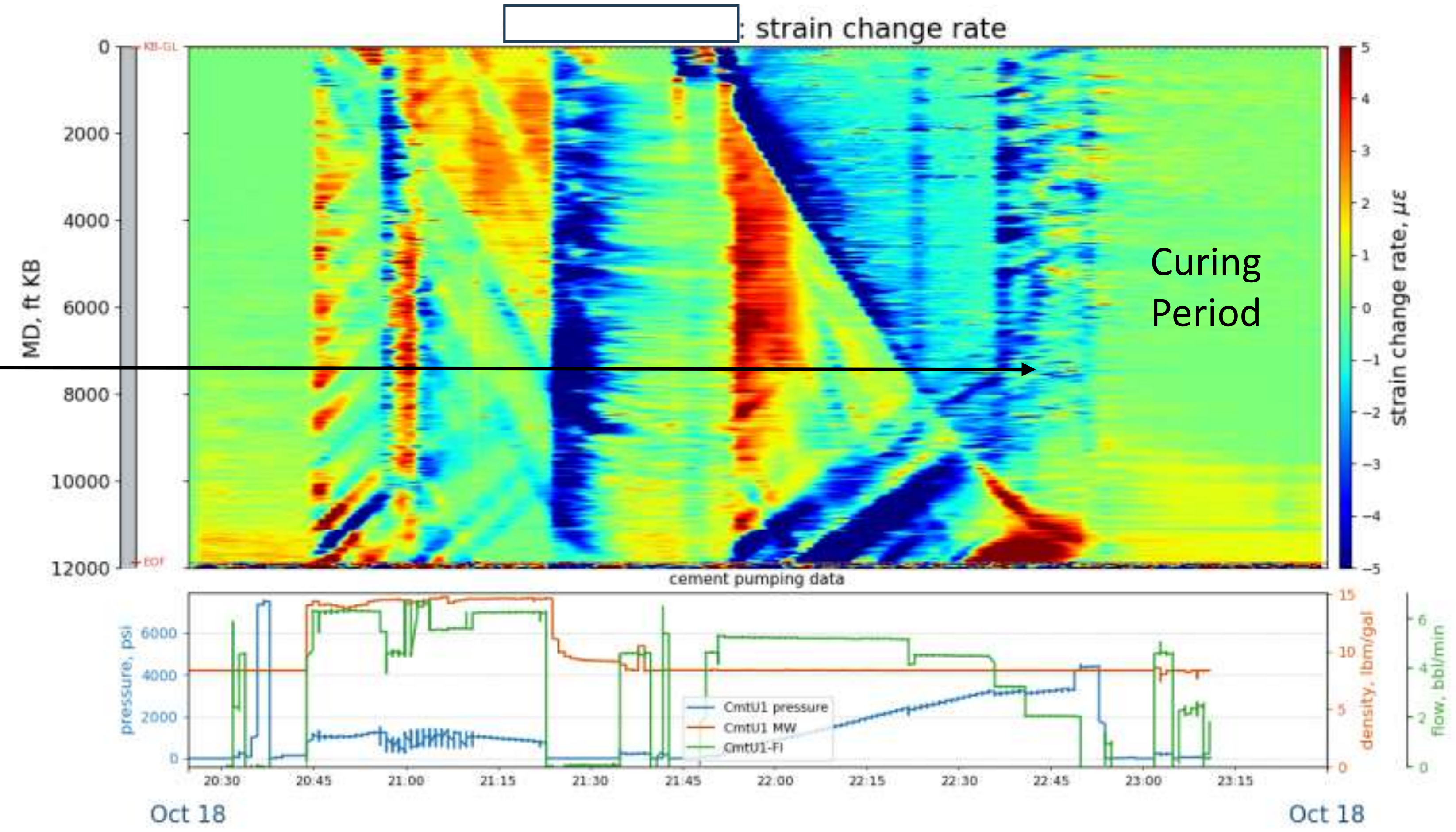
Cross-coupling Clamp

Mid Joint Clamp

Centralizer

Cable Installation to 12,000 ft. Cement Monitoring with Fiber

Cement front at right depth and exact time of operation



Example of Rayleigh Frequency Shift Distributed Strain Sensing (RFS DSS) strain change results after installation of the DSS Cable outside of Pipe and Cemented into well. The cement front was clearly observed with high resolution and quality. The know-how of DSS fiber optic cable installation is achieved.

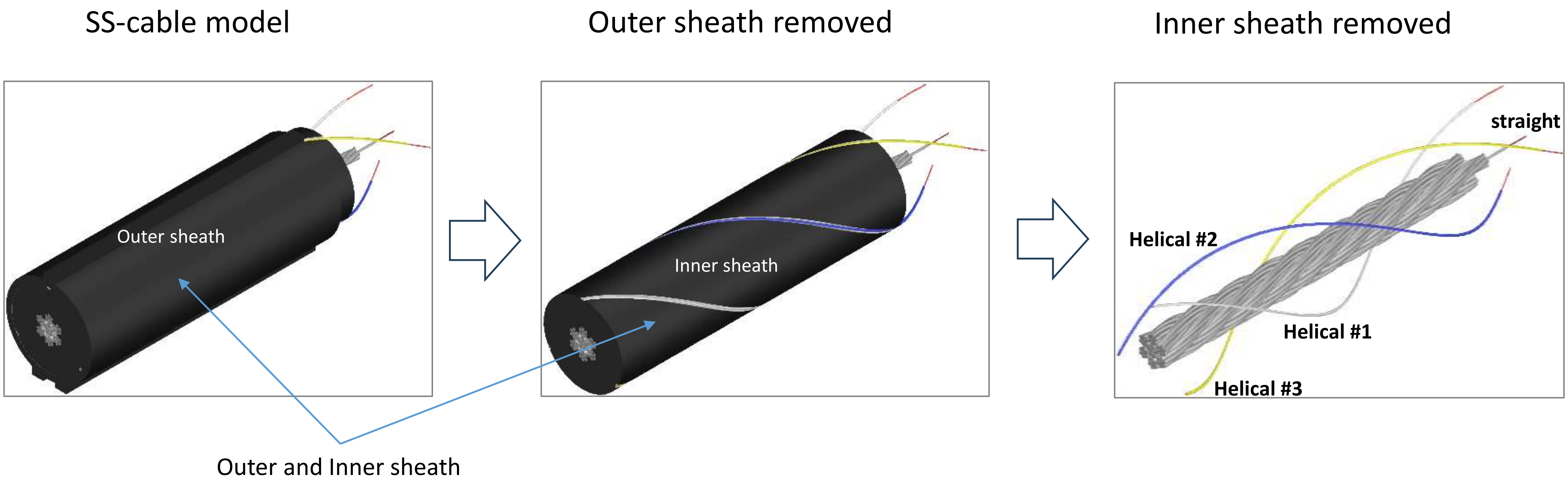
光センシングケーブルの最新動向　（２）

Road to 3C surface seismic by helical

Omni-seismic was the target since 2016 (As MFOSS JIP of Neubrex and Petronas). The effects of helical is limited by the small size of downhole cable. However, surface cable can expect a good helical effects, and better impedance matching. 2C to 3C Surface Seismic Cable (SSC) in rapidly on the way of developing.

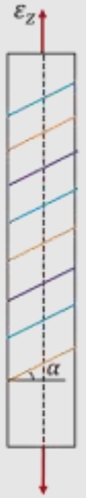
From GNR to Surface Seismic application

		pitch(mm)	FO D(mm)	FO helical length(mm)	α (deg)	cos^2	Shealth thickness	Real core (mm)
GNR	Inner	360	11.5	361.8	84.27	0.010		800
	outer	360	15.5	363.3	82.30	0.018	2.2	800
Surface Seismic	helical	100	20.0	118.1	57.86	0.283	2.2	800
Ref. paper		105	20.0	122.4	59.10	0.264	/	/



Inversion theory: **Mechanics**

Pure axial strain



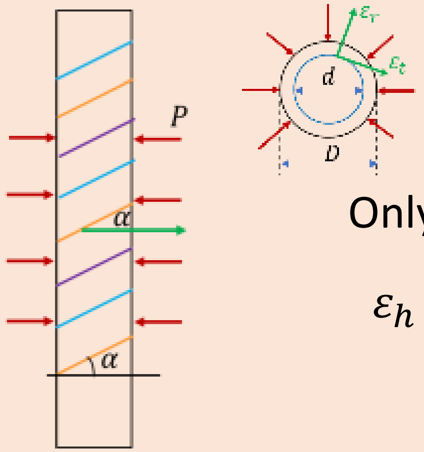
Axial strain
felt by central straight fiber

$$\varepsilon_s = \varepsilon_z$$

felt by three helical fibers

$$\varepsilon_{h,1} = \varepsilon_{h,2} = \varepsilon_{h,3} = \varepsilon_z \sin^2 \alpha$$

Pure pressure



Only helical fibers can feel the pressure

$$\varepsilon_h = \varepsilon_t \cos^2 \alpha = \left(\frac{d}{D} - 1\right) \cos^2 \alpha = k\ P \cos^2 \alpha$$

$k < 0$, pressure-strain coefficient

Pure axial strain + Pure pressure

Strain
felt by central straight fiber

$$\varepsilon_s = \varepsilon_z$$

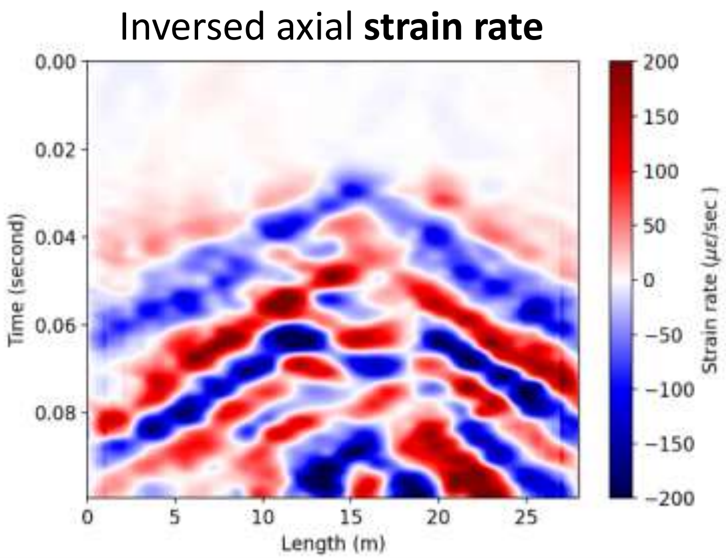
felt by three helical fibers

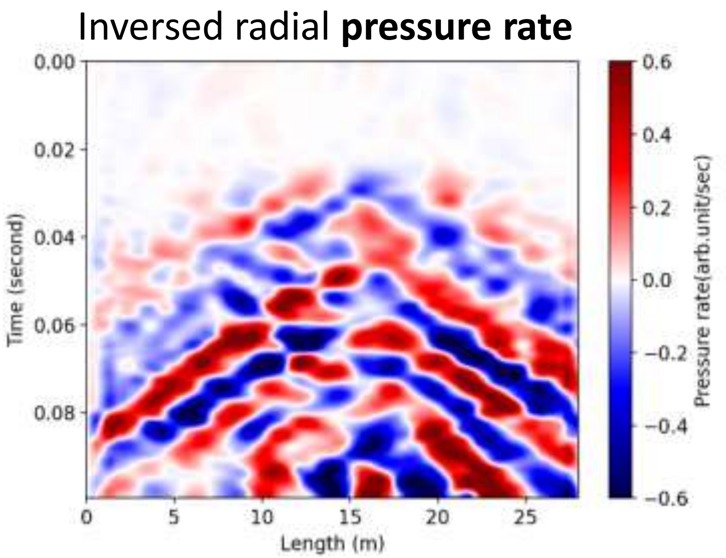
$$\varepsilon_{h,1} = \varepsilon_{h,2} = \varepsilon_{h,3} = \varepsilon_z \sin^2 \alpha + k\ P \cos^2 \alpha$$

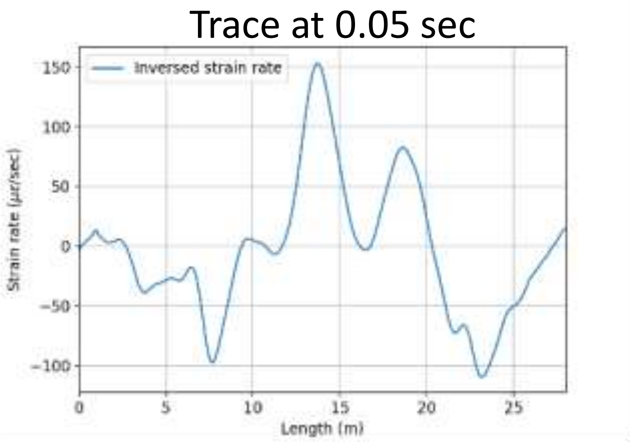
the value is when ε_z is zero. Then you can still see the signal of seismic, that is the portion perpendicular to cable

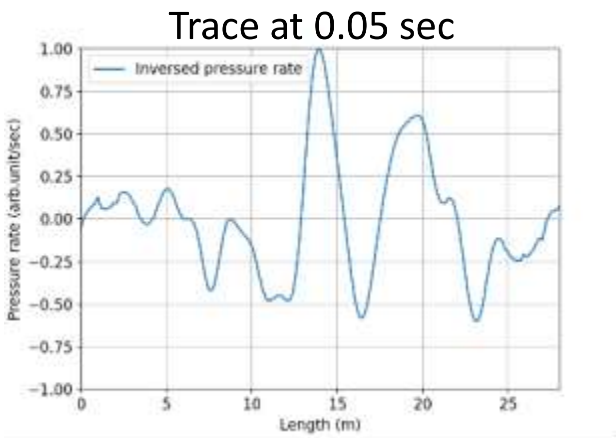
Inversion: **Obtain Strain Rate and Pressure Rate**

- Through conducting the inversion $s = (A^T A + \lambda^2 C^T C)^{-1} A^T \varepsilon_m$, strain rate and pressure rate are obtained.









DFOSの最新動向　(1)

RFAS – Rayleigh Frequency Acoustic and Strain

Capable from slow to fast.

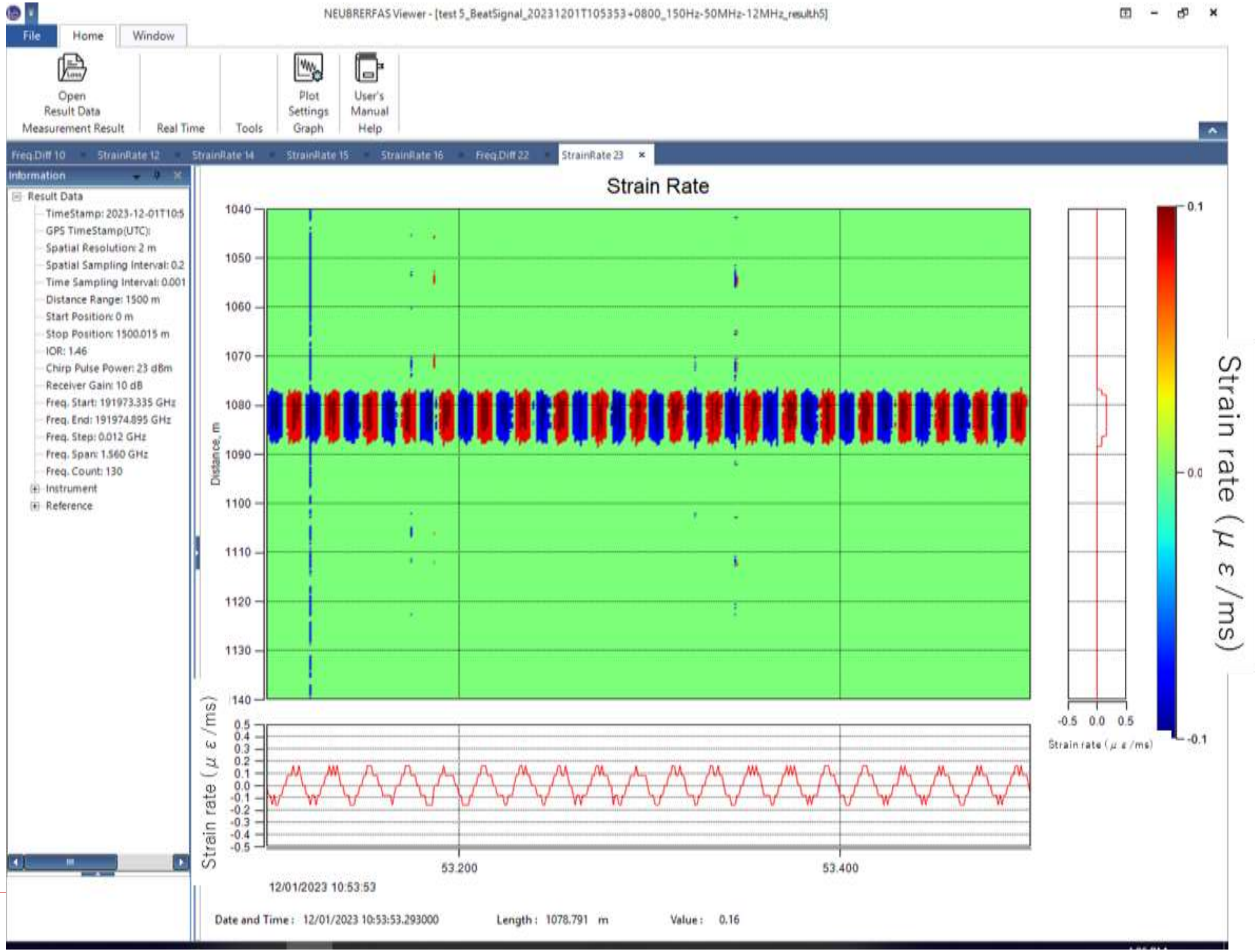
With fingerprint remembered as initial state, and can view the history of changes.

各空間分解による測定結果

2．動的変化の測定(PZTにSin波に加える信号を50Hz、ΔV=20Vにし、約 1.2μεになります。)

2-1-2-2

NBX-7800
Chirp幅=2GHz
Sub Band=50MHz(2m)
Chirp周波数範囲：200MHz～1800MHz
Step:12MHz
Counts:128
測定速度：1KSps
記録時間：5s
表示範囲：0.5s、1040m～1140m



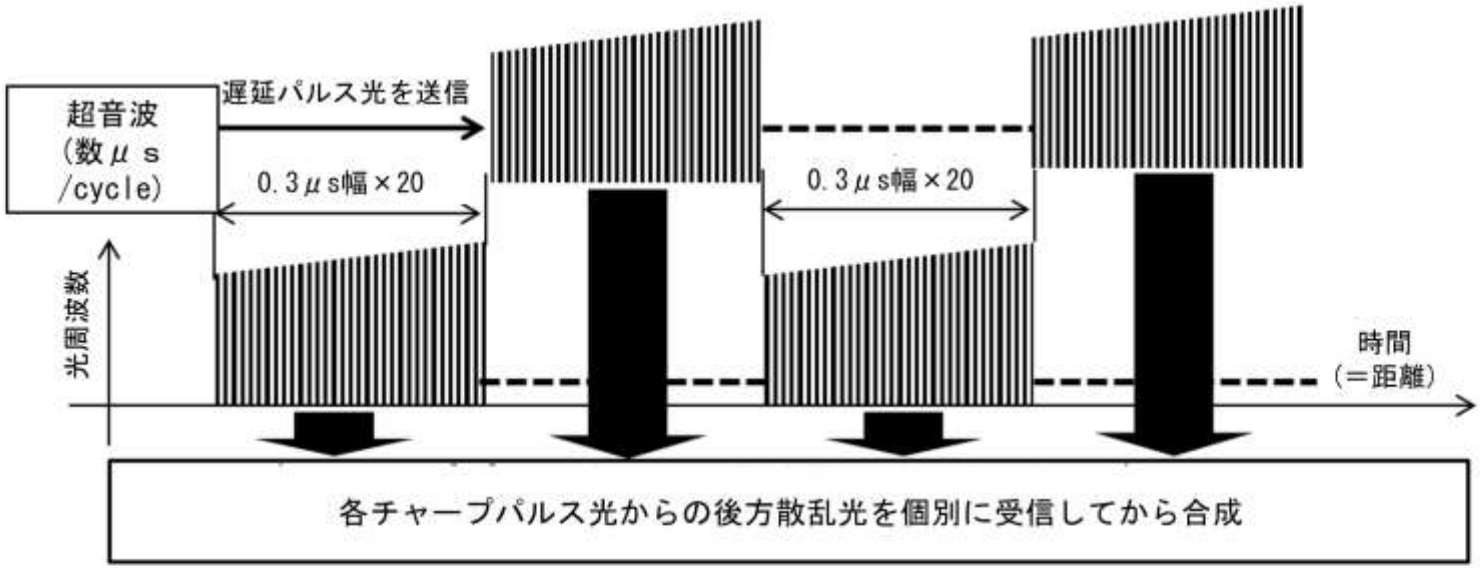
超音波DAS 3MHz/30Km +

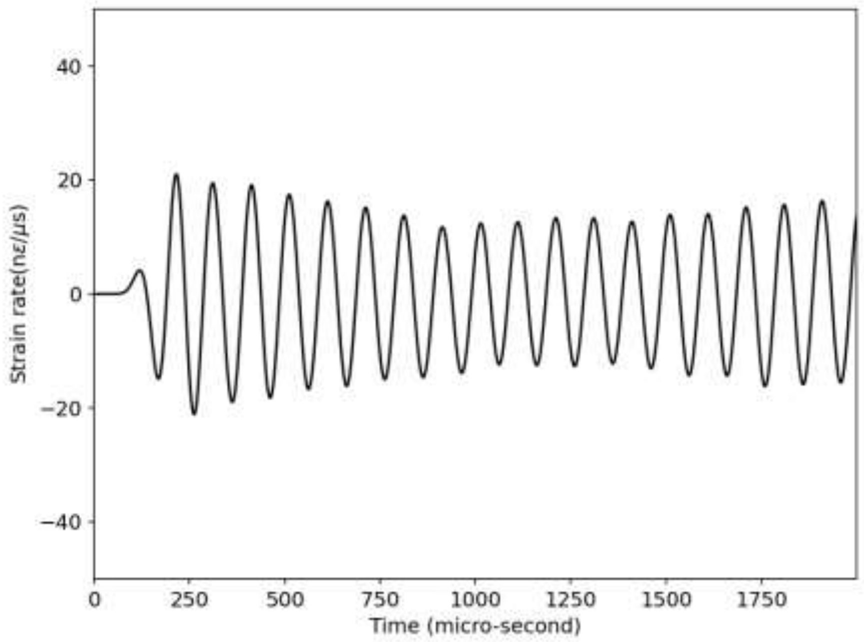
Capable from slow to fast.

With fingerprint remembered as initial state, and can view the history of changes.

長距離超音波DASの取り込み（NEDO洋上風力）

30km先の洋上風力を3MHzの超音波速度での監視。DASの速度限界を突破する





DFOSの最新動向　(3)

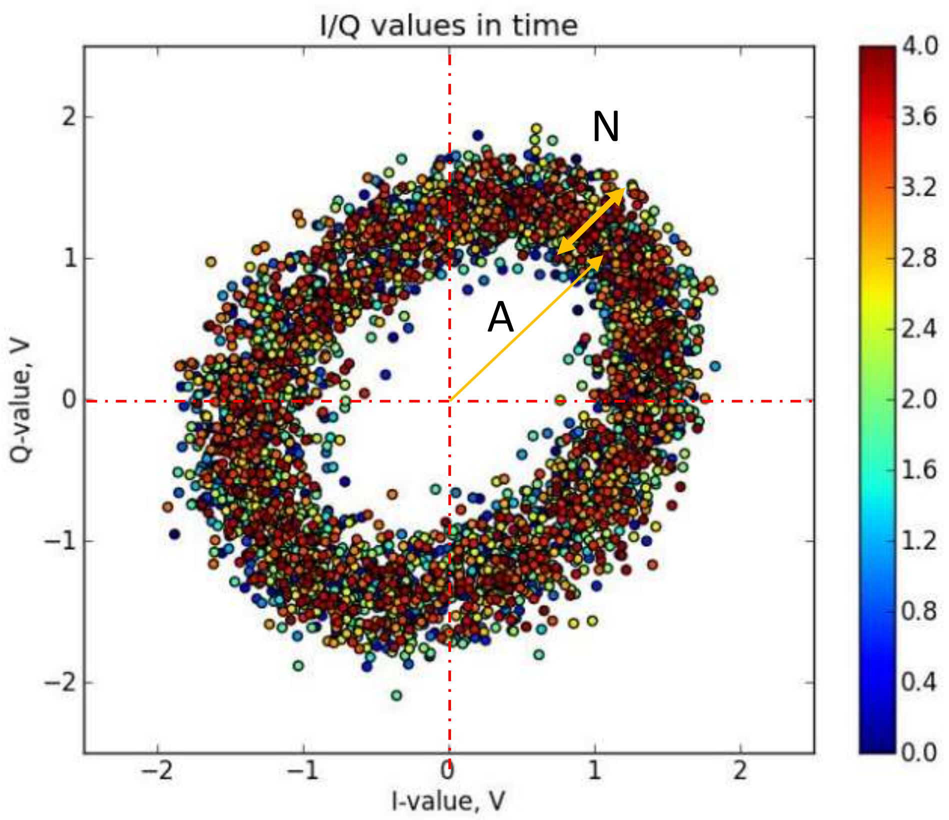
強地震対応型DAS

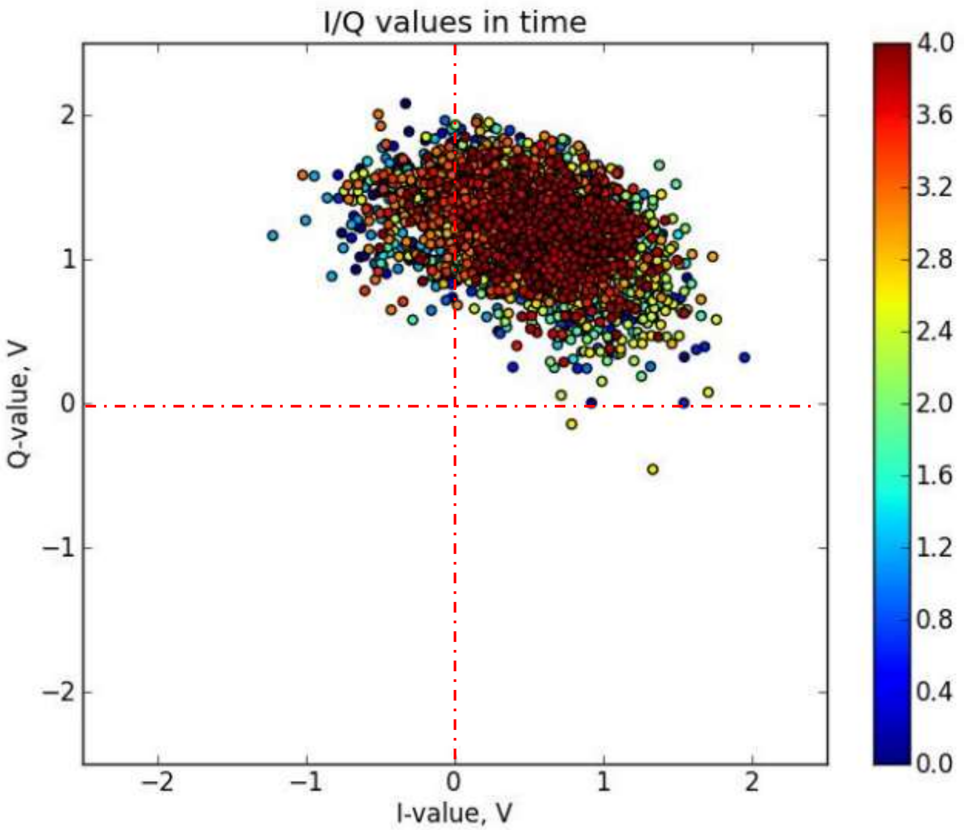
Capable from slow to fast.

With fingerprint remembered as initial state, and can view the history of changes.

レイリー散乱と位相計測の基礎

5 m光パルスに得られた信号例



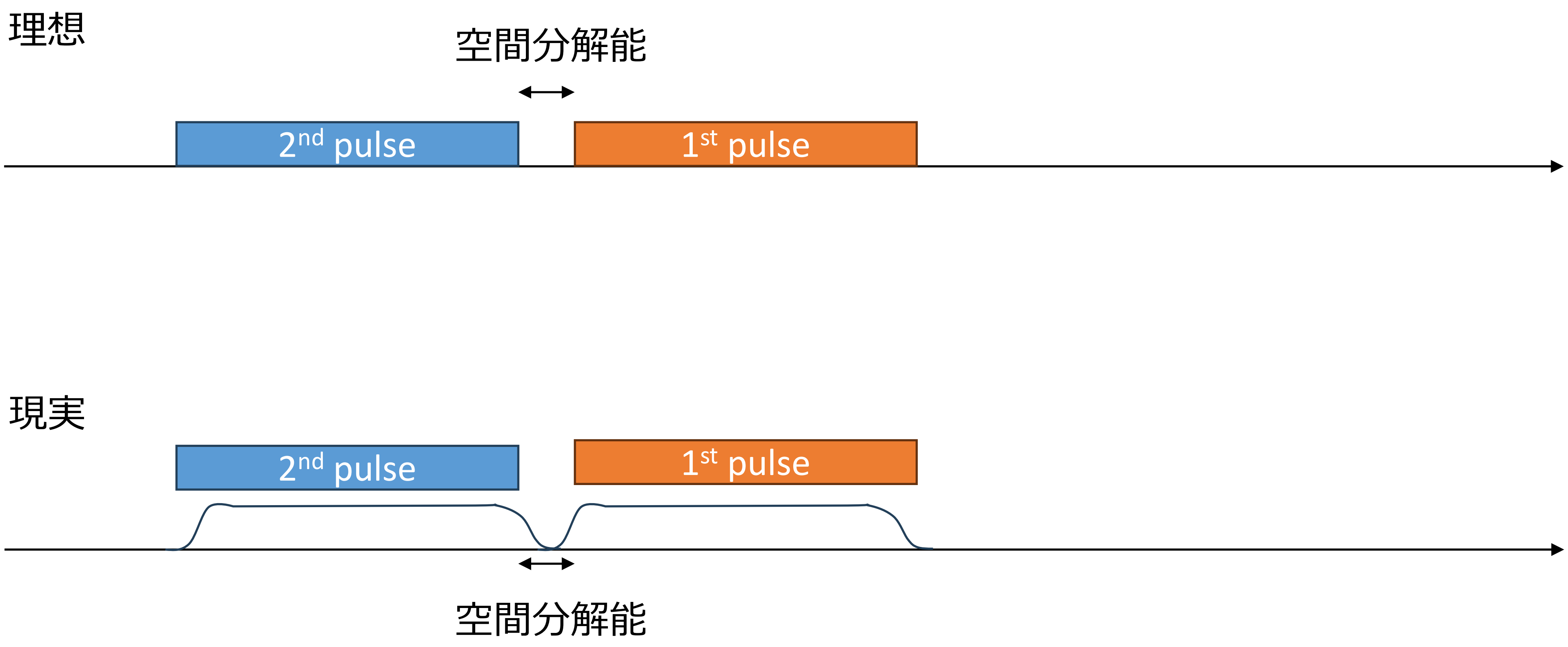


Good signal
S=A+N
SNR=S/N~3 = 1.7dB

S:signal
A: Truth
N: Noise

Bad signal　ー　有効的な位相を見えない
（Phase fading）

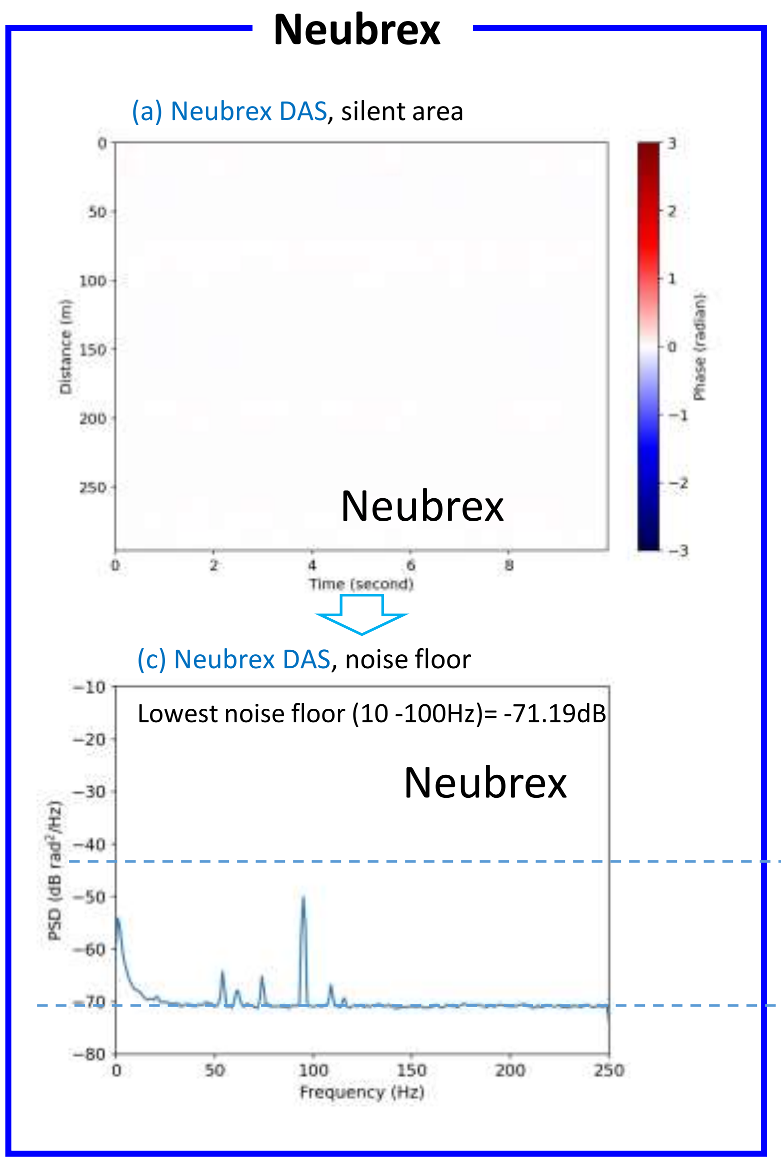
Dark pulse to achieve higher Spatial resolution（競合他社）

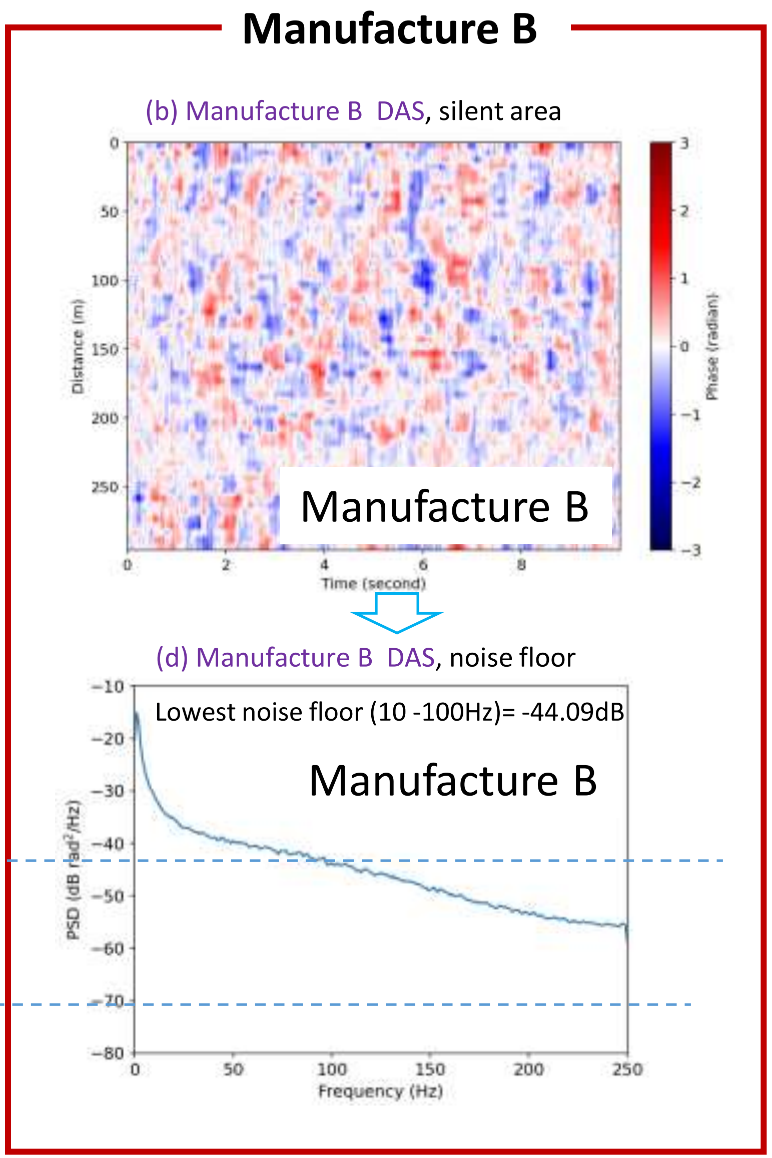


200MhzのAOMを用いた場合、立上げる時間は5ns （50cm、One-sigma），Dark Pulseの間隔は1m以下できない。

Noise floor comparison with other manufacture's DAS

- Comparison under same conditions
  - Same gauge length 40m
  - Same IU-rate 500Hz
  - Same fiber under test
- As shown in right figures, silent area (waterfall) and PSD result are given, and the noise floor are summarized in table below. Superiority of Neubrex DAS is obvious.





Lowest noise floor winthin 10 -100 Hz

PSD unit	Manufacture B	Neubrex DAS	
	gauge length 40m	gauge length 5m	gauge length 40m
dB radian^2/Hz	-44.09	-54.40	-71.19
dB nε^2/Hz	-35.66	-45.97	-62.76

Saturation observed by beam Vibration experiment

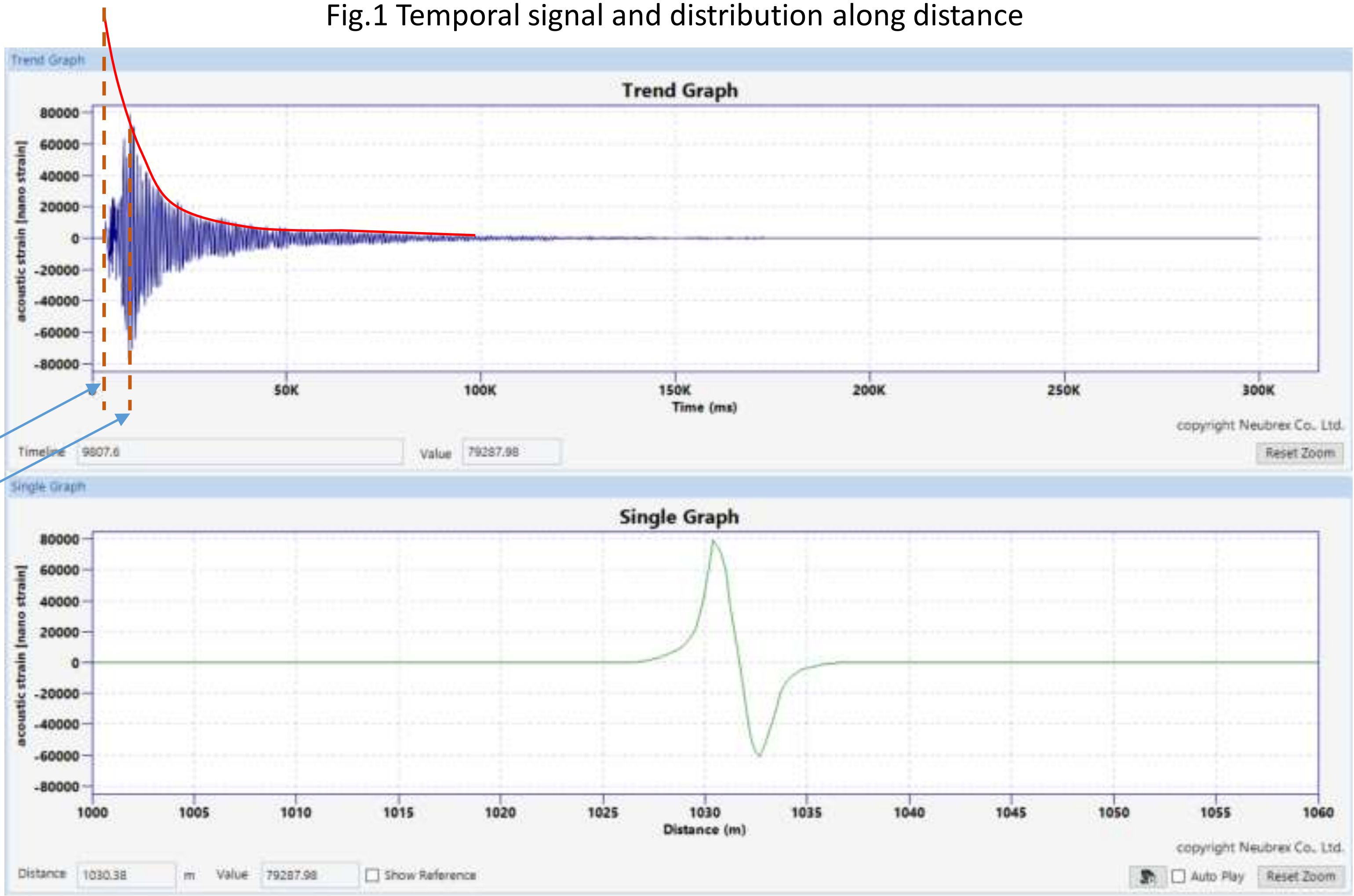
- Measurement performed at:
  Interrogation rate: **5ksps**
  recording time: **5 min**
  Vibration starts from ~3 sec

- This measurement aims at demonstrating the vibration decay with time, so we measured a long time, 5 minutes. The temporal signal is given in Fig.1. It is seen that the decay pattern starts from ~10 sec, and the maximum strain is 79 $\mu\varepsilon$.

- According to the decay trend plotted on Fig.1 with red curve and the experiences on vibrating the Al plate, there should be much larger strain in the range of [3sec,10 sec], but there is not. We think that the reason is the failure of unwrapping, because the strain changes too much (unwrapping condition is not satisfied anymore) between the adjacent pulses during this period.

- The zoom-in figure is given in next page.

Fig.1 Temporal signal and distribution along distance



DFOS from option to necessary

Capable from slow to fast.

With fingerprint remembered as initial state, and can view the history of changes.

ニューブレクス株式会社　概要

NEUBREX

会社概要

- 会社名　ニューブレクス株式会社
- 住所　神戸市中央区栄町通１－１－２４
- 設立　２００２年１１月
- 資本金　１億円
- 代表者　代表取締役　岸田　欣増
- 関連会社
  - Neubrex Energy Services(US), LLC：米国
    ・北米での油井モニタリングサービス事業
  - Neubrex Infra AG：スイス
    ・欧州、中東向け計測機・ケーブル販売拠点

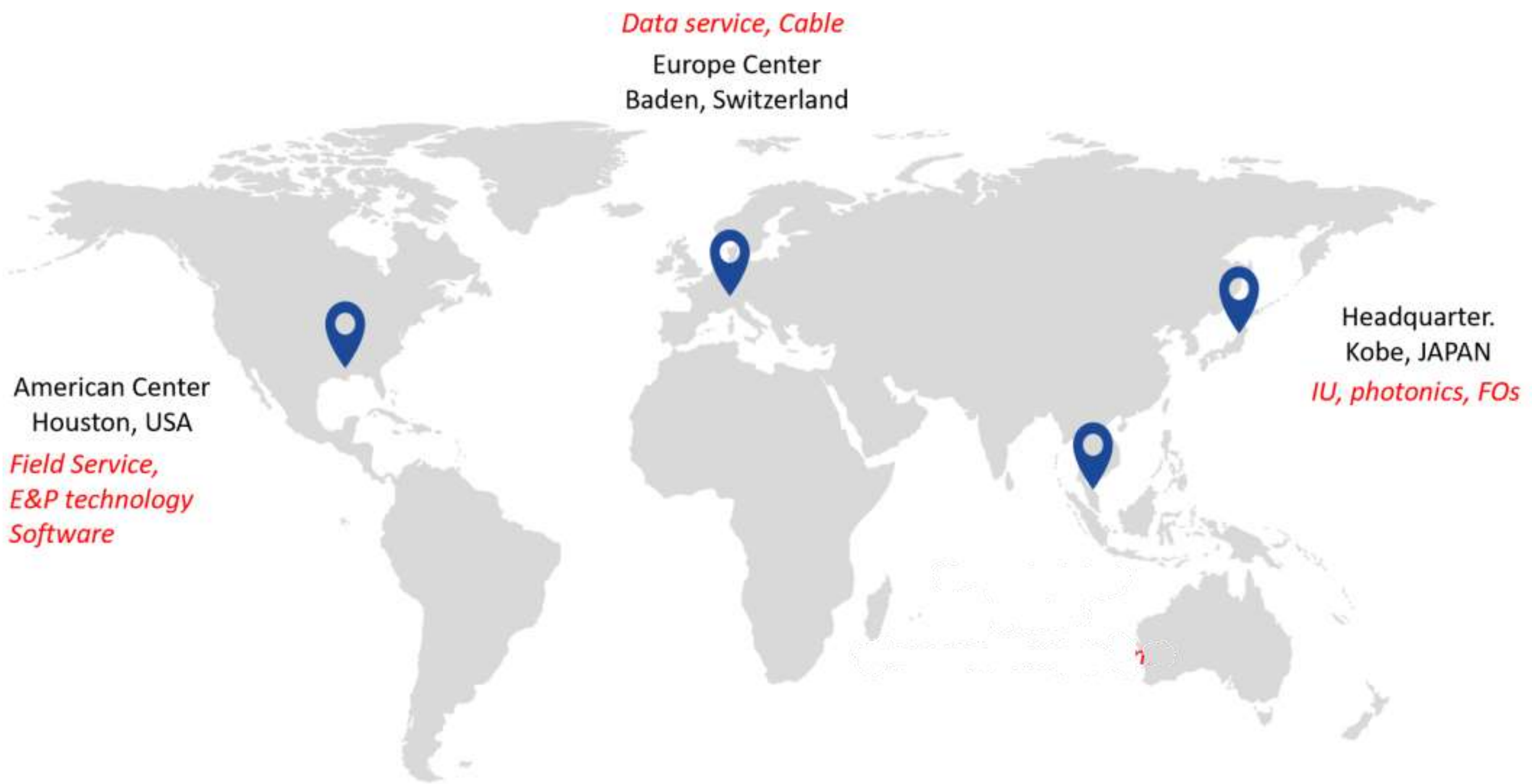
- 事業内容
  - 光ファイバ高精度ひずみ・温度分布**計測器**「NEUBRESCOPE」の開発・製造・販売
  - **計測データ管理・解析**のためのソフトウェア「NEUBREGATE」・サービスの開発・販売
  - **光ファイバセンサケーブル**の開発・製造・販売
  - これらを統合した構造物の**監視システム**の提供
- 採用実績
  - エネルギー分野：国内・米国石油開発大手企業
  - 土木インフラ分野：国内各大手ゼネコン
  - 原子力廃棄物分野：国内・欧州の管理機関
  - その他、電線・ケーブルメーカー、研究機関等

油井への光ファイバセンサケーブル設置作業

DFOS技術での取り組み

- **独自のバリューチェン認識で技術を発展に取り込んでいる。単独項目にしても、製品構成も常に業界のリーダー役を維持してきた。**
- 各分野のリーディング大学、研究機関、企業と緊密な連携を行い、次々新技術製品を創造し続けている。

Neubrex Group: | Neubrex | Energy Services | Infra



Evolution of Neubrex

Team perfect for the value chain of M-FOSS. Provide one-stop shop for all the fabrication, field deployment, data analysis and service, and inhouse operator experts to provide value to the customers.

Photonic team
Creative Only-One interrogators in DFOS as Japanese national team.
Technical roots from 1987

Data/Analysis Team
Boardless data service, processing and analysis team
Data to information 100% self developed software tools on InterNet

Operator Expert Team
Key persons from ConocoPhilips and Shell in their DFOS team.
+ plus Petronas leading

2002 2007 2008 ~ 2016 2018 2022

Sensing Cable Team
Fabricate Fiber Optic sensing cable from NEEDS and POSSIBILITY
Experts 40+ know-how, worldwide facilities committed

Field Team
Partner of biggest installation company (SageRider) and own field technicians.
Most experiences team on downhole cable.

Top page of JPT
Downhole Strain introduced to petroleum 1st time in history.
Direct sales to Exxonmobile and meeting in its head quarter during Kishida visit.

光ファイバがインフラの見守り役になる（実用・実証済み）

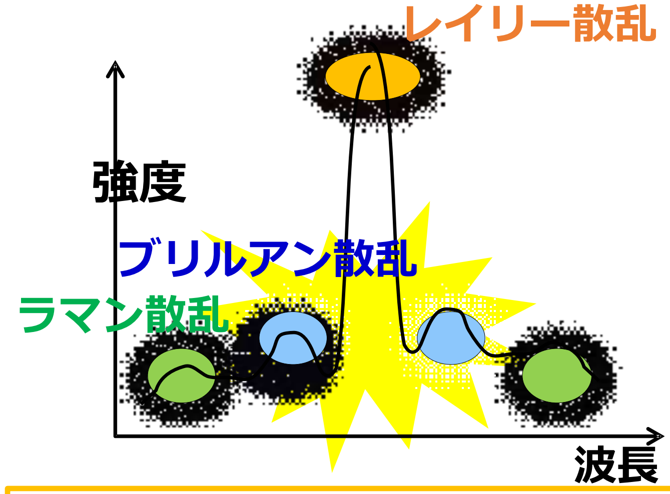
数十年の開発期間を経て、この技術は日本での革新的なインフラ監視手法として認知された

https://www.kajima.co.jp/news/digest/apr_2023/feature/index.html

橋梁やトンネル，ダムなど高度経済成長期に集中的に整備されたわが国のインフラが，経年劣化や自然災害による損傷によって急速に老朽化していくことが懸念されている。
そのような中，鹿島は光ファイバの計測技術を，直接視認できない箇所のひずみ・温度・振動を
高精度かつ広範囲にわたりリアルタイムで把握できる革新的な技術へ発展。
世界で初めてインフラに導入した。
今後，施工管理から維持管理へ，さらには新たな付加価値をもつインフラの実現へ，
世界に大きな変革をもたらす可能性を秘めた当社開発の光ファイバでどんな世界が描けるのか，
実適用事例とともに紹介する。

光ファイバ散乱光の利用とニューブレクスの新しい計測技術

NEUBREX



ラマン散乱：温度により散乱光レベルが変化；旧来より利用

ブリルアン散乱：圧力・温度・ひずみにより散乱光周波数が変化
；旧来より利用されていたが、精度が低かった

従来の光ファイバとして認識されている技術

レイリー散乱：強度が強く、圧力・温度・ひずみにより散乱光の波形が変化することがわかっていたが、高度な光周波数制御と大量高速の信号処理が困難で分布計測に活用することが出来なかった。

ニューブレクスによるこれからの光ファイバ計測技術

独自のハード技術（高度な光周波数制御から大量高速信号処理まで自社技術を確立）
独自のソフト技術（散乱光の分析：温度とひずみの分離・計測位置とその変化の特定、自動データ処理など）により、
高精度、高空間分解能、短計測時間の分布計測を実現

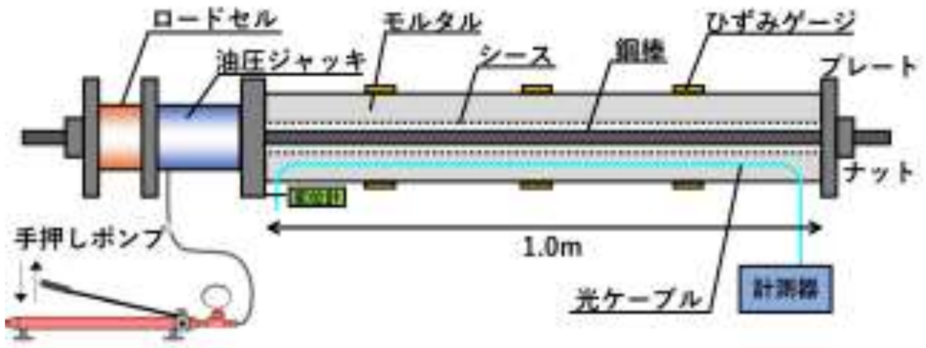
項目	電気計測	光ファイバ分布計測	
		ニューブレクス	従来技術
		レイリー方式	ブリルアン方式
センサ	ひずみゲージ Pt温度計	光ファイバ	光ファイバ
最大計測範囲	数cm程度	数十km	数十km
最小サンプリング間隔	―	1cm	1m程度
ひずみ計測精度	1με程度	1με以下	50～100με
温度計測精度	1℃程度	0.1℃以下	5℃程度
最高空間分解能	(0.5～3cm)程度*1	2cm	1m程度
計測時間	―*2	数分/回	数十分/回
長期耐久性	△	○	
防爆性	×(要対策)	○	

＊1：ひずみゲージのベース長

＊2：分布計測ではないので比較しない（測点数が多いと時間がかかる）

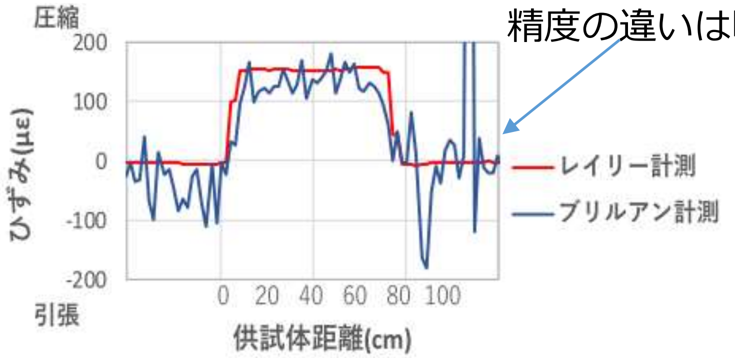
ニューブレクス光ファイバ計測の高精度の実証

従来技術に比べ圧倒的に高精度



図－2　室内試験全体概要

精度の違いは明らか

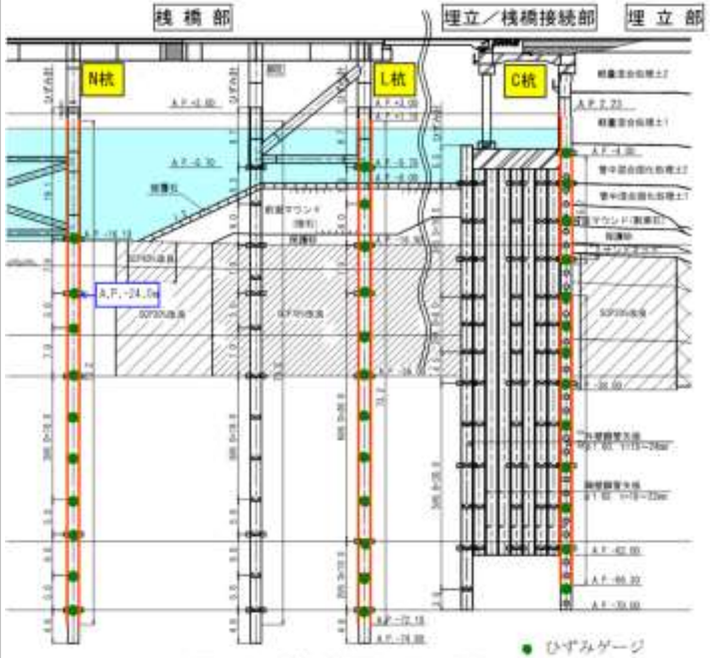


図－6　レイリー計測とブリルアン計測の比較

ラボー試験で精度検証

引用元：黒川紗季,岡田侑子, 小泉悠,升元一彦,今井道男, 川端淳一, “光ファイバによるトンネル支保の応力計測に関する室内検討”, 土木学会第75回年次学術講演会講演概要集(Ⅲ-105) 75th, 2020年

ひずみゲージ計測値に一致、この高精度でさらに分布計測が可能



図－2　計測位置（断面図）

引用元：樽谷早智子,新原雄二,新井崇裕,今井道男,平佐健一,野津厚,小濱英司,大矢陽介,山路徹:羽田空港 D 滑走路における光ファイバレイリー計測による維持管理への適用検討,土木学会第78回年次学術講演会講演概要集(CS9-15) 78th, 2023年

羽田空港D滑走路の既設の光ファイバにNB技術を適用。これまでの技術で計測出来なかった高精度のデータを取得

ひずみ（レイリー計測・ひずみゲージ）計測結果（A.P.-24.0m）

N杭AP-24m地点のひずみ
レイリー計測は
ひずみゲージの計測値と一致