Verteilte faseroptische Sensoren: Prinzip, Anwendung und Simulation mit MATLAB

Seminar: Matlab und Simulink für HTL
20.03.2023

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Institut für Elektrische Messtechnik

Wedergang

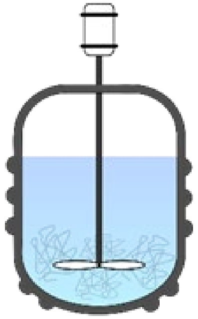
- 1992 – 1996 Techniker für Elektronik (entspricht Berufsausbildung mit Matura)
- 1996 – 1998 Grundstudium Elektrotechnik an der UTFPR (Brasilien)
- 1999 – 2002 Hauptstudium Elektrotechnik an der TU Dresden (DE)
- 2004 bis 2009 Wiss. Mitarbeiter am HZDR (DE)
- 2008 Dissertation mit dem Thema „Impedance Sensors for Fast Multiphase Flow Measurement and Imaging“
- 2010 – 2022 A/Prof. @UTFPR
- Seit Sept/2022 Univ.-Prof. und Vorstand Institut für Elektrische Messtechnik an der JKU

  https://www.jku.at/imt

→ Wissenschaftliche Fokus: Mess- und Sensortechnik für industrielle Anwendungen

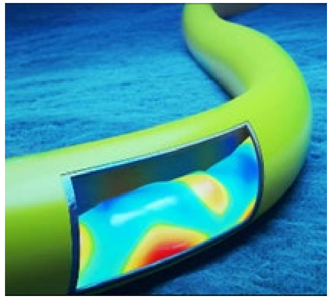
F&E am IMT

Messtechnik für verfahrenstechnische Prozesse

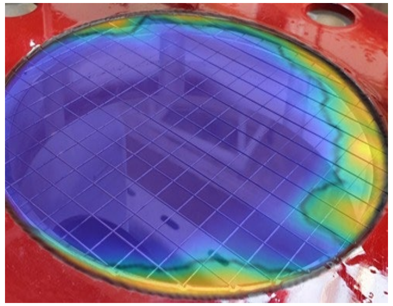


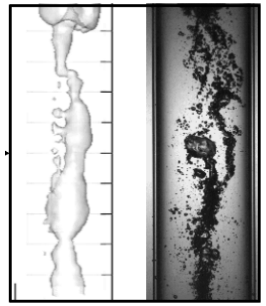
Kristallisation

Bioreaktor (auch Fermenter)

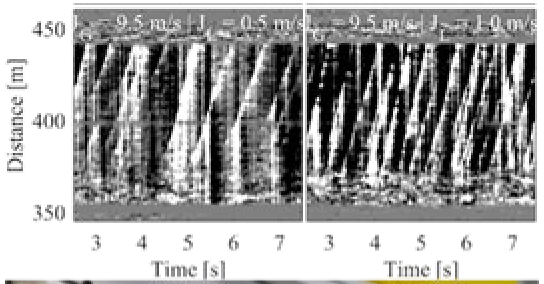


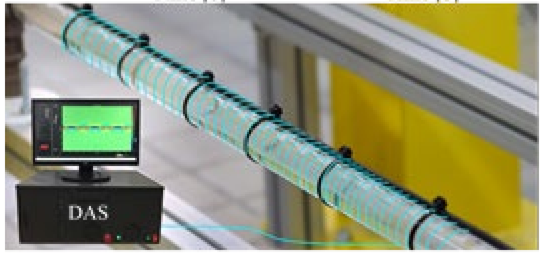
Mehrphasenströmungen





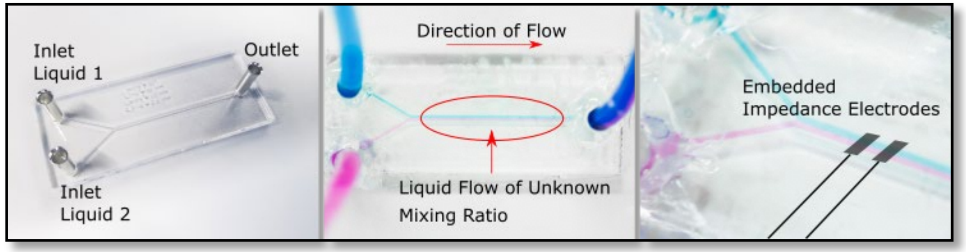
Faseroptische Sensoren





http://dx.doi.org/10.1109/jsen.2022.3232269

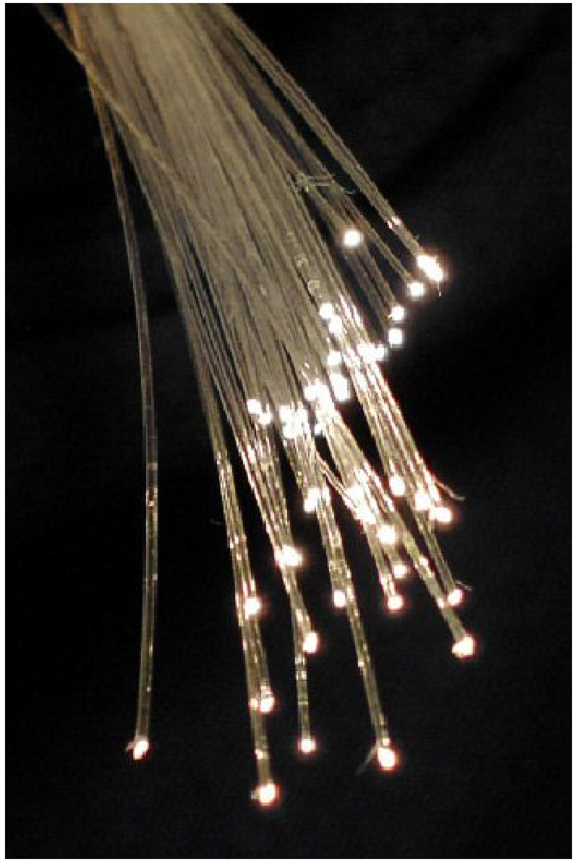
Sensorik für Mikrokanäle

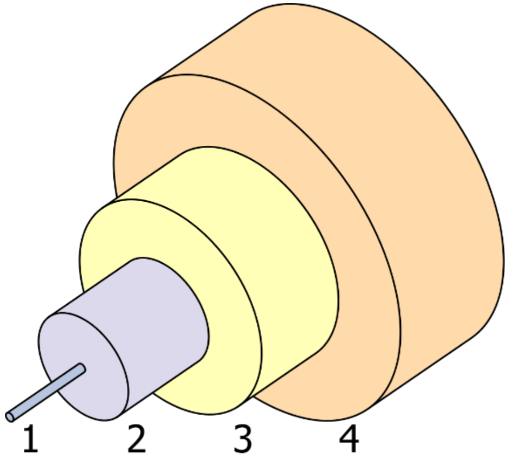


Lab-on-a-Chip (auch Chiplabor

Verteilte faseroptische Sensoren

Lichtwellenleiter (optische Faser)



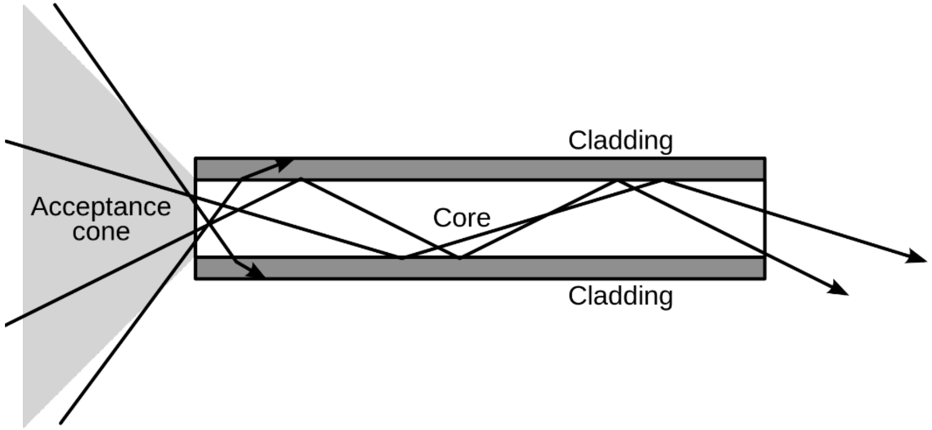


1 – Kern (engl. *core*)
2 – Mantel (engl. *cladding*) mit $n_K > n_M$
3 – Schutzbeschichtung (engl. *coating* und/oder *buffer*)
4 – äußere Hülle (engl. *jacket*).

Bsp. für Stufenindexfaser

- aus dem snelliusschen Brechungsgesetz

$$\theta_{\max} = \arcsin\left(\frac{1}{n_0}\sqrt{{n_K}^2 - {n_M}^2}\right)$$



Quelle: https://de.wikipedia.org/wiki/Lichtwellenleiter

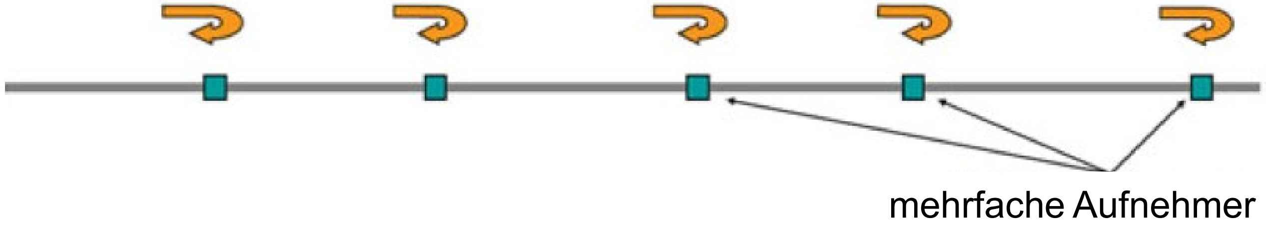
Faseroptische Sensoren

Einzelpunktsensor

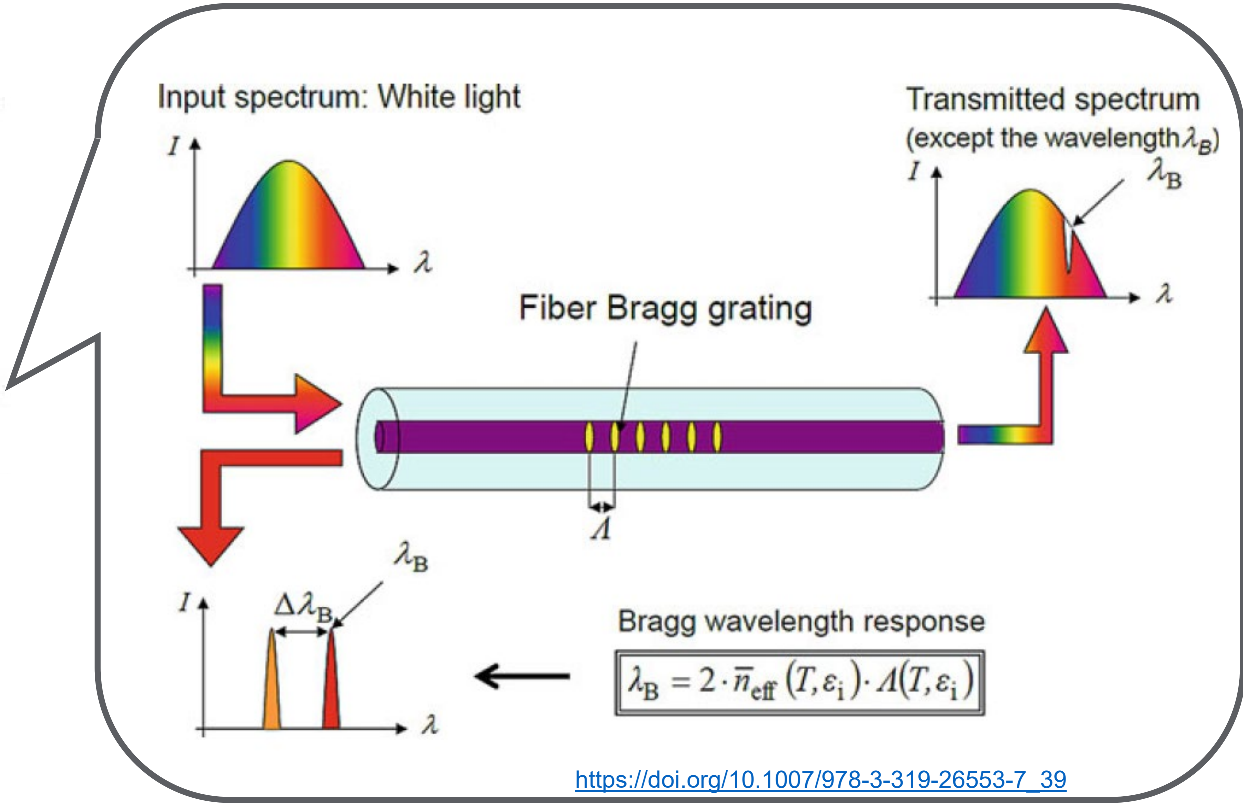
LWL

Aufnehmer

Mehrpunktsensor (*quasi-distributed*)



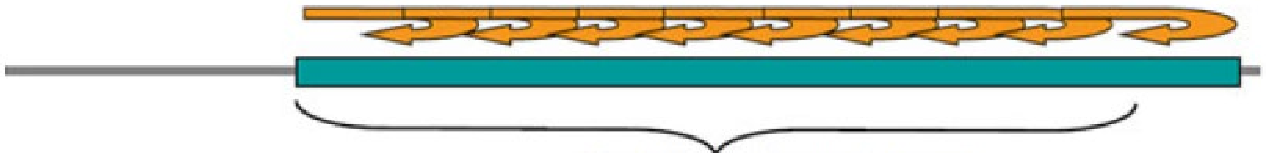
mehrfache Aufnehmer



$$\lambda_B = 2 \cdot \bar{n}_{eff}(T, \varepsilon_i) \cdot \Lambda(T, \varepsilon_i)$$

https://doi.org/10.1007/978-3-319-26553-7_39

Verteilte Sensor (*distributed*)

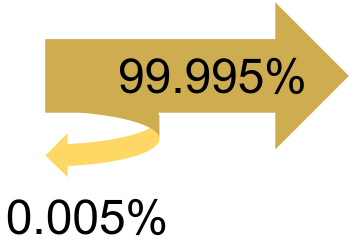


kontinuierlicher Aufnehmer

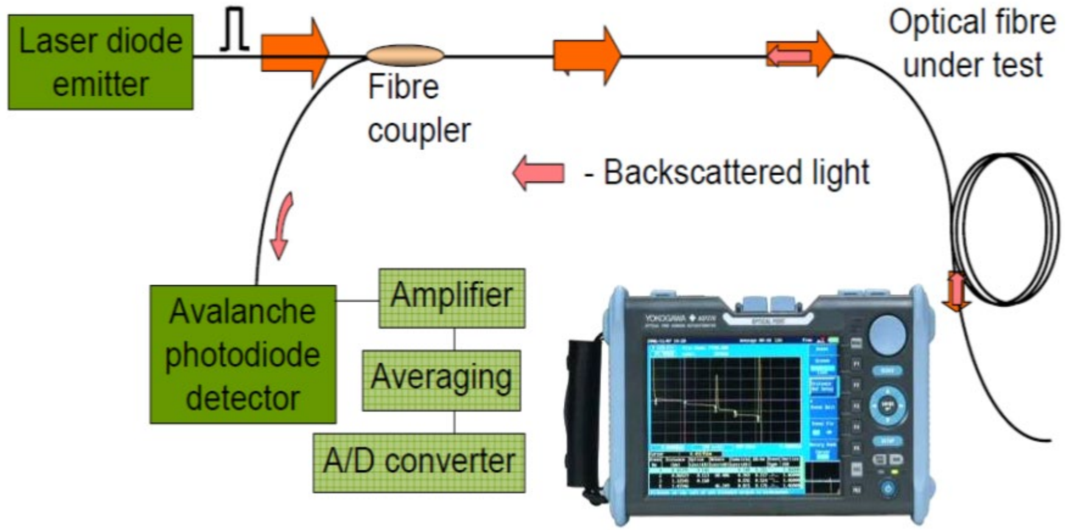
Quelle: A.H. Hartog, **An Introduction to Distributed Optical Fibre Sensors**, CRC Press, 2017

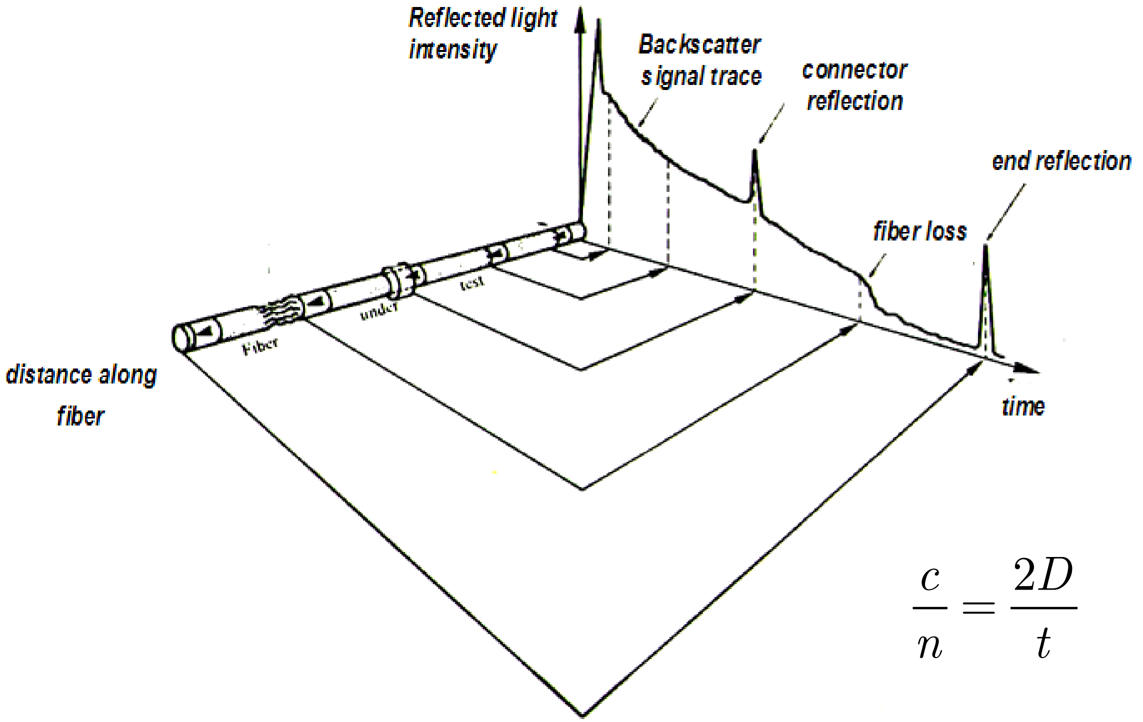
optische Zeitbereichsreflektometrie (OTDR)

(engl. *optical time domain reflectometer* - OTDR)



Dämpfung ≈ 0,2 dB/km

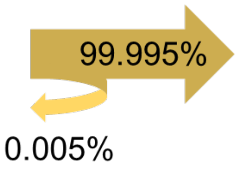


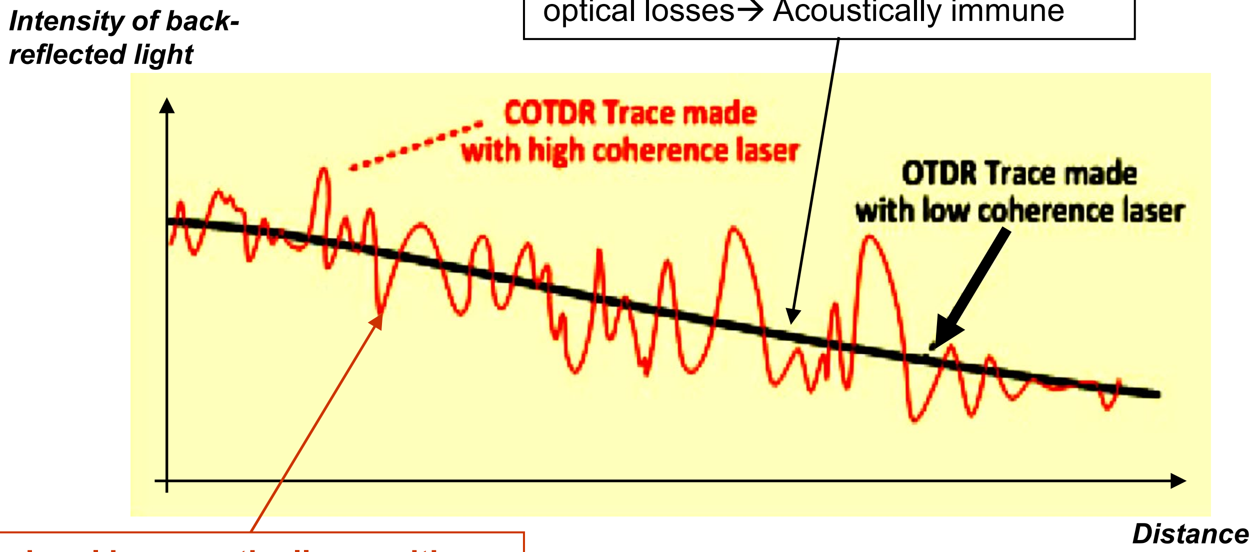


$$\frac{c}{n} = \frac{2D}{t}$$

- Für c = 3.10^8 ms^{-1}, n = 1.5, D = 1 km
  - *round trip* = 100 ns
  - max. Wiederholungsfrequenz = 100 kHz

Rayleigh scattering and optical coherence

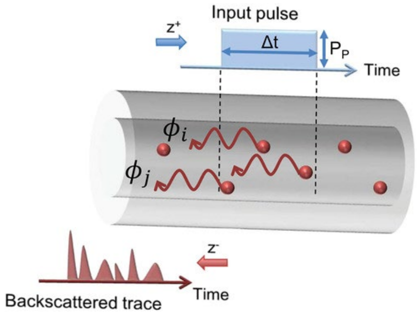




Conventional OTDR signal only detects fiber imperfections and optical losses→ Acoustically immune

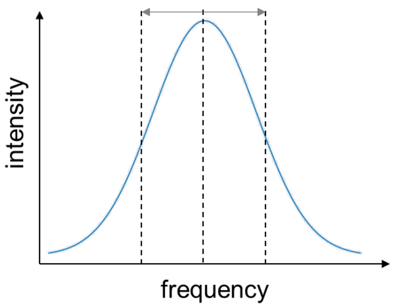
C-OTDR signal is acoustically sensitive and makes fiber optically self-interfering with external perturbations → **narrow line width, high coherence laser**

Rayleigh-Streuung

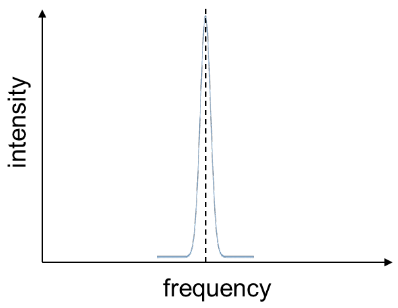


- Für c = 3.10^8 ms^{-1}, n = 1.5, Δt = 100ns
  - spatial resolution= 10m

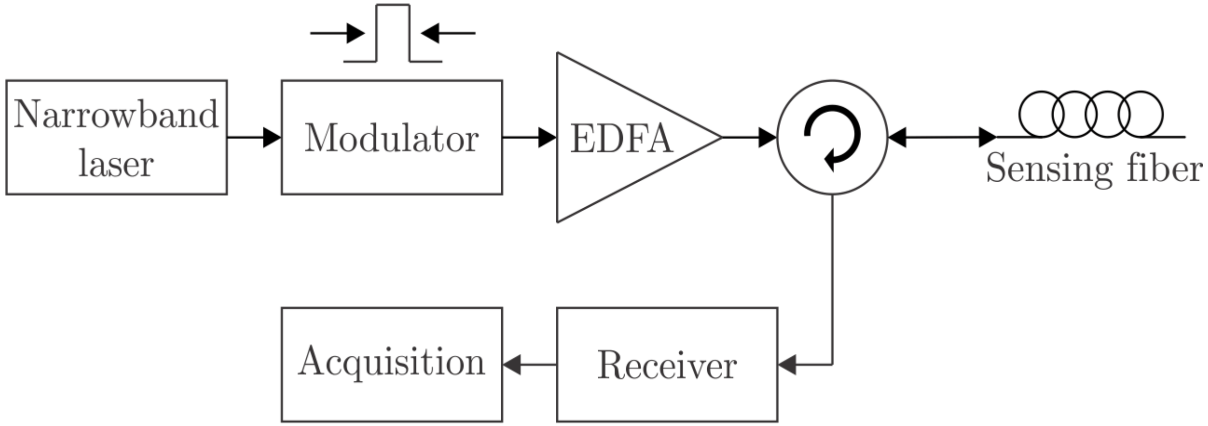
Non-coherent source

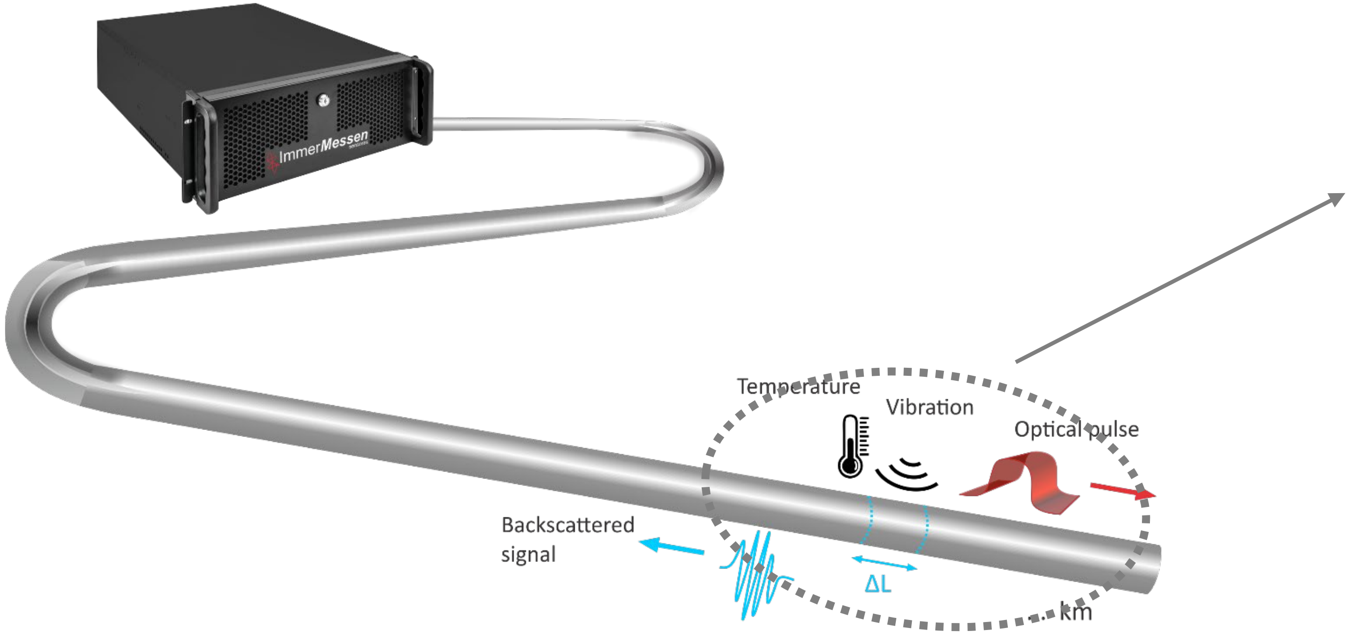


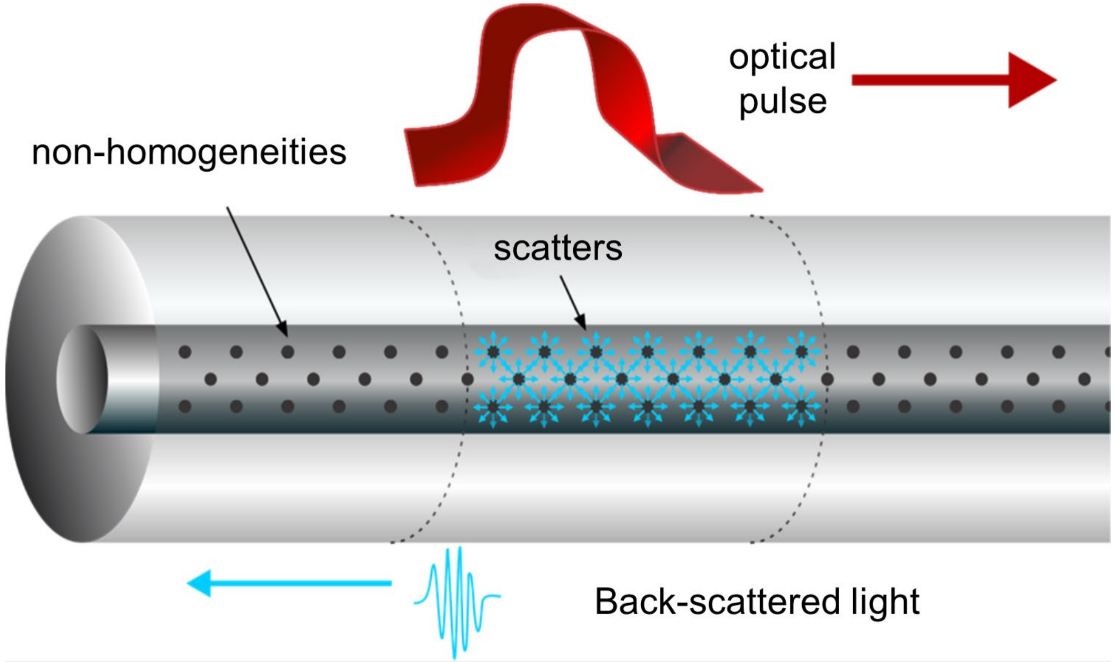
Coherence source
(Narrow Line-Width)



Distributed Acoustic Sensing (DAS)


Narrowband laser
Modulator
EDFA
Sensing fiber
Acquisition
Receiver





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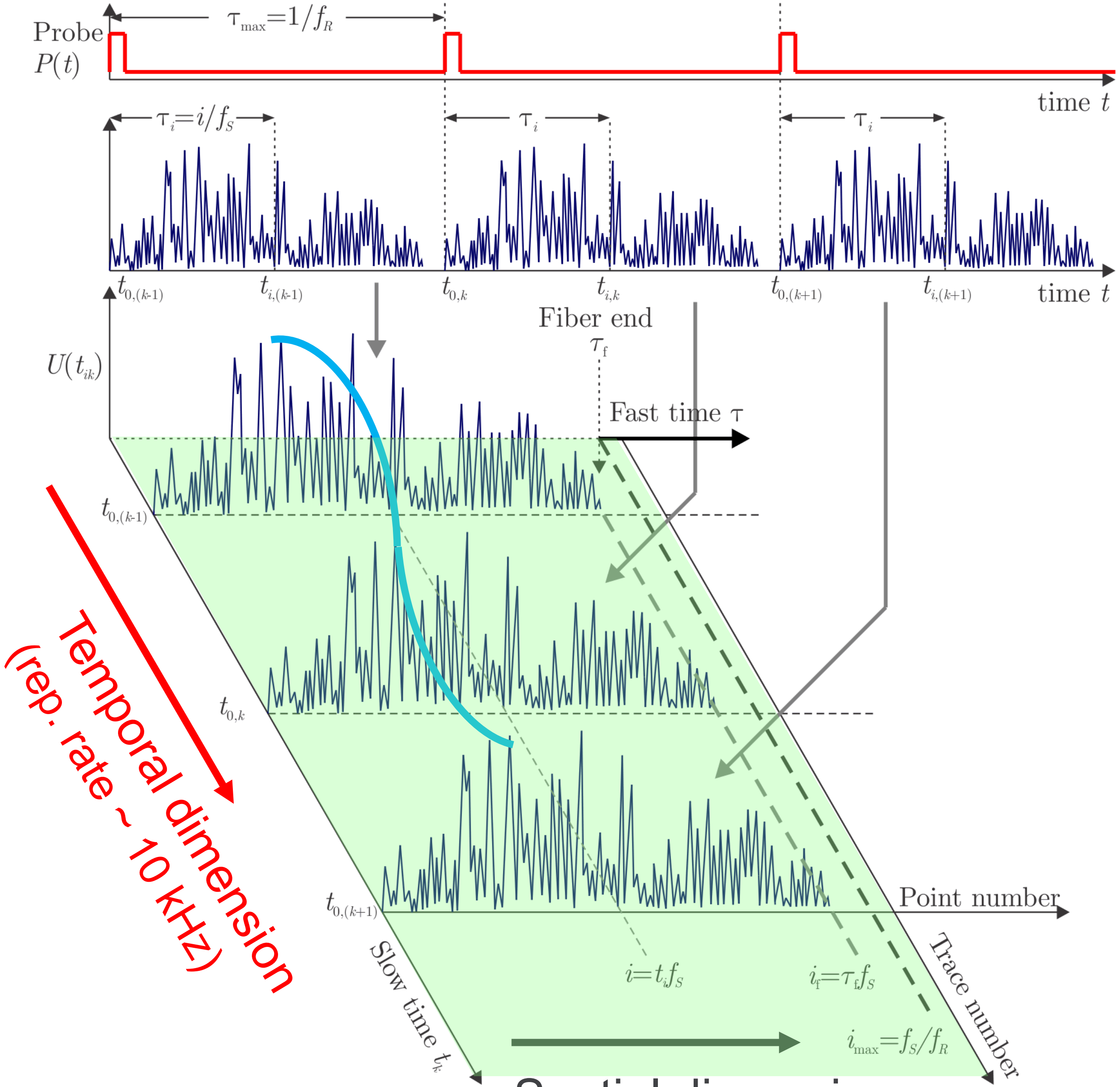
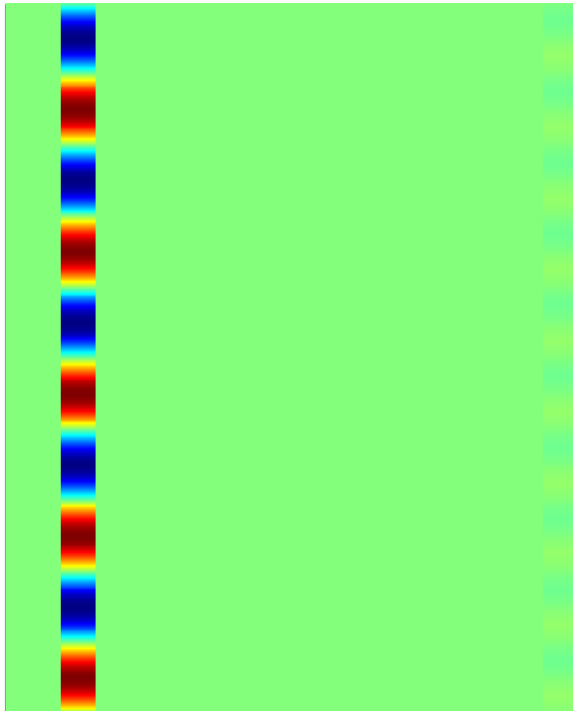
Distributed Acoustic Sensing



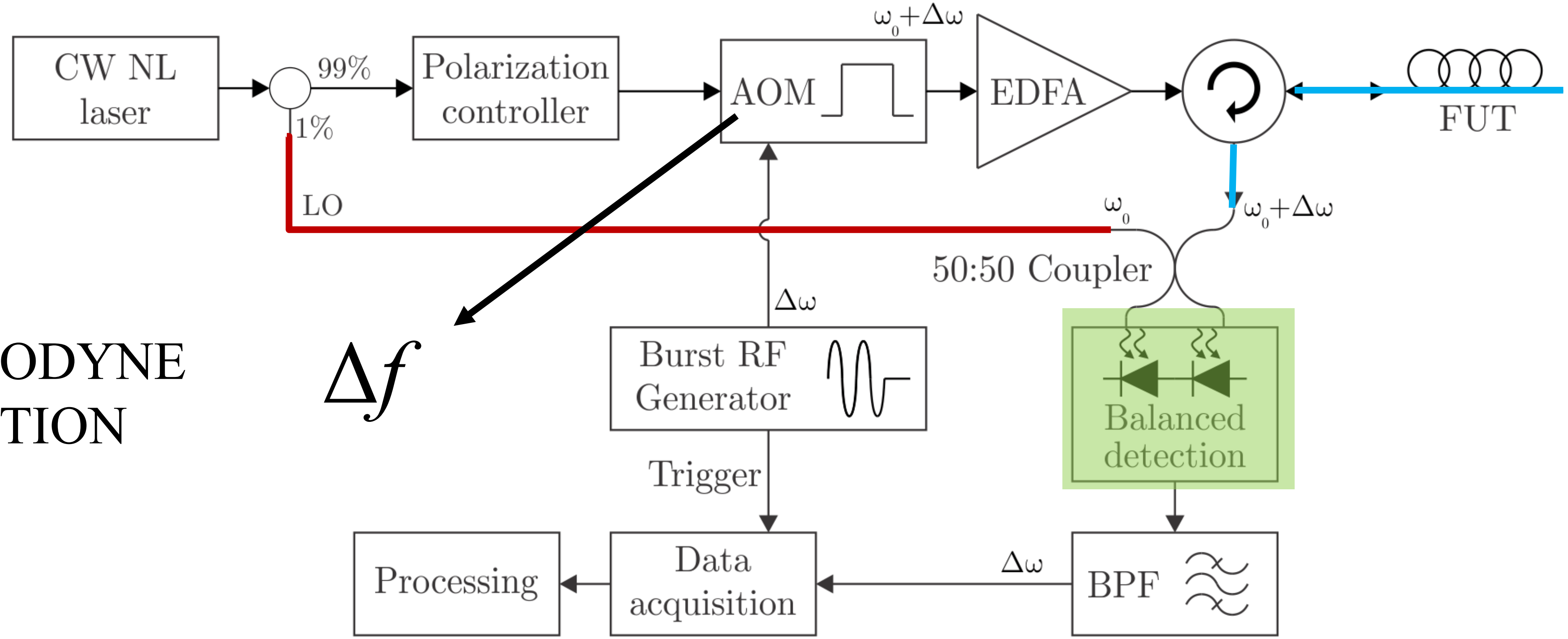
Temporal dimension
(rep. rate ~ 10 kHz)

Spatial dimension
(sampling rate: 500 MS/s ~ 20.43 cm)

heat map



DAS SIMULATOR TOOL: Modulation



HETERODYNE DETECTION

Δf

$$E_{LO}(t) = E_l \exp\left[j\left(2\pi f_0 t + \varphi_t\right)\right]$$

$$E_R(t) = E_r \sum_{i=1}^{N_S} a_i \exp\left(-\alpha v \tau_i\right) \mathrm{rect}\left(\frac{t-\tau_i}{W}\right) \exp\left\{j\left[2\pi\left(f_0+\Delta f\right)\left(t-\tau_i\right)\right]+\varphi_0+\phi_i\right\}$$

DAS SIMULATOR TOOL: Methodology

Balanced photodetector detects the AC component of the beating signal:

$$I(t) = 2E_l E_r \sum_{i=1}^{N_S} a_i \exp(-\alpha v \tau_i)\,\mathrm{rect}\left(\frac{t-\tau_i}{W}\right)\cos\left(2\pi\Delta f t + \boxed{\Delta\varphi_i}\right)$$

[1] HEALEY, 1984b

External Disturbances

$$\delta\phi = \frac{4\pi n G \xi \varepsilon}{\lambda}$$

[2] SEAFOM, 2018

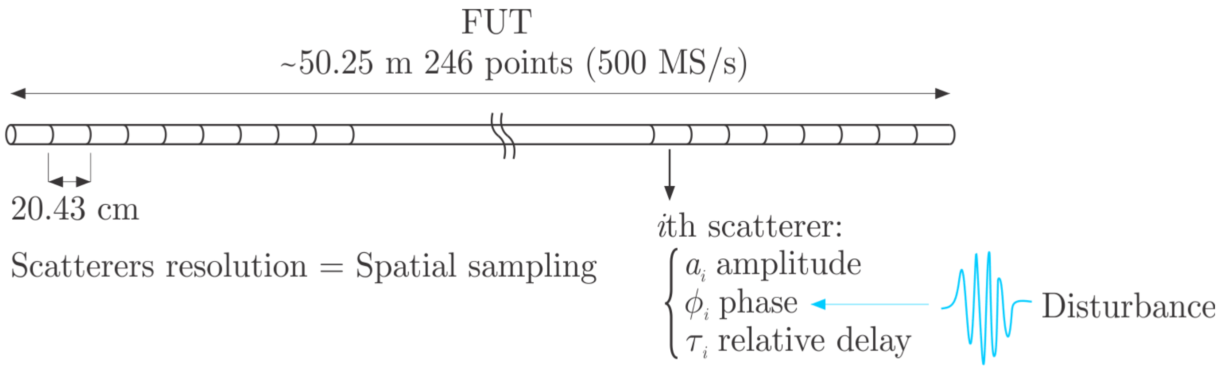
$$\boxed{\Delta\varphi_i} = -\underbrace{2\pi\left(f_0 + \Delta f\right)}_{\text{Local phase due to wave propagation}}\tau_i + \varphi_0 - \varphi_t + \boxed{\phi_i}$$

ϕ_i → Phase associated with the i_{th} scatterer group

φ_t → Laser phase noise (rand + AWGN)

φ_0 → Laser initial phase (rand)

DAS SIMULATOR TOOL: Modulation



FUT

~50.25 m 246 points (500 MS/s)

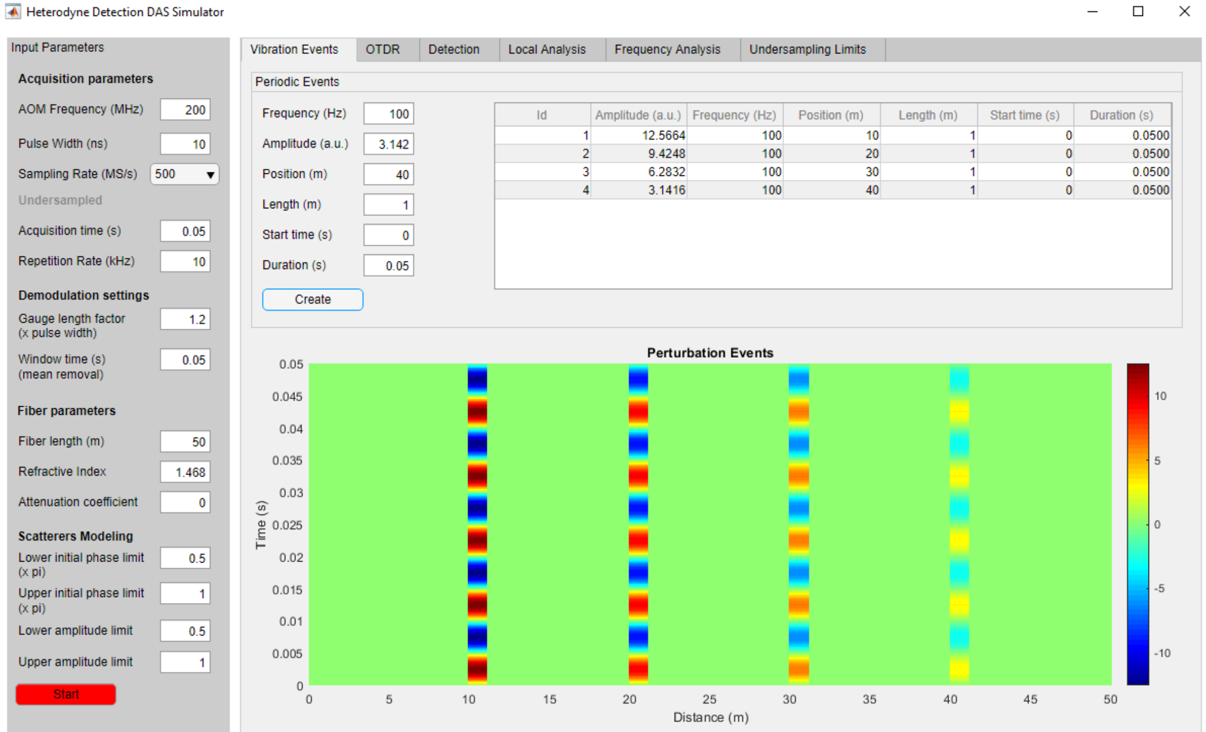
20.43 cm

Scatterers resolution = Spatial sampling

ith scatterer:

- a_i amplitude
- ϕ_i phase
- τ_i relative delay

Disturbance



Input Parameters

Acquisition parameters

AOM Frequency (MHz): 200

Pulse Width (ns): 10

Sampling Rate (MS/s): 500

Undersampled

Acquisition time (s): 0.05

Repetition Rate (kHz): 10

Demodulation settings

Gauge length factor (x pulse width): 1.2

Window time (s) (mean removal): 0.05

Fiber parameters

Fiber length (m): 50

Refractive Index: 1.468

Attenuation coefficient: 0

Scatterers Modeling

Lower initial phase limit (x pi): 0.5

Upper initial phase limit (x pi): 1

Lower amplitude limit: 0.5

Upper amplitude limit: 1

Periodic Events

Frequency (Hz): 100

Amplitude (a.u.): 3.142

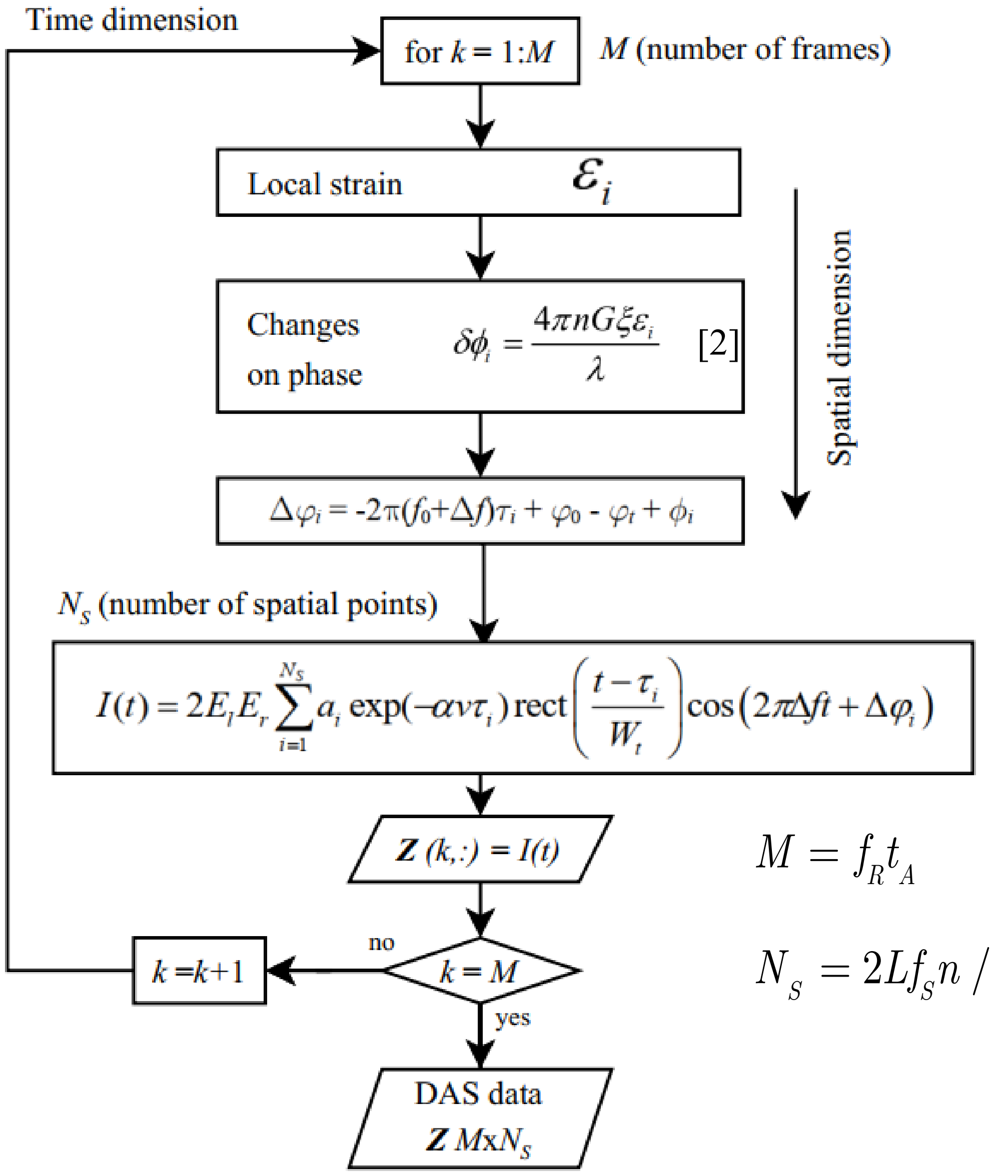
Position (m): 40

Length (m): 1

Start time (s): 0

Duration (s): 0.05

Id	Amplitude (a.u.)	Frequency (Hz)	Position (m)	Length (m)	Start time (s)	Duration (s)
1	12.5664	100	10	1	0	0.0500
2	9.4248	100	20	1	0	0.0500
3	6.2832	100	30	1	0	0.0500
4	3.1416	100	40	1	0	0.0500



Time dimension

for $k = 1{:}M$ M (number of frames)

Local strain ε_i

Changes on phase $\delta\phi_i = \dfrac{4\pi n G \xi \varepsilon_i}{\lambda}$ [2]

Spatial dimension

$\Delta\varphi_i = -2\pi(f_0+\Delta f)\tau_i + \varphi_0 - \varphi_t + \phi_i$

N_S (number of spatial points)

$$I(t) = 2E_l E_r \sum_{i=1}^{N_S} a_i \exp(-\alpha v \tau_i)\,\mathrm{rect}\left(\frac{t-\tau_i}{W_t}\right)\cos\left(2\pi\Delta f t + \Delta\varphi_i\right)$$

$Z\ (k,:) = I(t)$

$k = M$

no

$k = k+1$

yes

DAS data

Z MxN_S

$$M = f_R t_A$$

$$N_S = 2Lf_S n / c$$

[2] SEAFOM, 2018

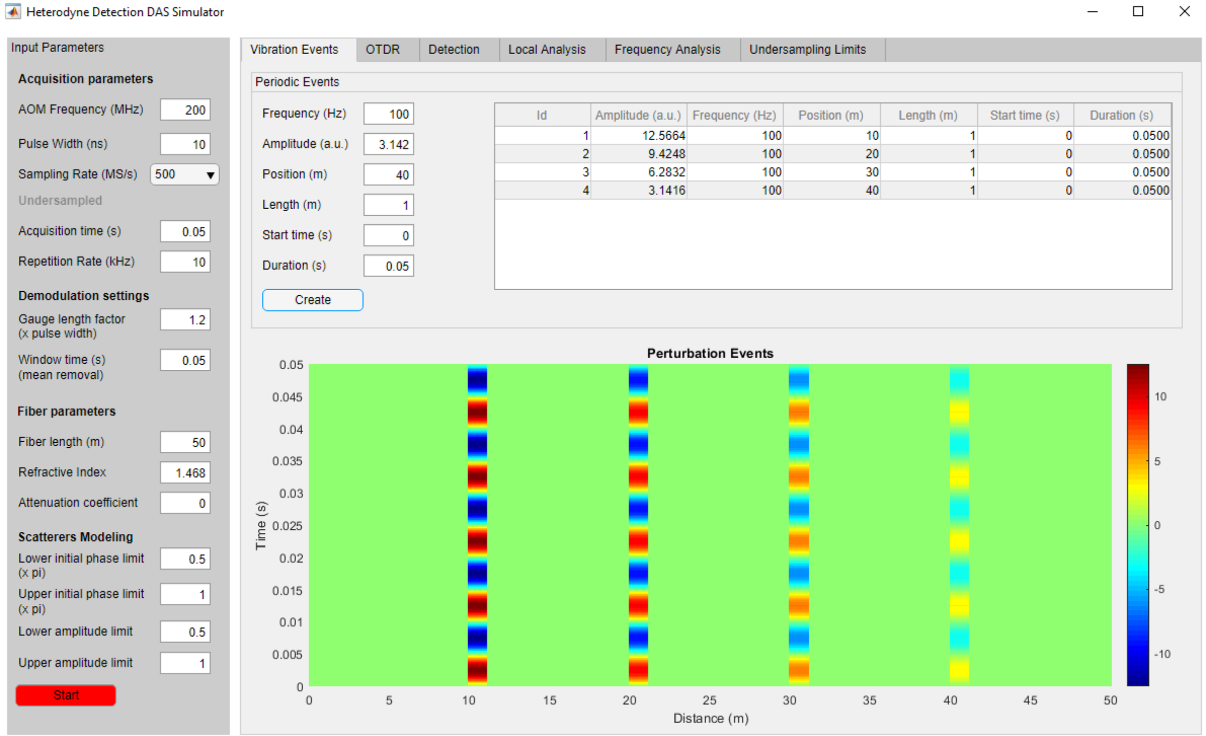
DAS SIMULATOR TOOL: Modulation

DAS Model

physical description of phenomena

steps for signal processing to extract information

yielding a **full input-output description of the system**



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Undersampled

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Demodulation settings

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Window time (s) (mean removal) 0.05

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Fiber length (m) 50

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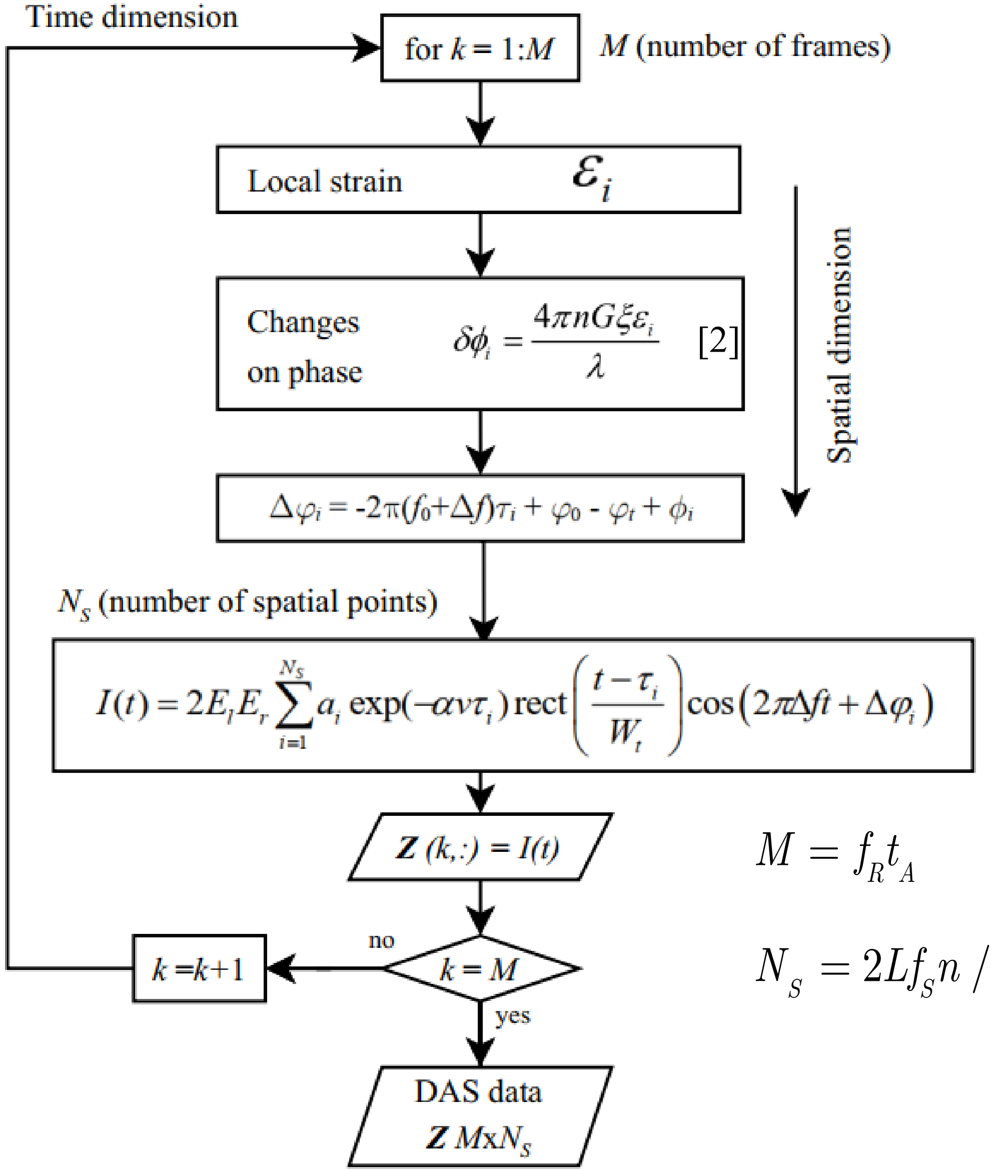

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for $k = 1{:}M$ M (number of frames)

Local strain ε_i

Changes on phase $\delta\phi_i = \dfrac{4\pi nG\xi\varepsilon_i}{\lambda}$ [2]

$\Delta\varphi_i = -2\pi(f_0+\Delta f)\tau_i + \varphi_0 - \varphi_t + \phi_i$

Spatial dimension

N_S (number of spatial points)

$$I(t) = 2E_l E_r \sum_{i=1}^{N_S} a_i \exp(-\alpha v\tau_i)\,\mathrm{rect}\left(\frac{t-\tau_i}{W_t}\right)\cos\left(2\pi\Delta f t + \Delta\varphi_i\right)$$

$Z(k,:) = I(t)$

$k = M$

no

$k = k+1$

yes

DAS data Z $M\mathrm{x}N_S$

$$M = f_R t_A$$

$$N_S = 2Lf_S n / c$$

[2] SEAFOM, 2018

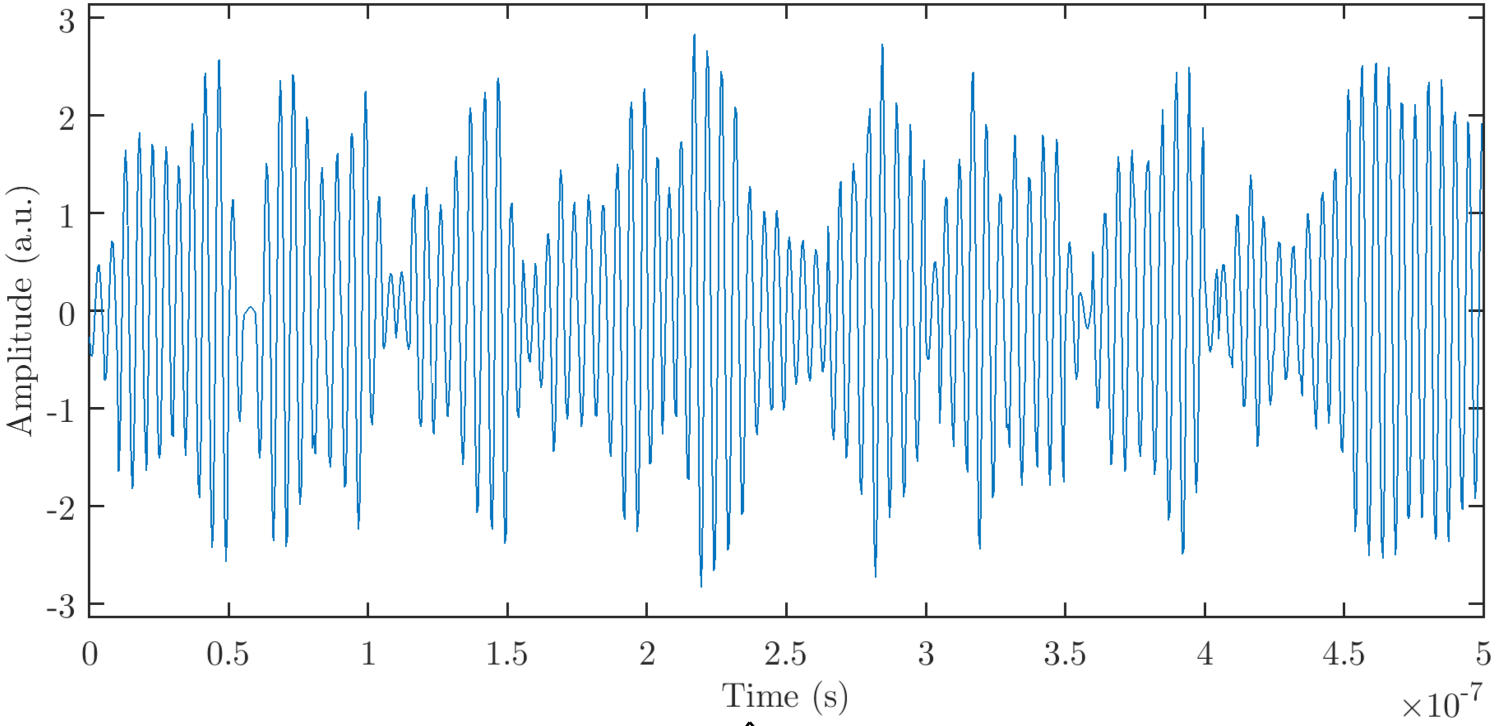
DAS SIMULATOR TOOL: Demodulation

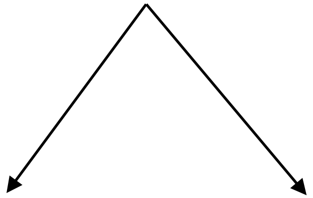
Acquired signal:

$$I_s(t) = A(t)\cos[2\pi f_c t + \phi(t)]$$

$$\downarrow$$

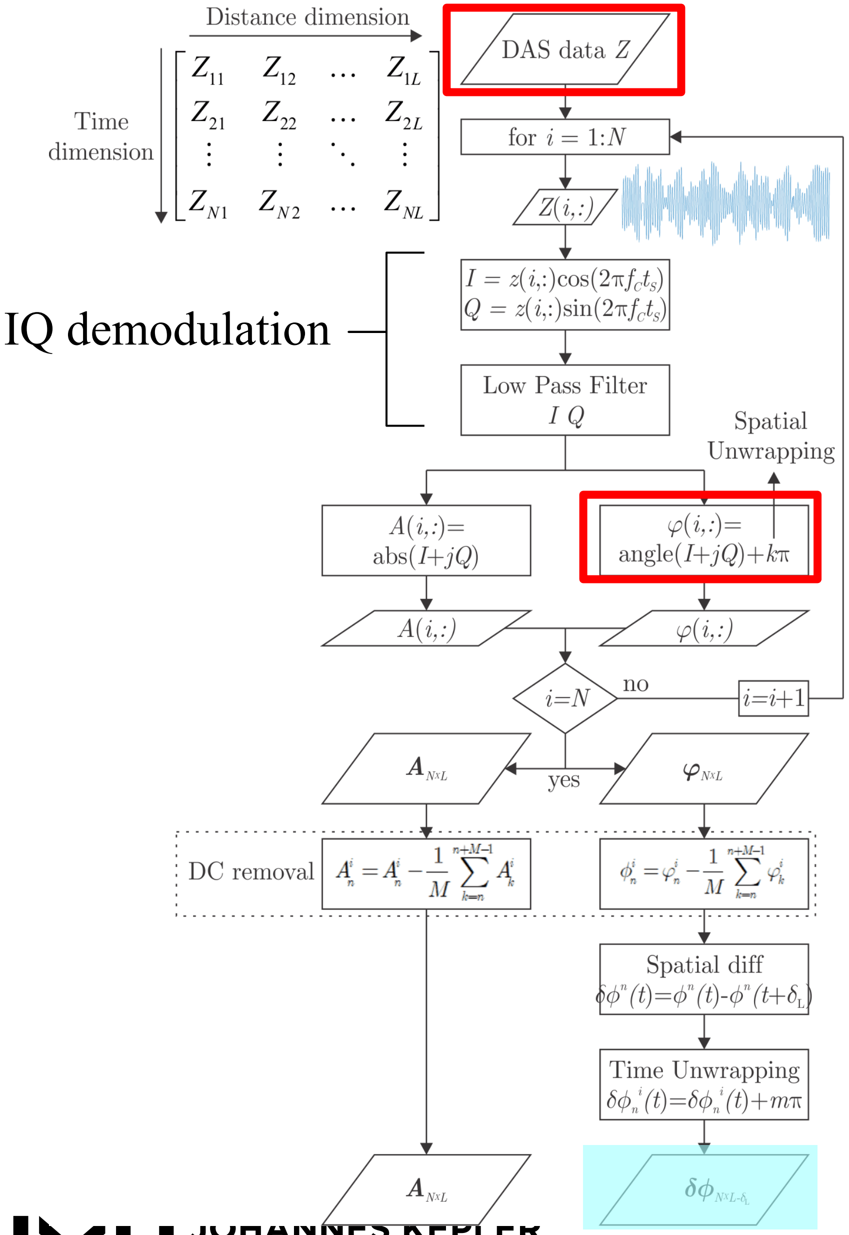
$$f_c = \Delta f$$

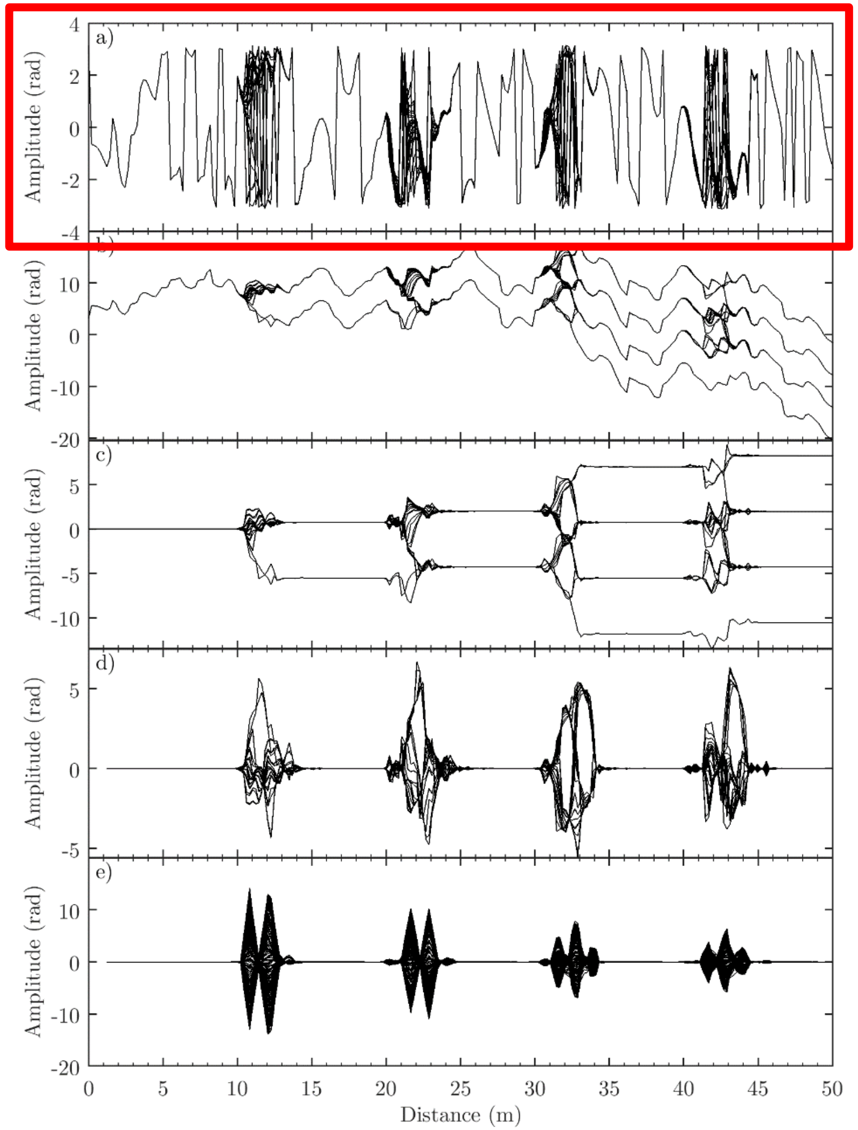




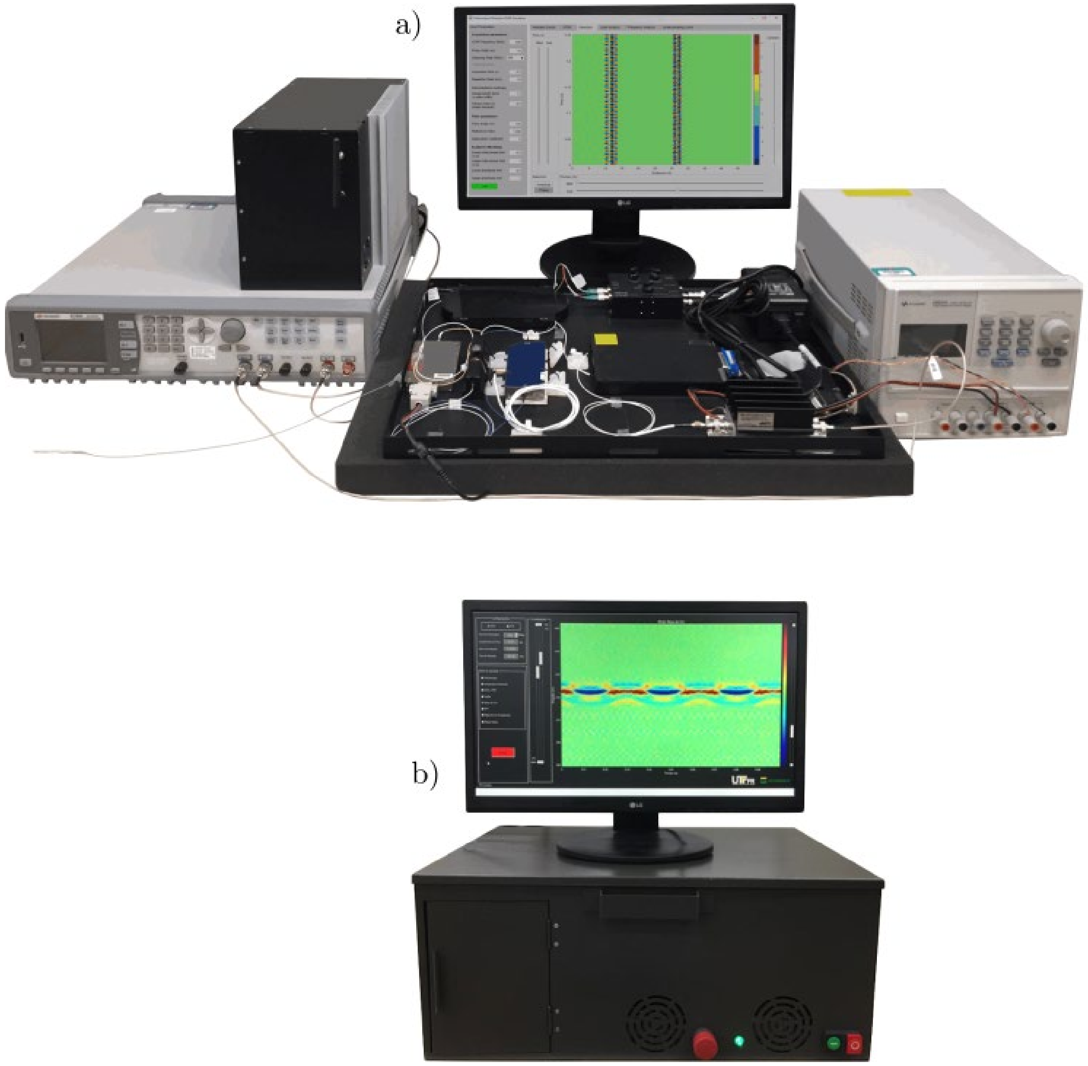
Amplitude $A(t)$ Phase $\phi(t)$

DAS SIMULATOR TOOL: Demodulation



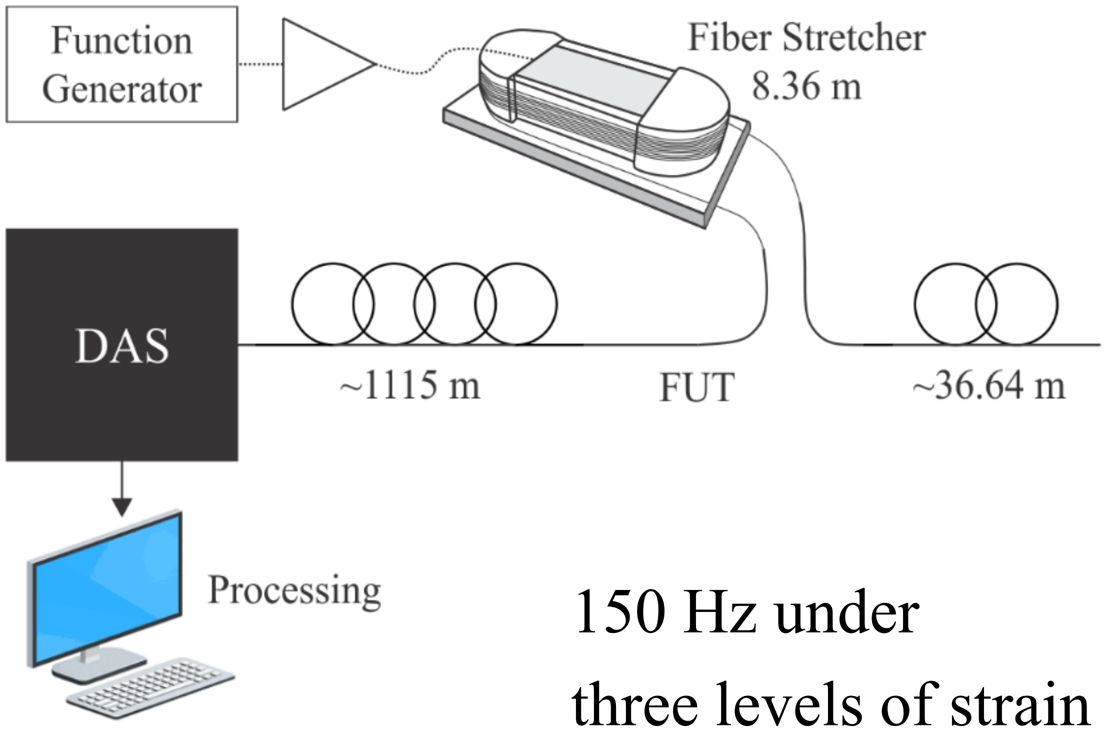


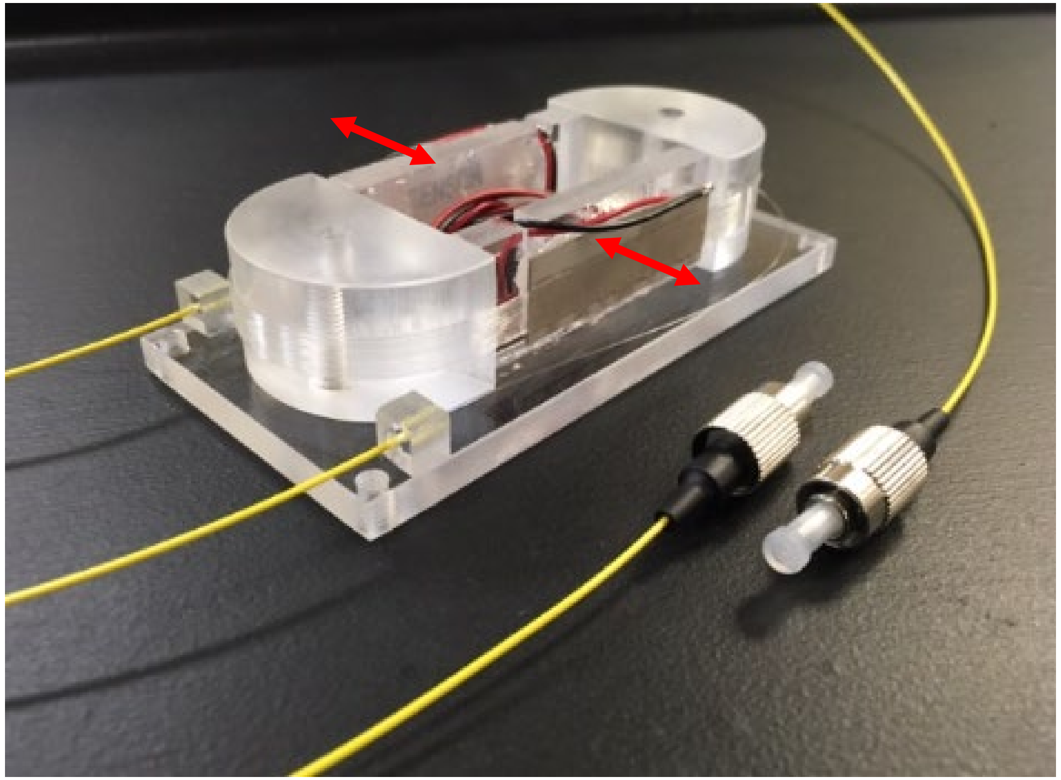
DAS SYSTEM AT UTFPR



COUPLING SIMULATION AND EXPERIMENTS

same experimental setup, mechanical perturbations, acquisition and demodulation parameters

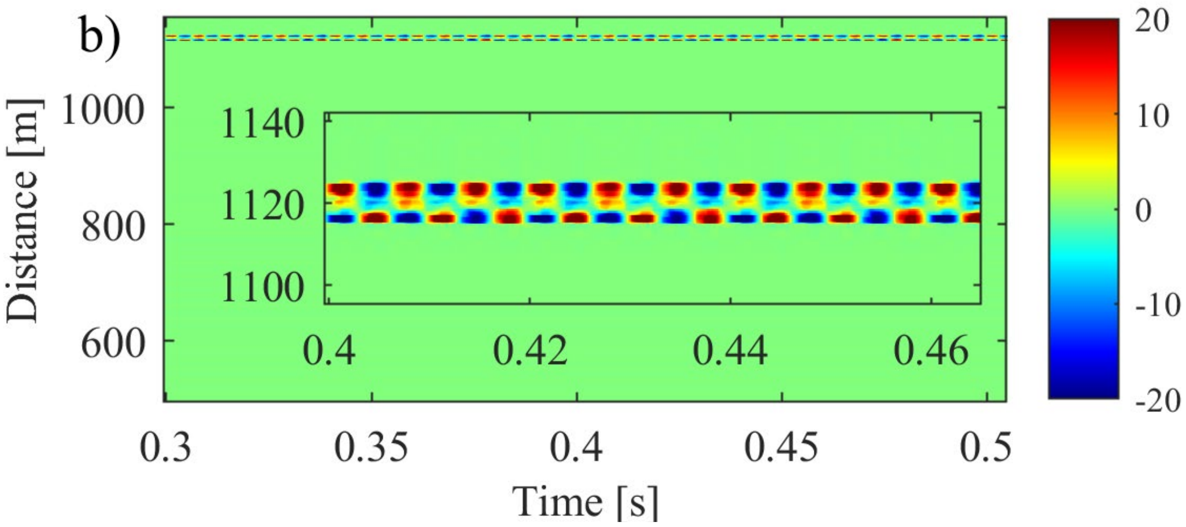




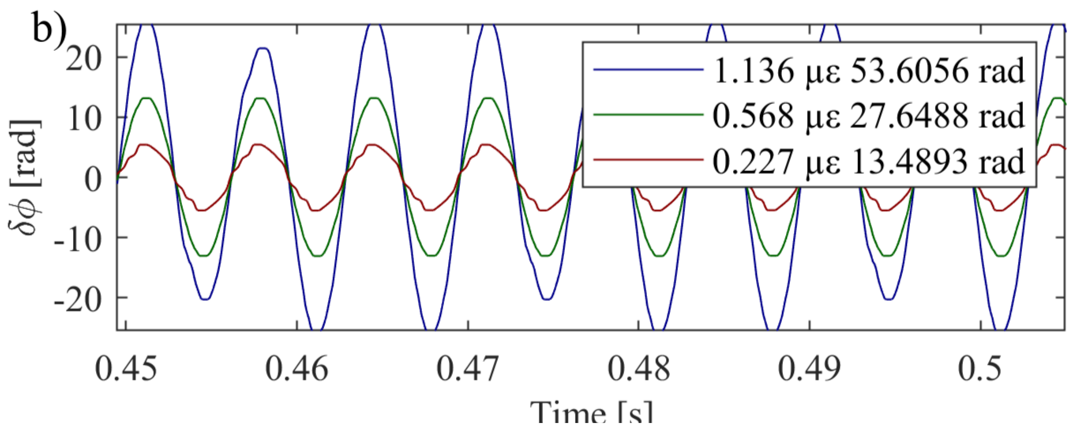
150 Hz under

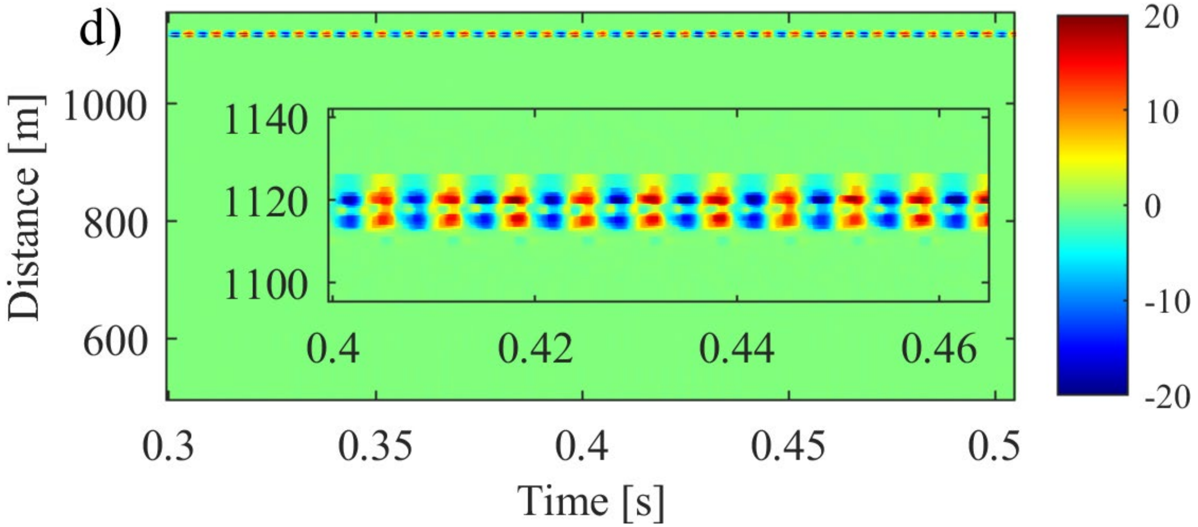
three levels of strain

COUPLING SIMULATION AND EXPERIMENTS

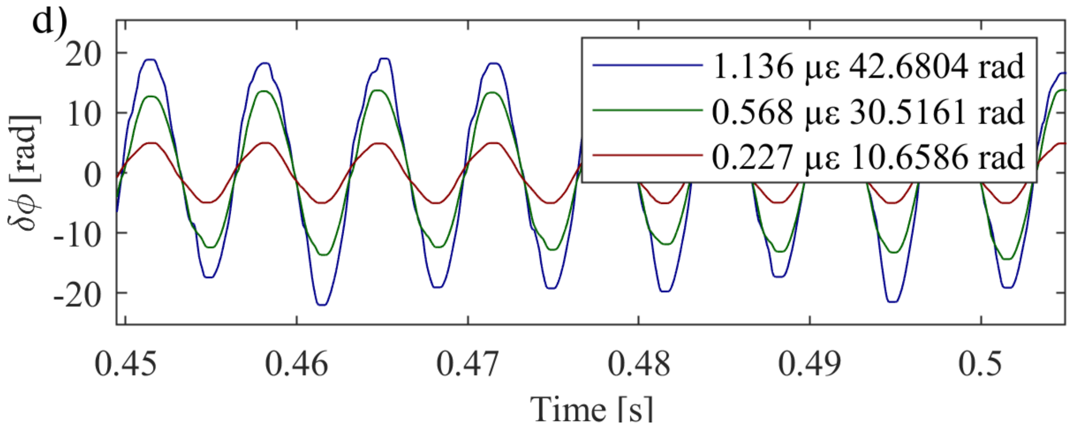


SIMULATION





EXPERIMENTS



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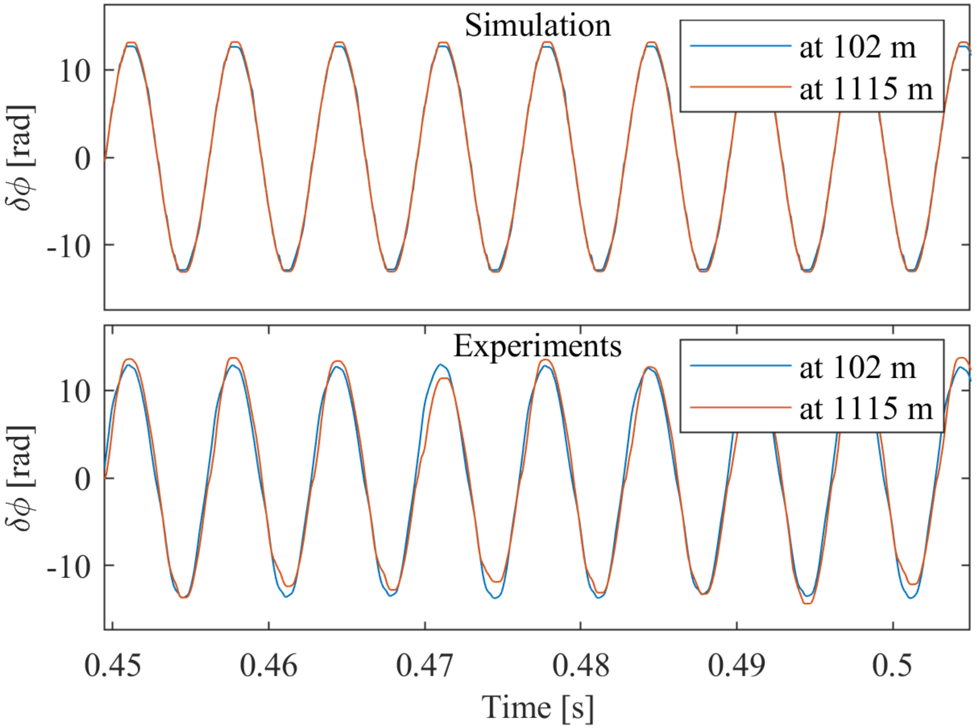

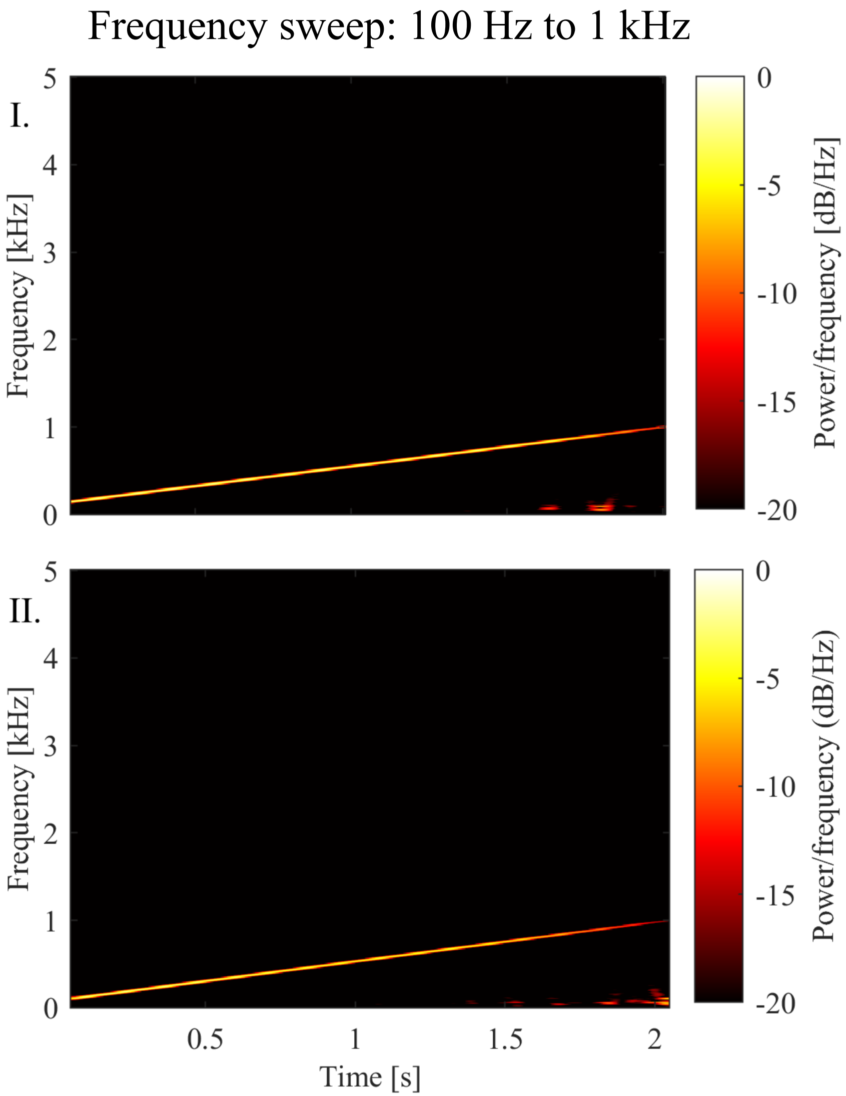

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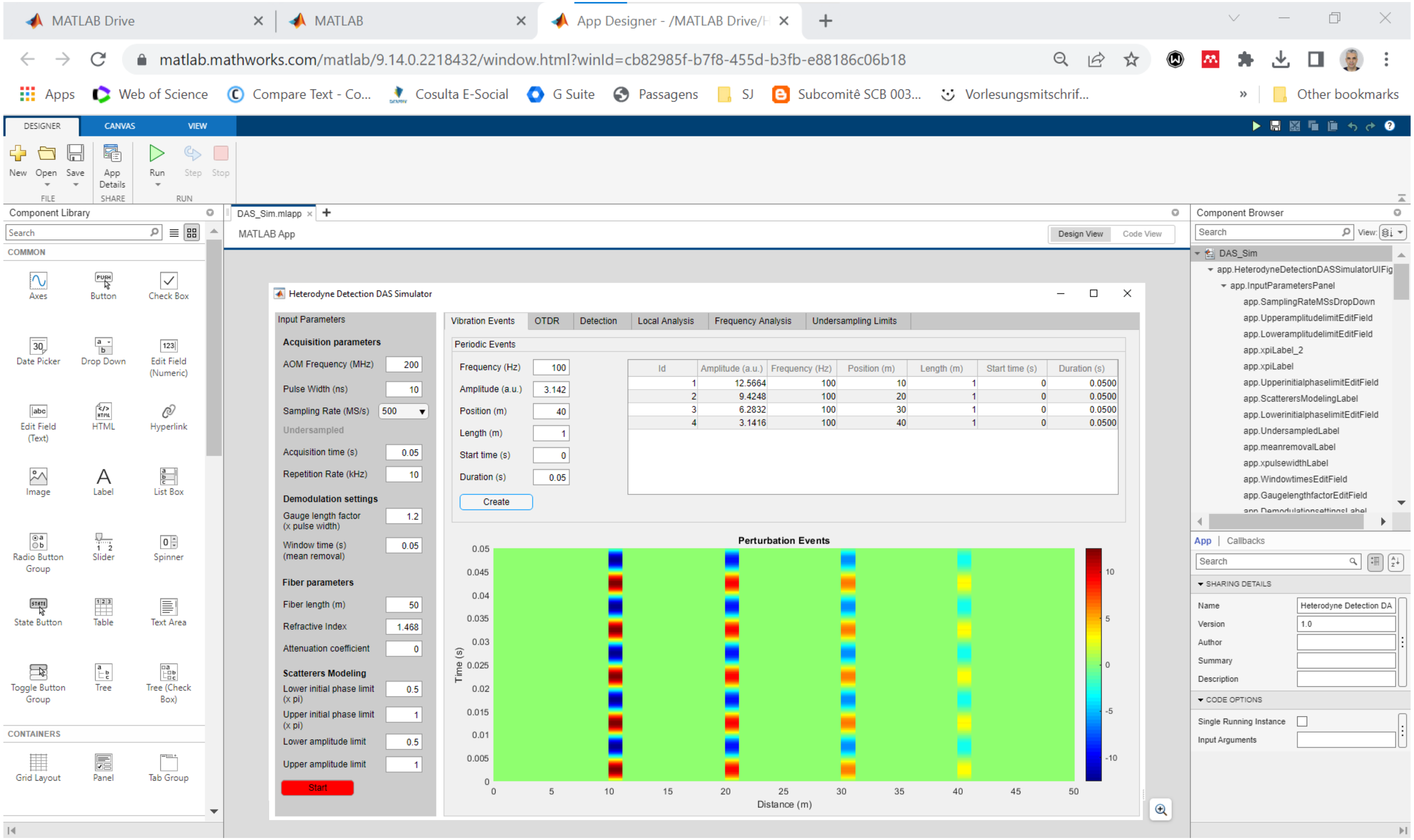
Modelling in MATLAB with “Design App”

https://de.mathworks.com/products/matlab/app-designer.html



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Refractive Index 1.468

Attenuation coefficient 0

Scatterers Modeling

Lower initial phase limit (x pi) 0.5

Upper initial phase limit (x pi) 1

Lower amplitude limit 0.5

Upper amplitude limit 1

Periodic Events

Frequency (Hz) 100

Amplitude (a.u.) 3.142

Position (m) 40

Length (m) 1

Start time (s) 0

Duration (s) 0.05

Id	Amplitude (a.u.)	Frequency (Hz)	Position (m)	Length (m)	Start time (s)	Duration (s)
1	12.5664	100	10	1	0	0.0500
2	9.4248	100	20	1	0	0.0500
3	6.2832	100	30	1	0	0.0500
4	3.1416	100	40	1	0	0.0500

Name Heterodyne Detection DA

Version 1.0

Author

Summary

Description

Single Running Instance ☐

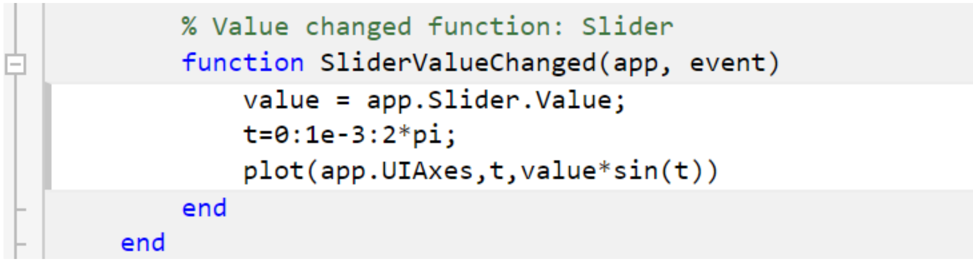
Input Arguments

Modelling in MATLAB with “Design App”

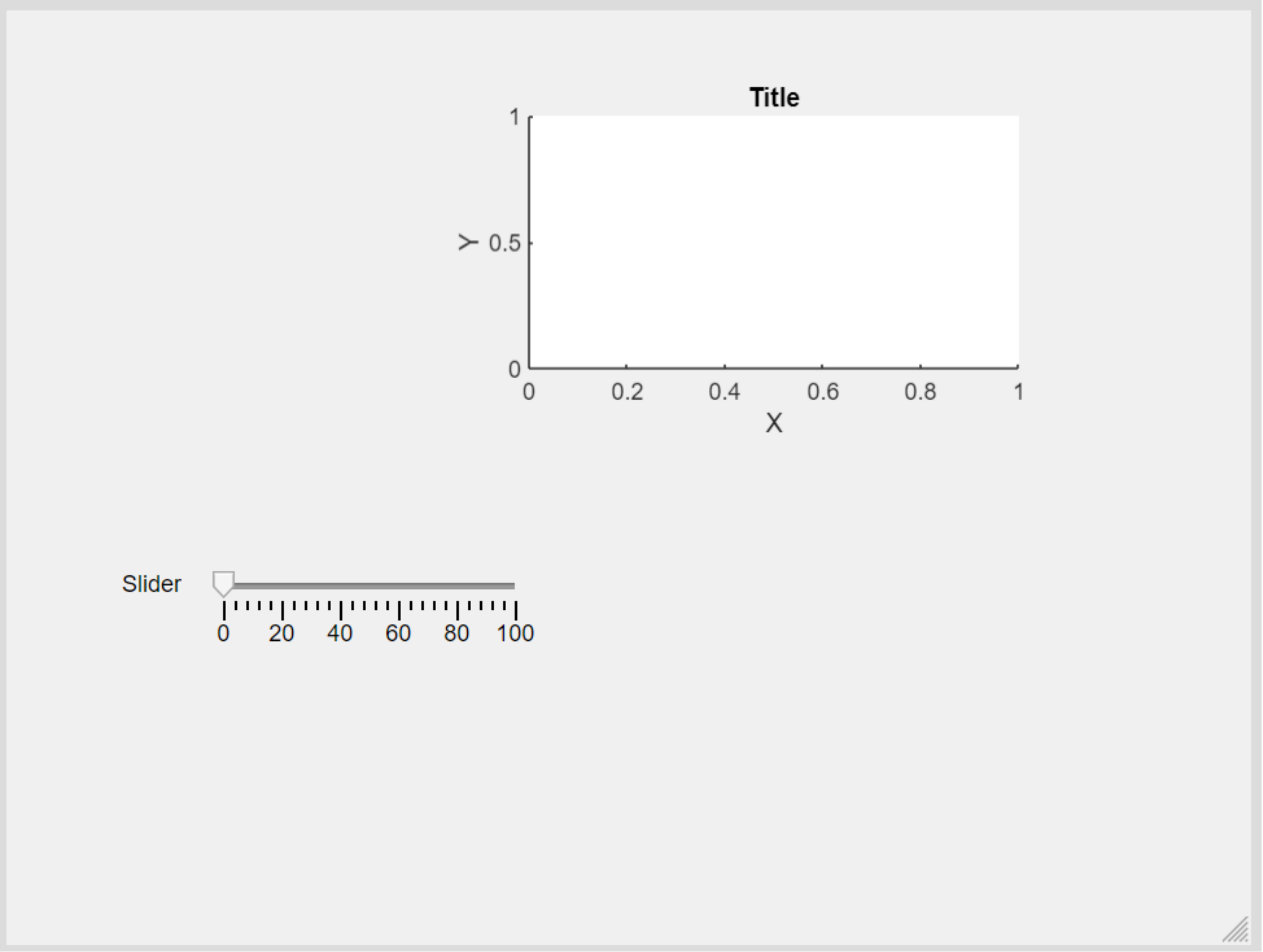
https://de.mathworks.com/products/matlab/app-designer.html

Kurze DEMO

Einfache Anwendung



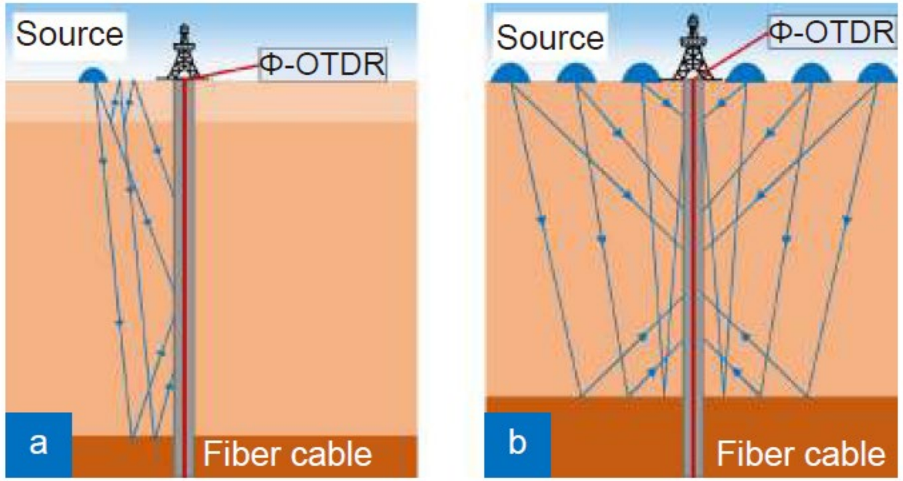
```
        % Value changed function: Slider
        function SliderValueChanged(app, event)
            value = app.Slider.Value;
            t=0:1e-3:2*pi;
            plot(app.UIAxes,t,value*sin(t))
        end
    end
```



DAS Applications

- **Geological exploration**

vertical seismic profiling (VSP)



(a) Zero-offset VSP. (b) Walk-away VSP.

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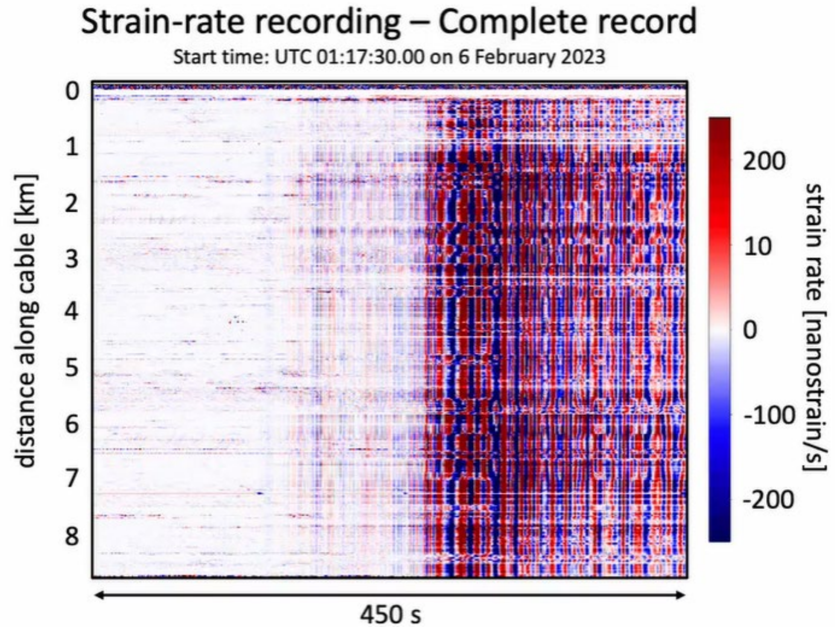
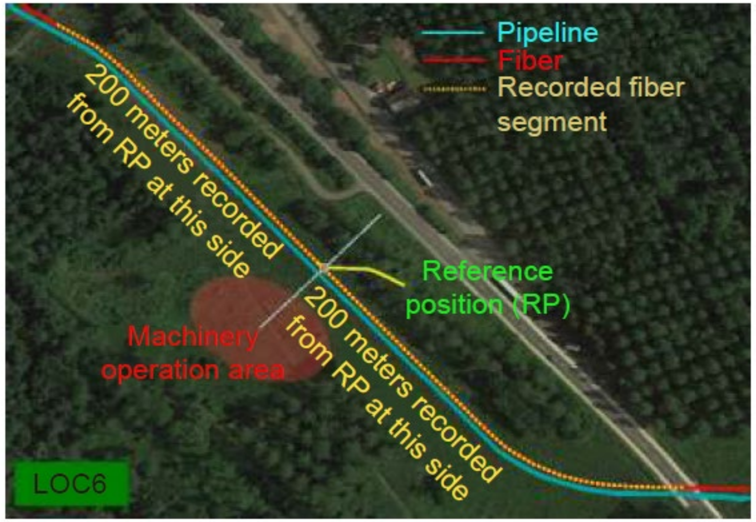
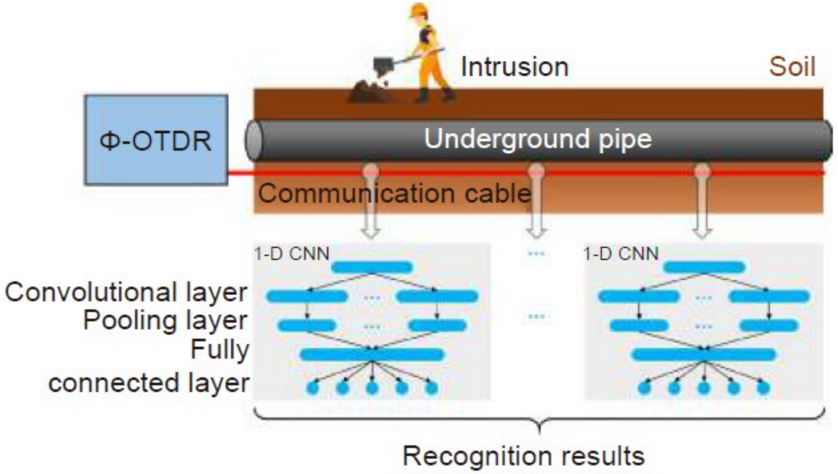


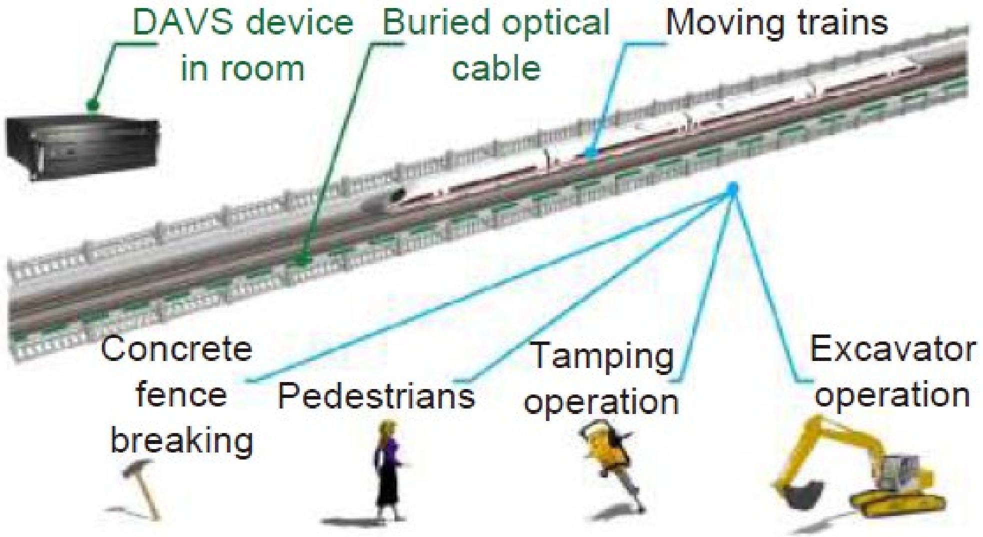
https://www.linkedin.com/posts/silixa-ltd%2E_earthquake-seismology-research-activity-7030822703792054272-nEt6?utm_source=share&utm_medium=member_desktop

DAS Applications

- **Perimeter monitoring**







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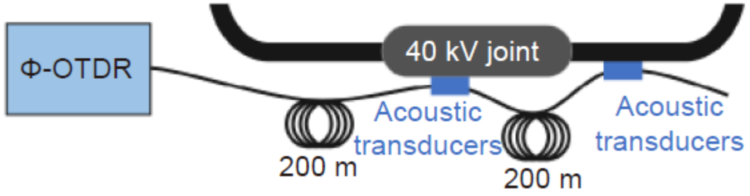
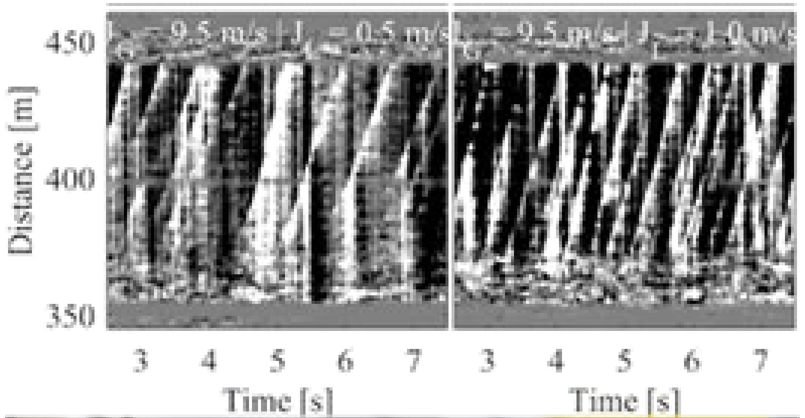
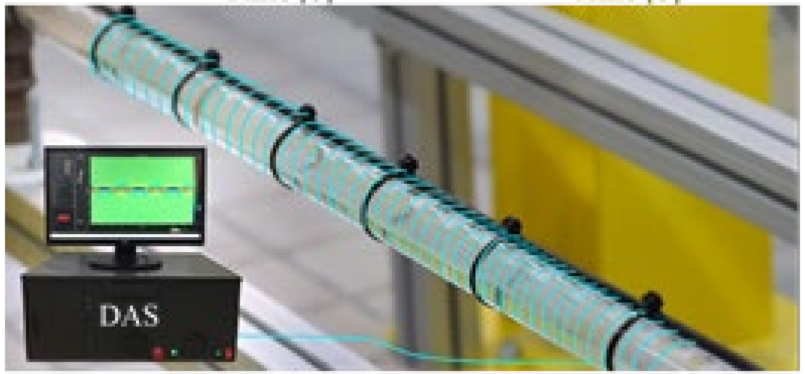
DAS Applications

- **Partial discharge monitoring**



- **Flow monitoring**





http://dx.doi.org/10.1109/jsen.2022.3232269

Liu SQ et al. *Opto-Electron Adv* **5**, 200078 (2022) https://doi.org/10.29026/oea.2022.200078