INSTITUTE OF THERMOMECHANICS
CZECH ACADEMY OF SCIENCES
Dolejškova 5, 182 00 Praha 8

The 14th International Conference
SPMS 2023
Stochastic and Physical Monitoring Systems
26.6. - 30.6.2023

New Observations on Fatigue Crack Growth Using Acoustic Emission

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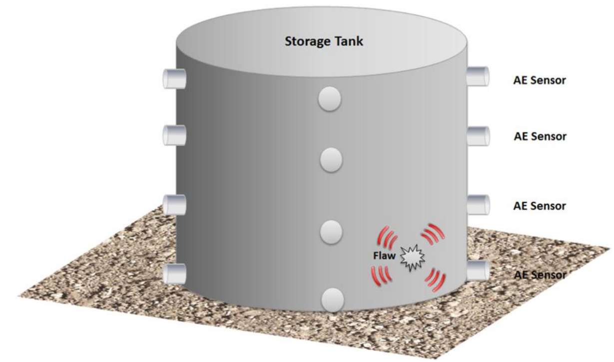
New Observations on Acoustic Emission

- Acoustic emission (AE)
- Analysis of AE source localisation possibilities
  detecting of critical areas
- Sensor configuration design
  two case studies
- AE source variable directivity problem
  limited possibility of AE detection
  explanation of the phenomenon

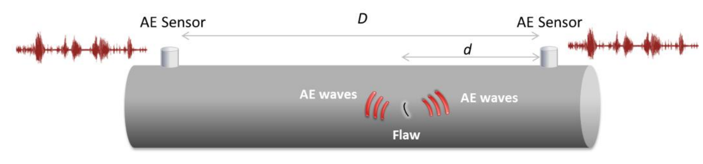
ACOUSTIC EMISSION (AE) METHOD

Passive monitoring of ultrasonic elastic waves initiated by various processes in materials.

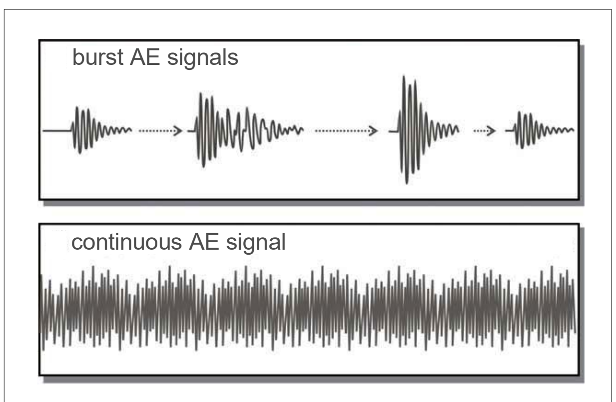


Burst AE: *plastic deformation of metals, crack growth, friction, material failure...*

Continuous AE: *leakage of liquids under pressure, machining, welding, monitoring of technological processes and devices...*



MACHINE LEARNING APPLICATIONS



Multilayer Back-propagation networks

Localization of material defects
(especially for cases of complex structures)

Convolutional neural networks (CNN)

Condition monitoring of rotating mechanisms
(bearings, gearboxes, etc.)

AE SOURCE LOCALIZATION *(IDENTIFICATION)* PROBLEM

- where to place sensors?

  (to enable good location results in evaluated area...)

- location method?

  (crossing of hyperboles, triangulation algorithm, database searching, ANN...)

- sensitivity to experimental and numerical errors?

  (robust method of arrival time estimate, shortest path finding...)

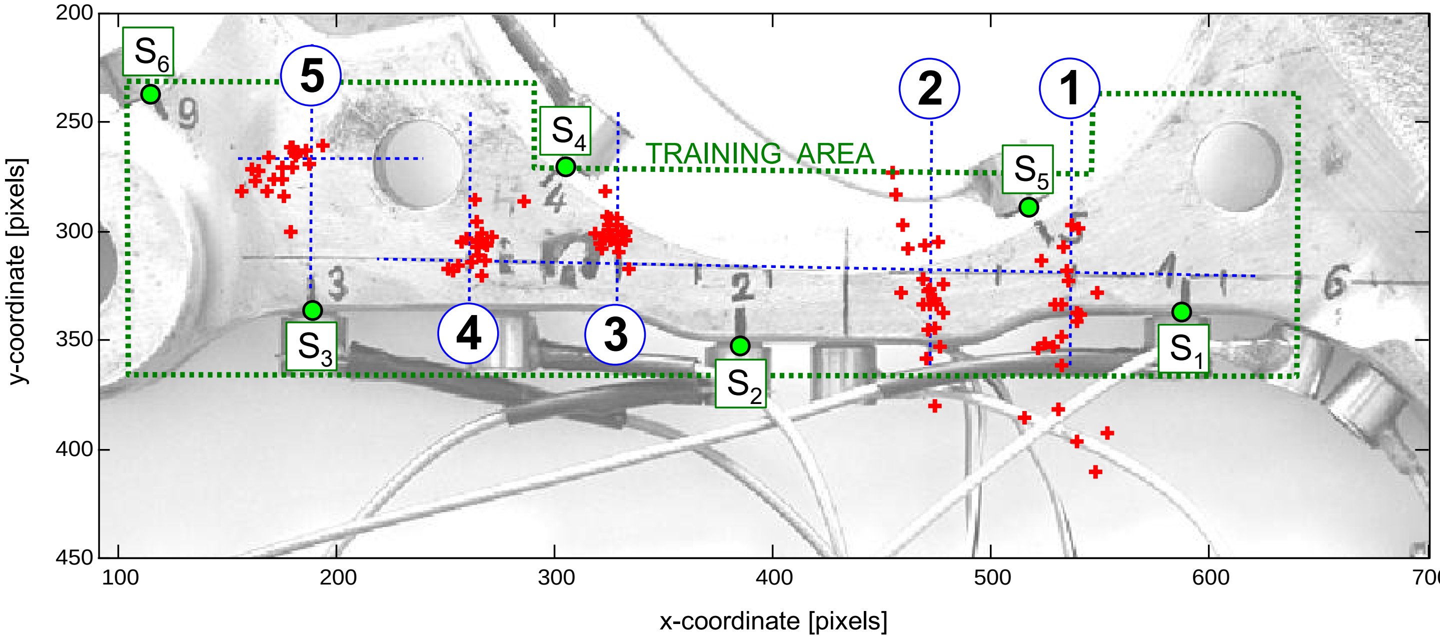
- ambiguity?

  (wheather the selected configuration of sensors generate unique chronologies of arrivals...)

Diversity of AE source localisation errors

How to explain diverse sensitivity to experimental and numerical errors?

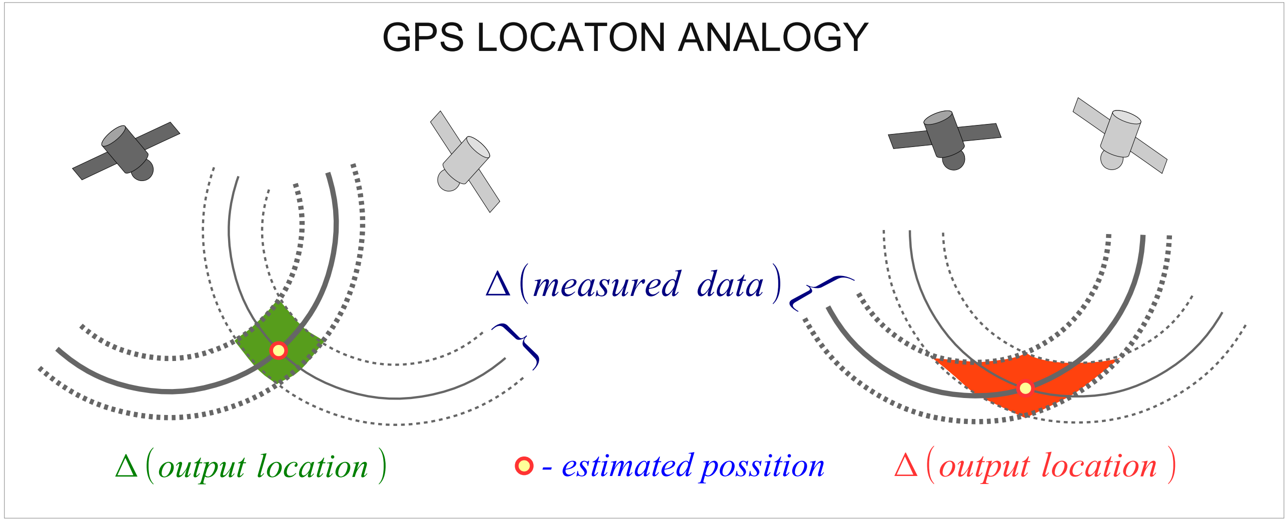
- artificial neural network pen-tests localization results
- five sets of 25 pen-tests at the original locations 1-5
  (cross points of blue dashed lines)



Geometric Dilution of Precision (GDOP)

GDOP - dimensionless parameter modeling expected location accuracy and how the errors in the measurement will affect the final location estimation

$$GDOP = \frac{\Delta\left(output\ location\right)}{\Delta\left(measured\ data\right)}$$



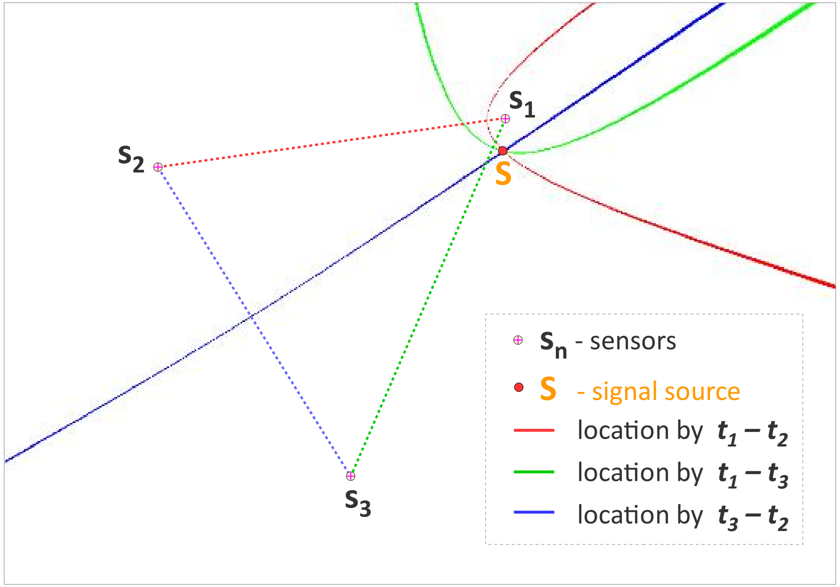
Well spaced satellites
Good GDOP - low uncertainty of position

Poorly spaced satellites
Poor GDOP - high uncertainty of position

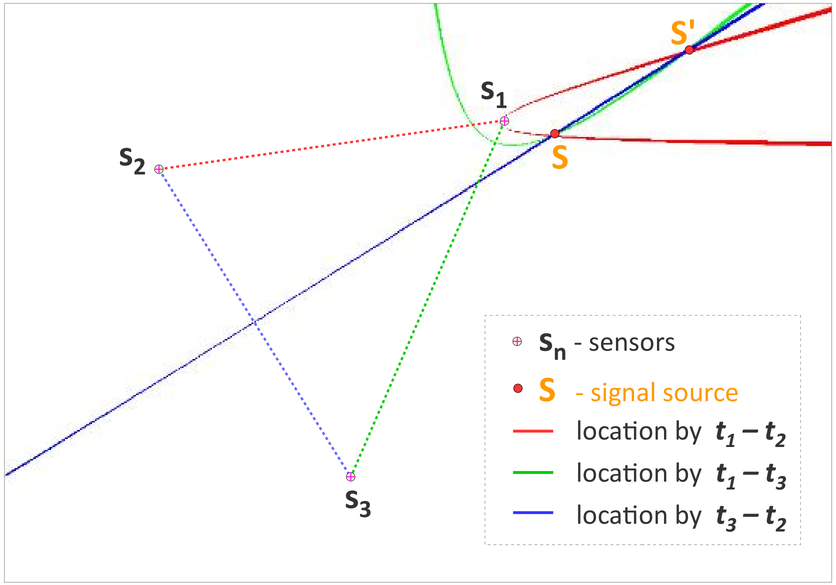
BURST ACOUSTIC EMISSION (planar localization)

Demonstration of AE source localization possibilities using signal arrival times to sensors (t_1, t_2, t_3)

Δt 2D location method by intersection of hyperboles



Δt 2D location method by intersection of hyperboles

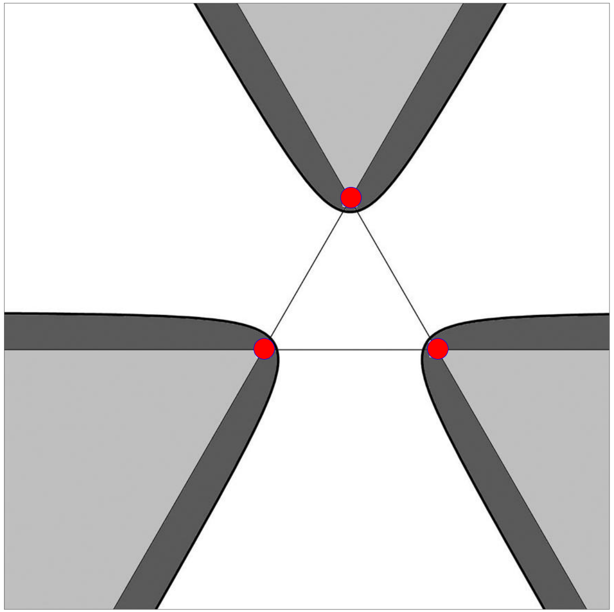


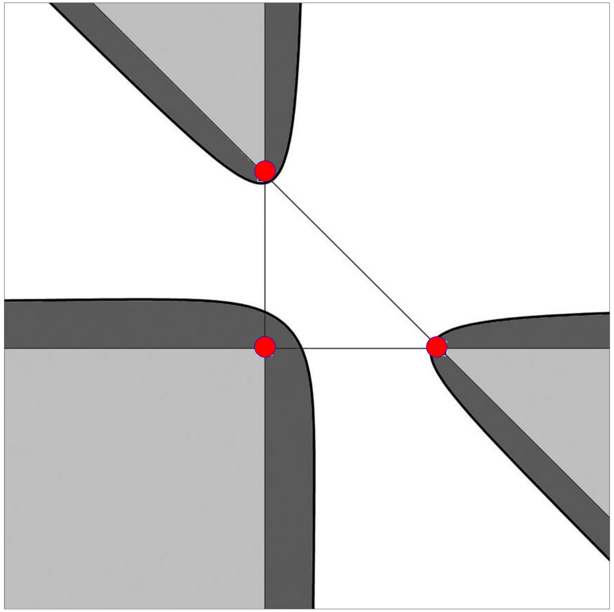
Ambiguity of 2-D AE source location using 3 AE transducers

(any AE source in dark grey area has the same time-differences corresponding to existing source in light grey area and vice versa)

EXAMPLE OF TWO TRIANGLE CONFIGURATIONS OF TRANSDUCERS

(rectangular and equiangular)





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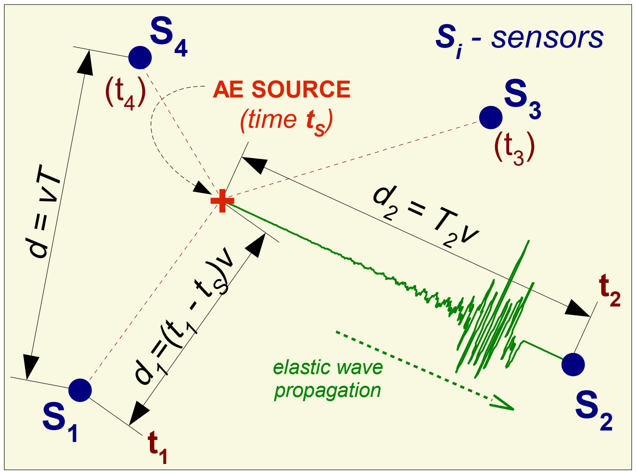
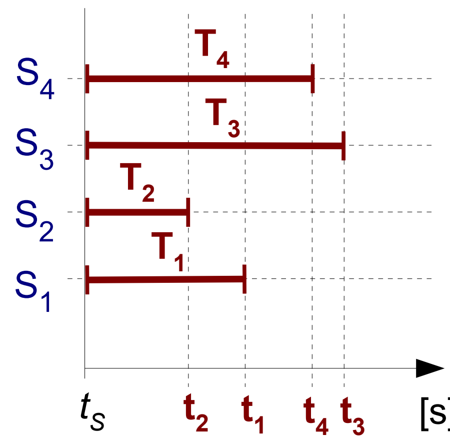
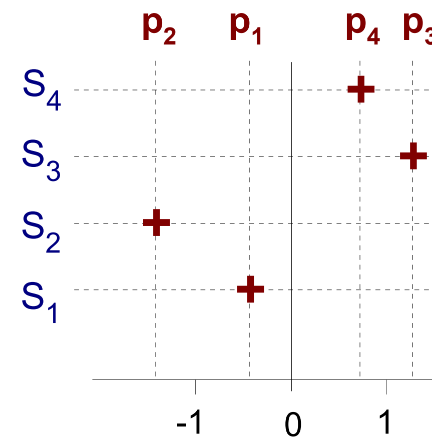
Arrival-time chronology parametrization



ARRIVAL TIMES



ARRIVAL-TIME PROFILE



Notation:

t_s - time of AE source inception
t_i - signal arrival time
T_i - signal propagation time to sensor Si
T - normalization period
d_i - the distance between AE source and sensor
d - the distance between two appropriately selected points corresponding to T
v - elastic wave velocity

Arrival-time profile $P=(p_1,\ldots,p_N)$ definition:

$$\boldsymbol{p_i} = \frac{\boldsymbol{T_i} - \frac{1}{\boldsymbol{N}}\sum_{j=1}^{\boldsymbol{N}} \boldsymbol{T_j}}{\boldsymbol{T}} = \frac{\boldsymbol{t_i} - \boldsymbol{t_S} - \frac{1}{\boldsymbol{N}}\sum_{j=1}^{\boldsymbol{N}} (\boldsymbol{t_j} - \boldsymbol{t_S})}{\boldsymbol{T}} = \frac{\boldsymbol{t_i} - \frac{1}{\boldsymbol{N}}\sum_{j=1}^{\boldsymbol{N}} \boldsymbol{t_j}}{\boldsymbol{T}}$$

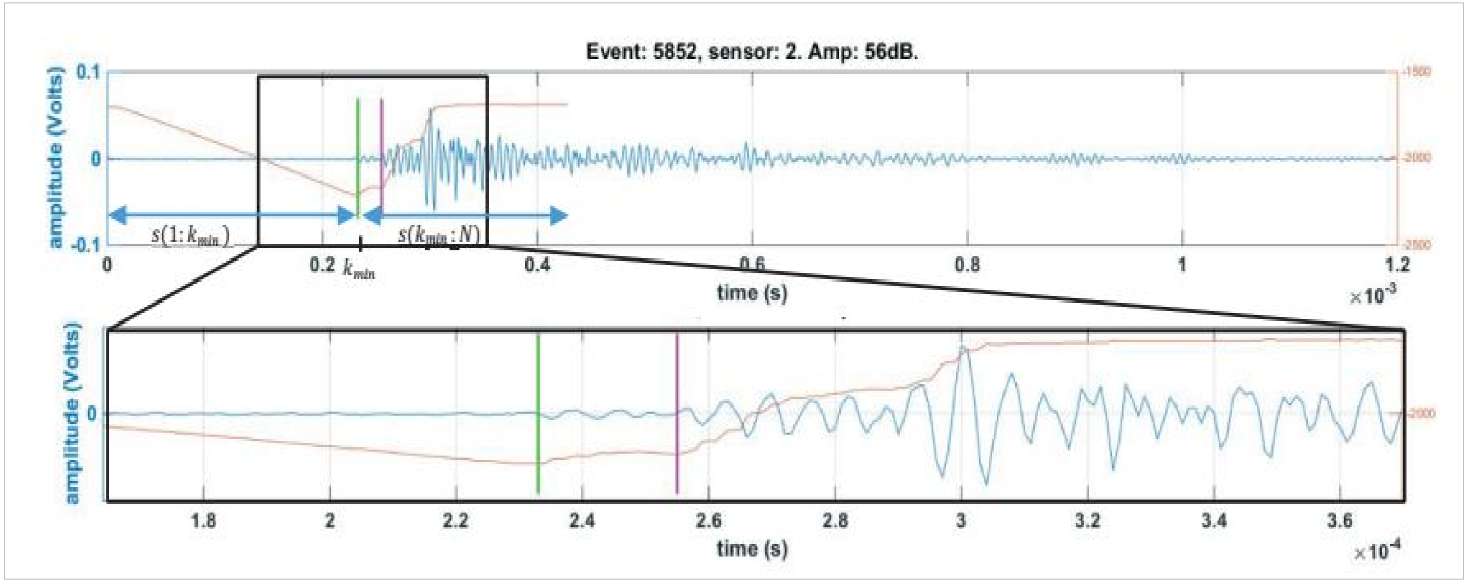
Independent on wave velocity and scale changes...

(AE) signal onset estimate

Akaike information criterion (AIC) picker

The idea is to compare the difference between standard deviation passed and forthcoming at each point of the signal:

$$AIC(k) = k \cdot \log[STD(s(1:k))] + (N-k) \cdot \log[STD(s(k:N))]$$



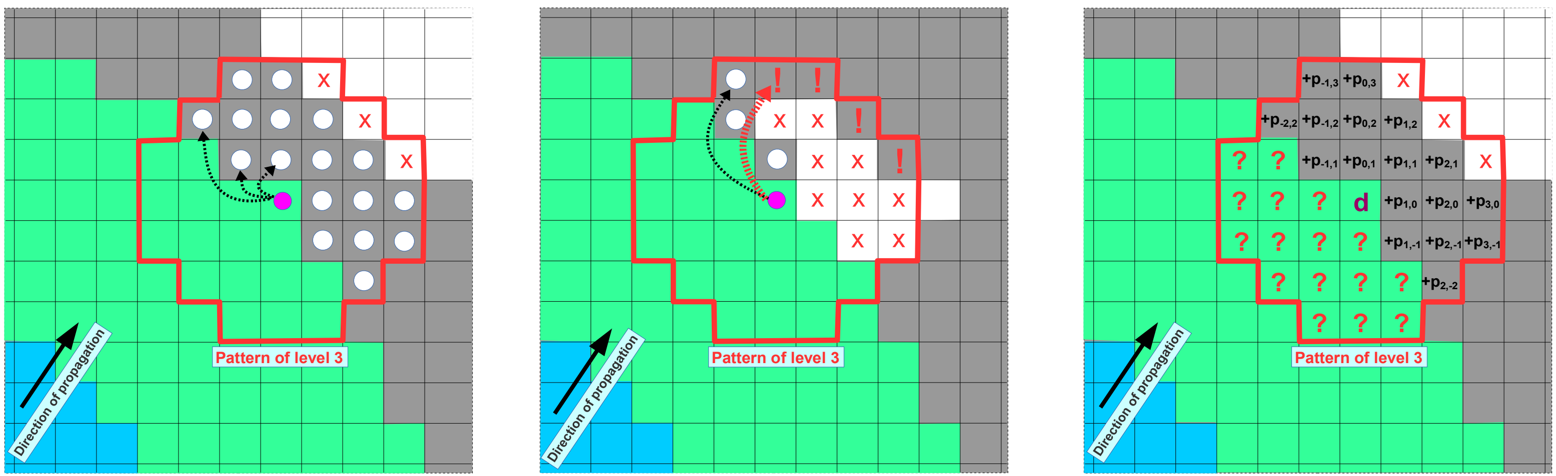
Typical acoustic waveform (blue) and results of two different picking techniques.
Fixed threshold (magenta), AIC function (orange) and its minimum (green).

Source: A. Boniface at al., COMPARISON OF LOCALIZATION STRATEGIES OF DAMAGE IN CONCRETE BY AE. (J AE, Vol. 33, 2016)

Shortest ways finding in discrete bodies („Flooding“ propagation)

The method was inspired by **Huygens' principle** as a simple to implement alternative suitable for **discrete bodies** derived from 2D or 3D bitmap pictures. Such approach also enables the **tracing of elastic waves** propagating through bodies of **complicated shape.**

FLOODING PROPAGATION | **A HOLE OVER-JUMPING PROBLEM** | **DISCRETE DISTANCE COMPUTATION**



- Not reached **body** pixels
- Already **reached** pixels
- **Actual** pixels *(wavefront points)*
- **Out-of-mass** pixels
- **Potentially next** pixels
- **Next** pixels
- **Over-jumping** problem
- **Default** pixel

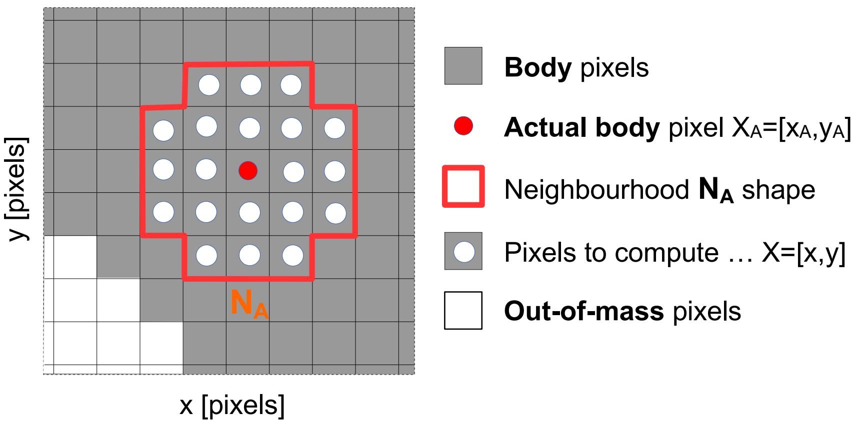
$$p_{i,j} = \sqrt{i^2 + j^2}$$ - *distance of pixel [i,j] from the center point of „next pixels“ pattern*

if $(d+p_{i,j}) < d_{ACT}$ *(actual value stored in pixel [i,j])* ***then*** $d_{ACT} := (d+p_{i,j})$

LOCATION ANALYSIS *(detecting of critical areas)*

- **Similarity Map**
  - *illustrates the topology of time-differences space*
  - *shows small regions of pixels with similar time-differences*

- **Location Ambiguity Map *(LAM)***
  - *Small numbers detect problematic areas of pixels for which somewhere exist points with nearly the same signal arrival chronology.*

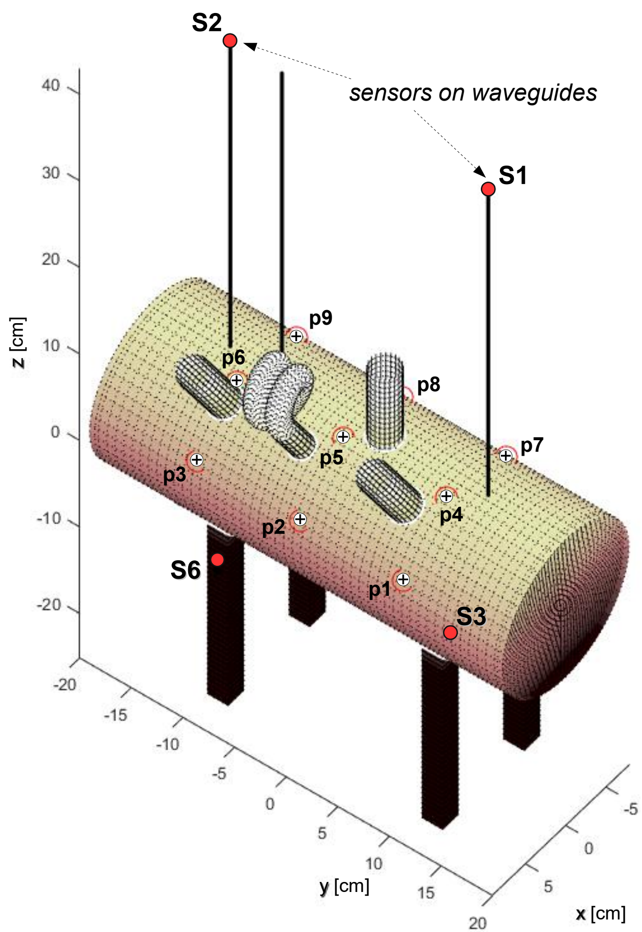


$P(X)$ *is ATP for pixel* X

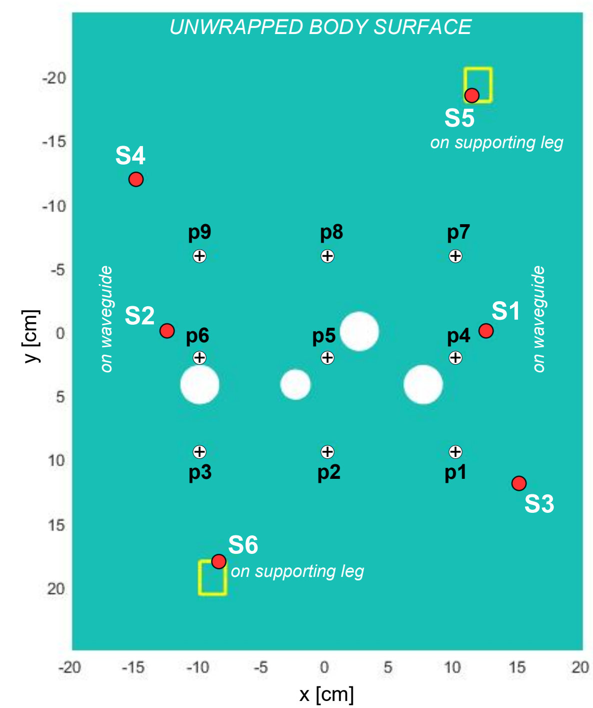
and $d_E(\dots,\dots)$ *is Euclidean distance*

$$LAM(X) = MEAN\left\{ \frac{d_E(P(X),P(X_i))}{d_E(X,X_i)} \;\middle|\; d_E(P(X),P(X_i)) < tol. \right\}$$

Experimental setup scheme

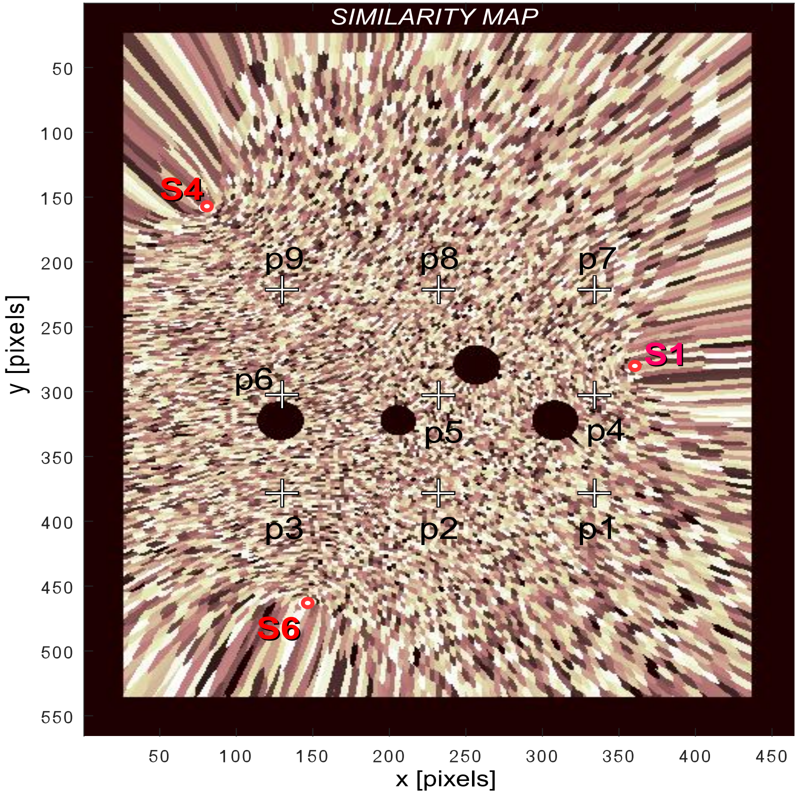


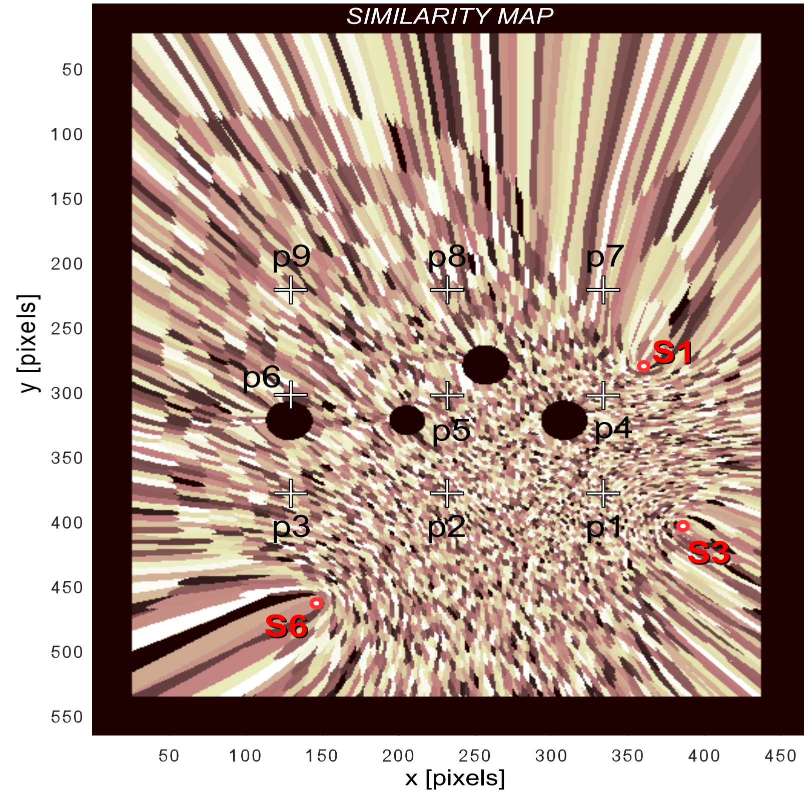
Goal: To predict the accuracy of AE source location for selected group of sensors.
The "numerical forecast" is then reviewed with nine sets of pencil- lead breaks.



Similarity maps

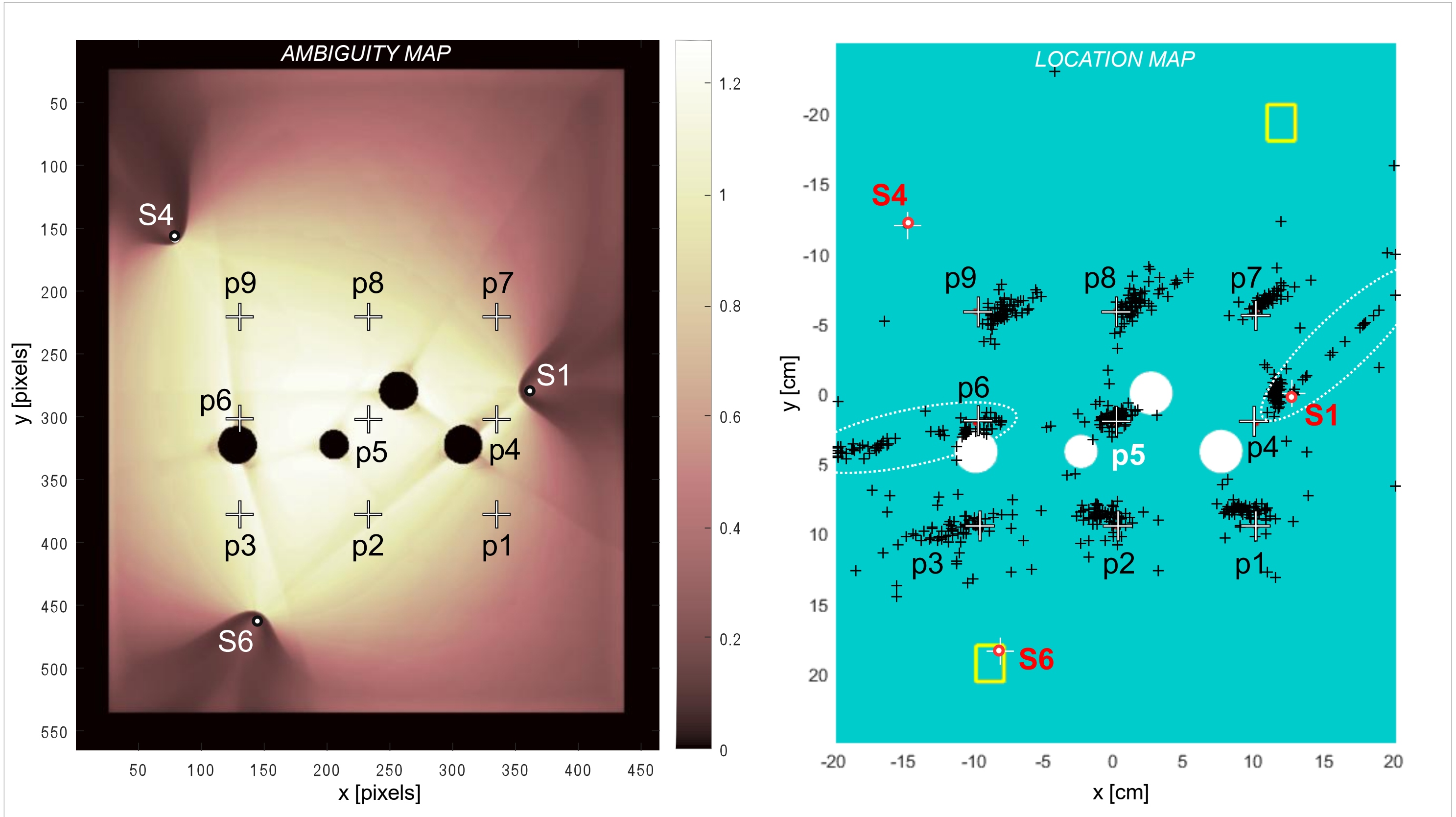
(for two selected typical combinations of three sensors)





Results of experimental verification

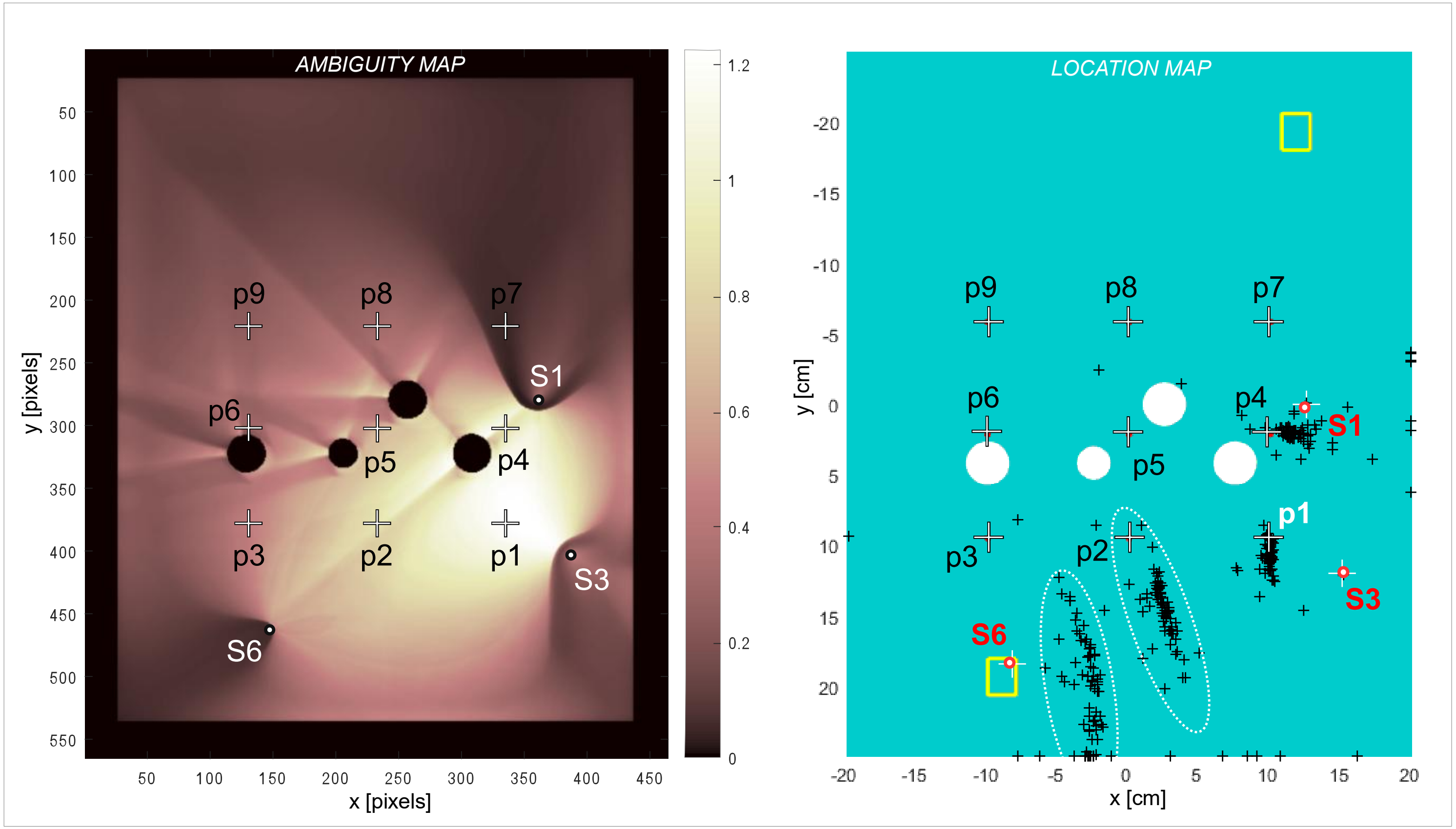
(localization of nine sets of pencil-lead breaks)



Location Ambiguity Map versus location results for sensor group 1-4-6.

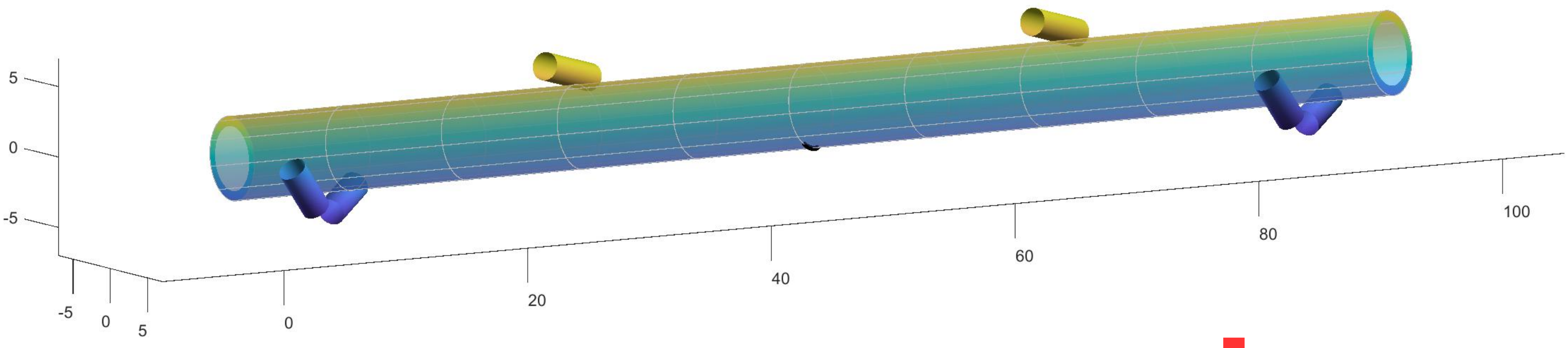
Results of experimental verification

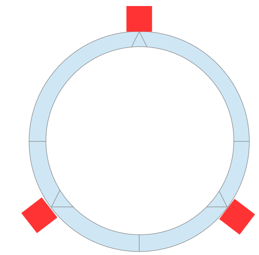
(localization of four sets of pencil-lead breaks)



***L**ocation **A**mbiguity **M**ap versus location results for sensor group **1-3-6**.*

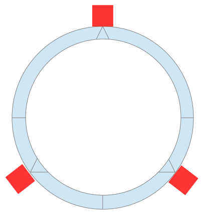
Sensor configuration design

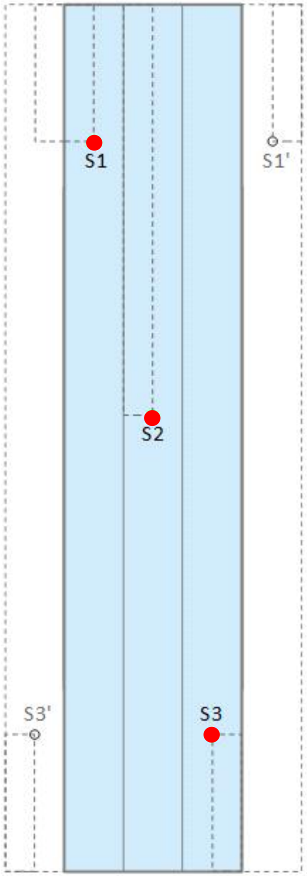


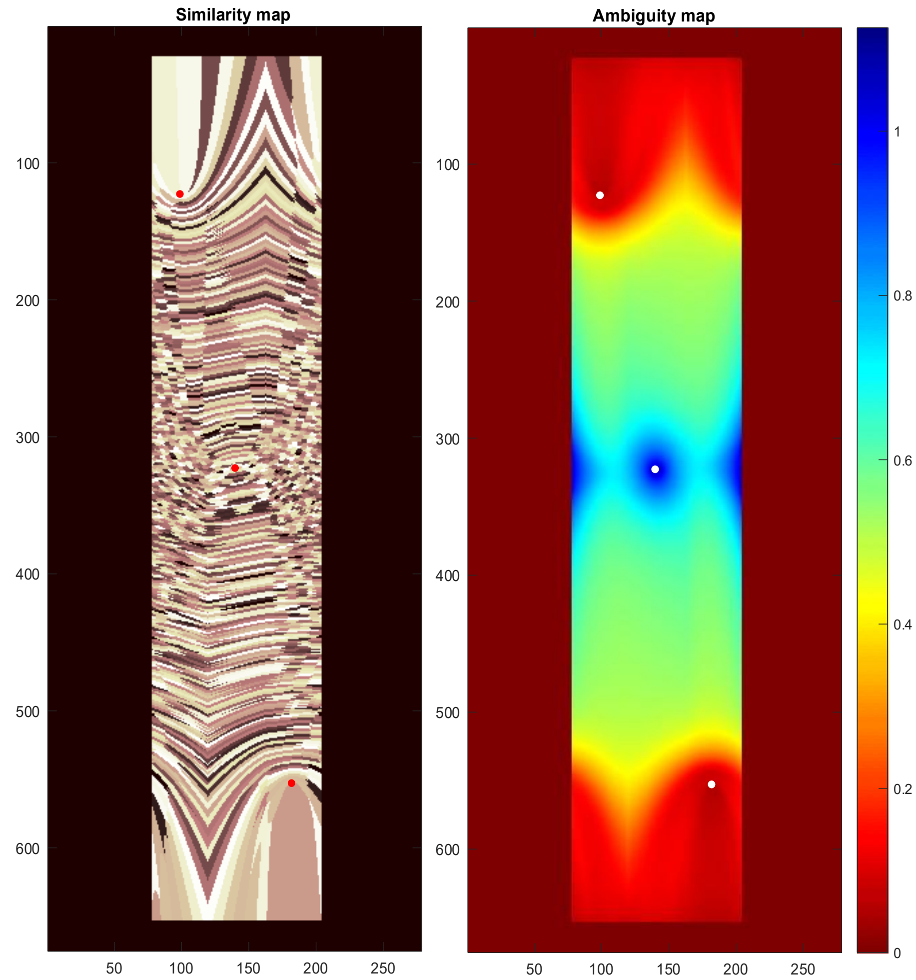


How many sensors needed?

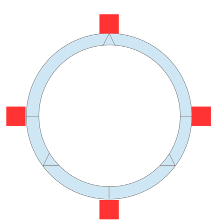
Sensor configuration analysis

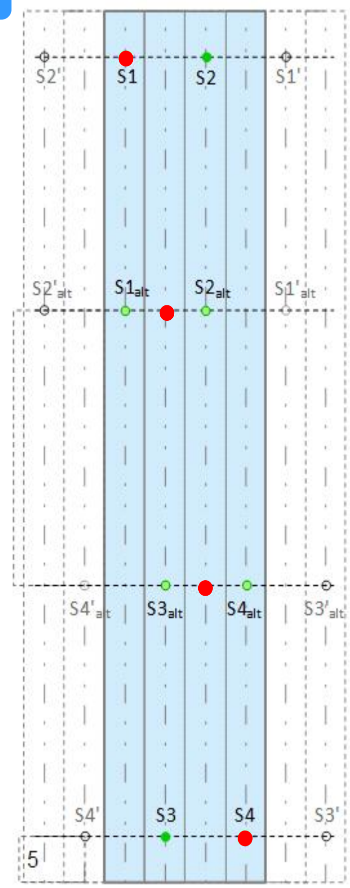


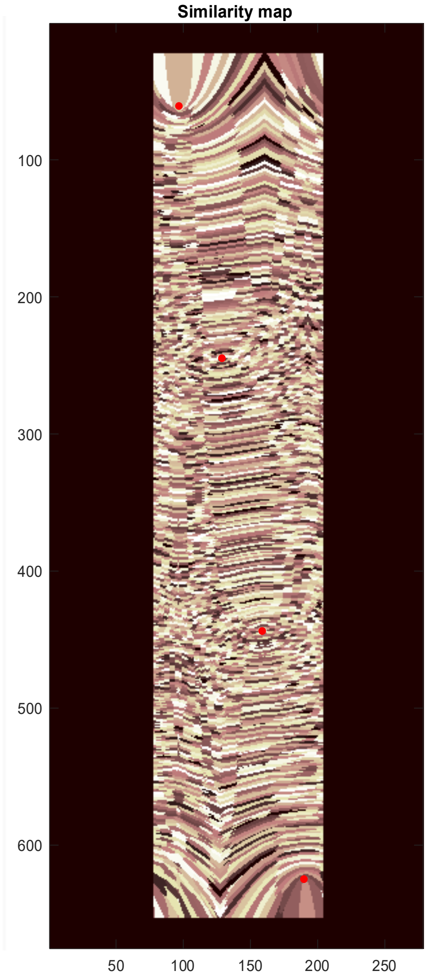


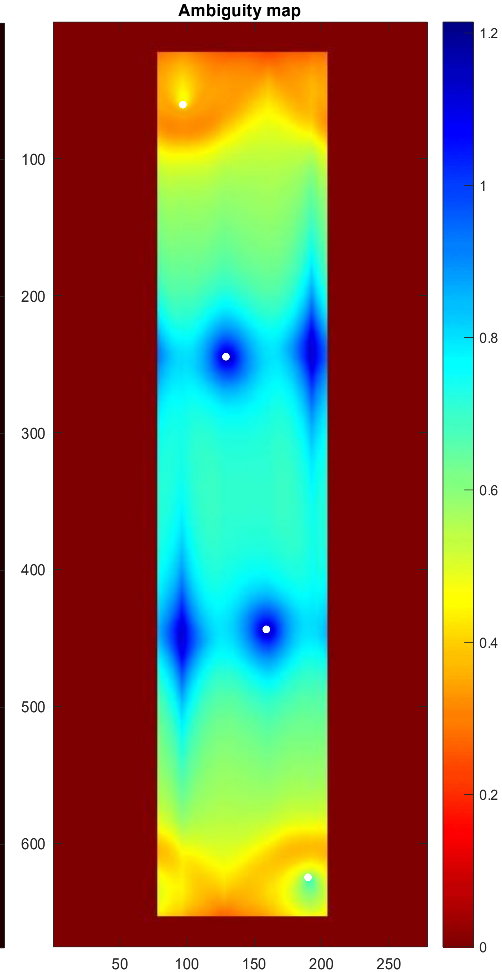


Sensor configuration analysis

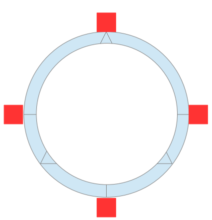


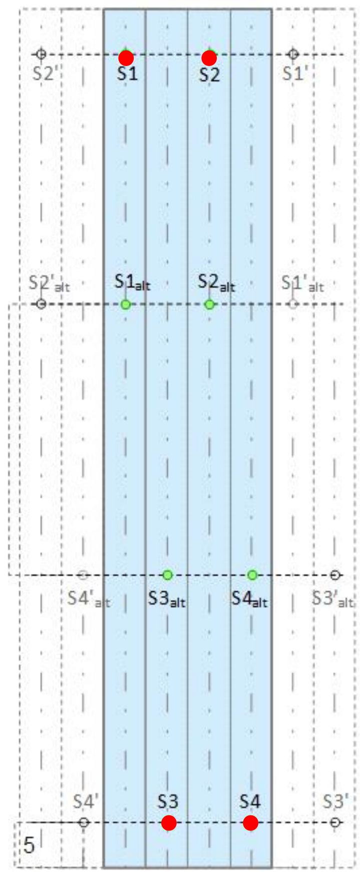


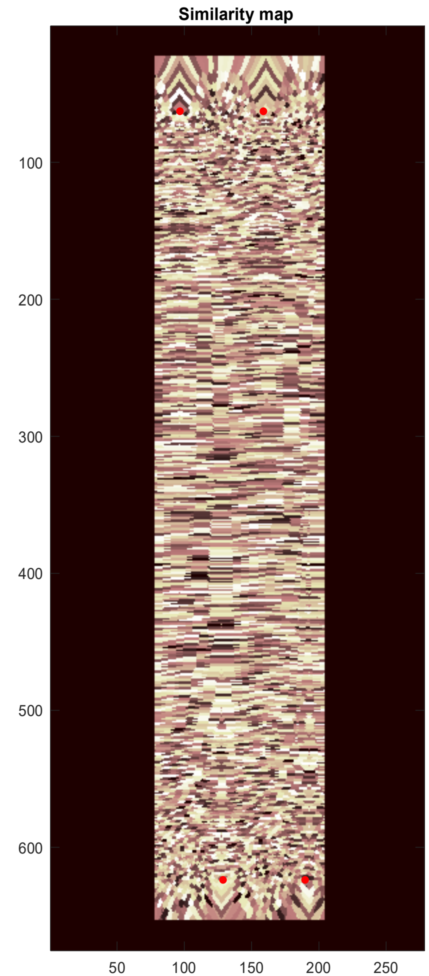


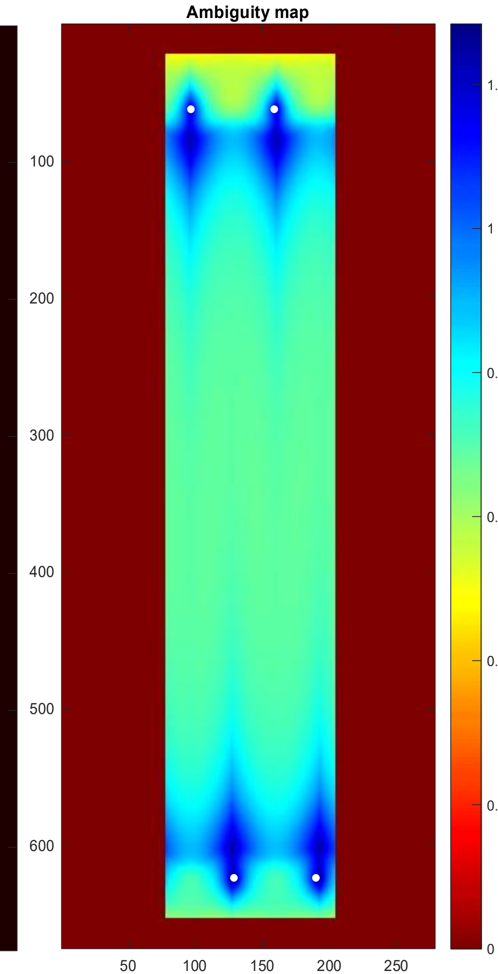


Sensor configuration analysis

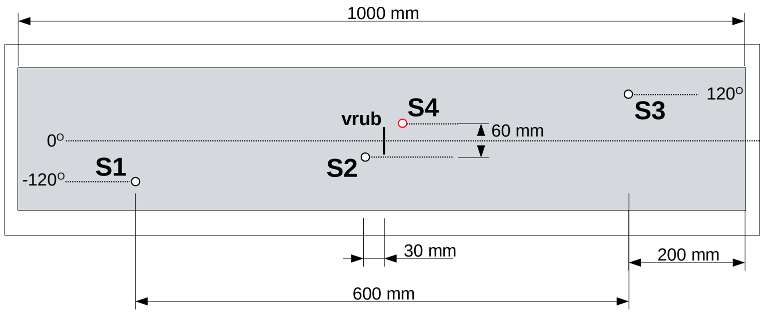


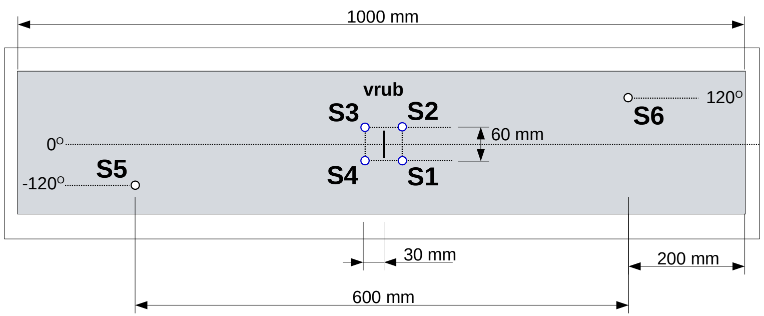




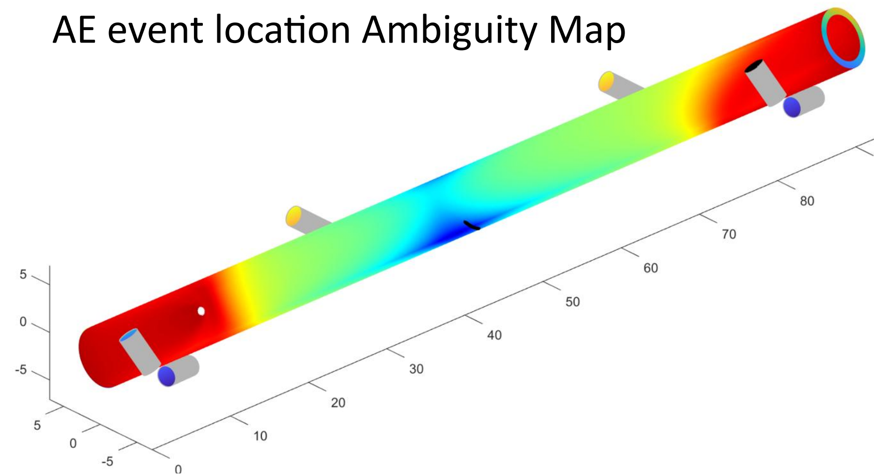


Optimization of sensor placement

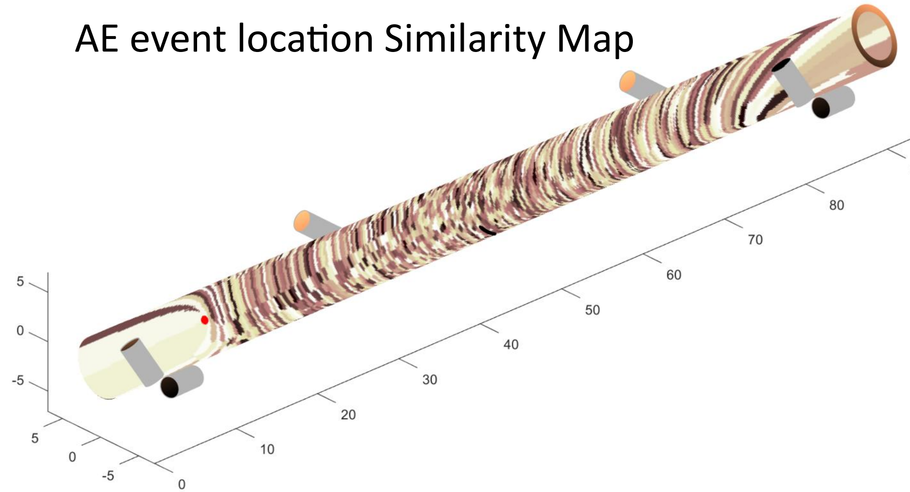




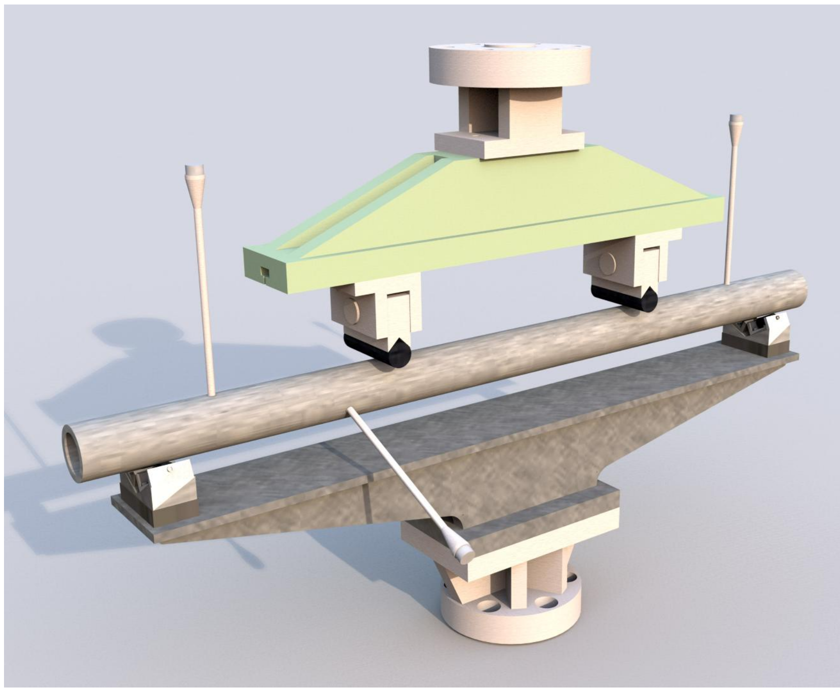
AE event location Ambiguity Map

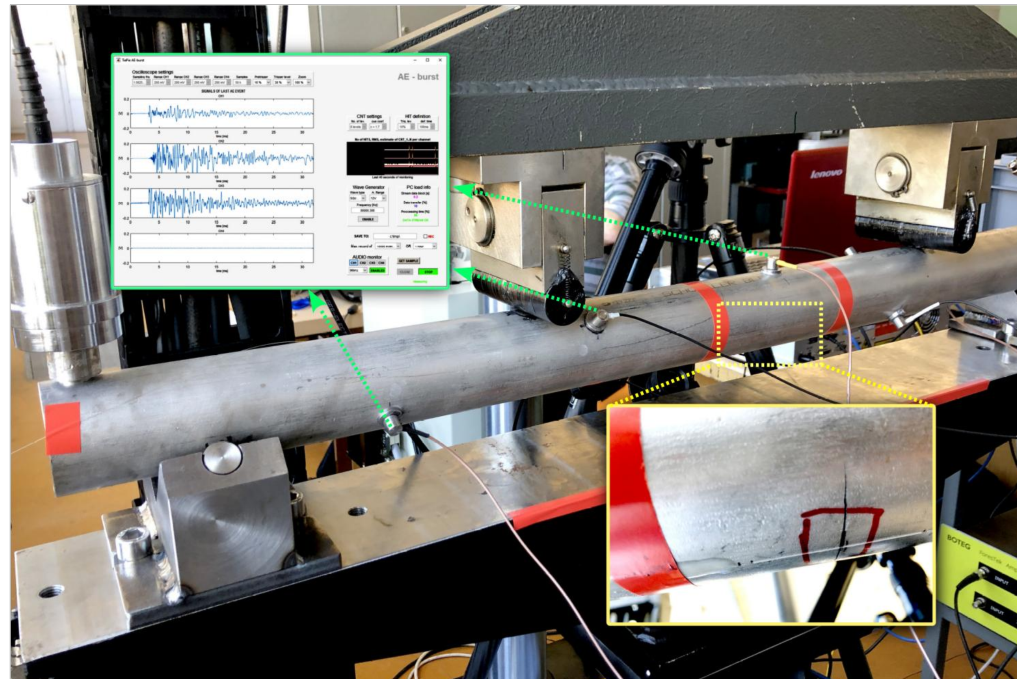


AE event location Similarity Map

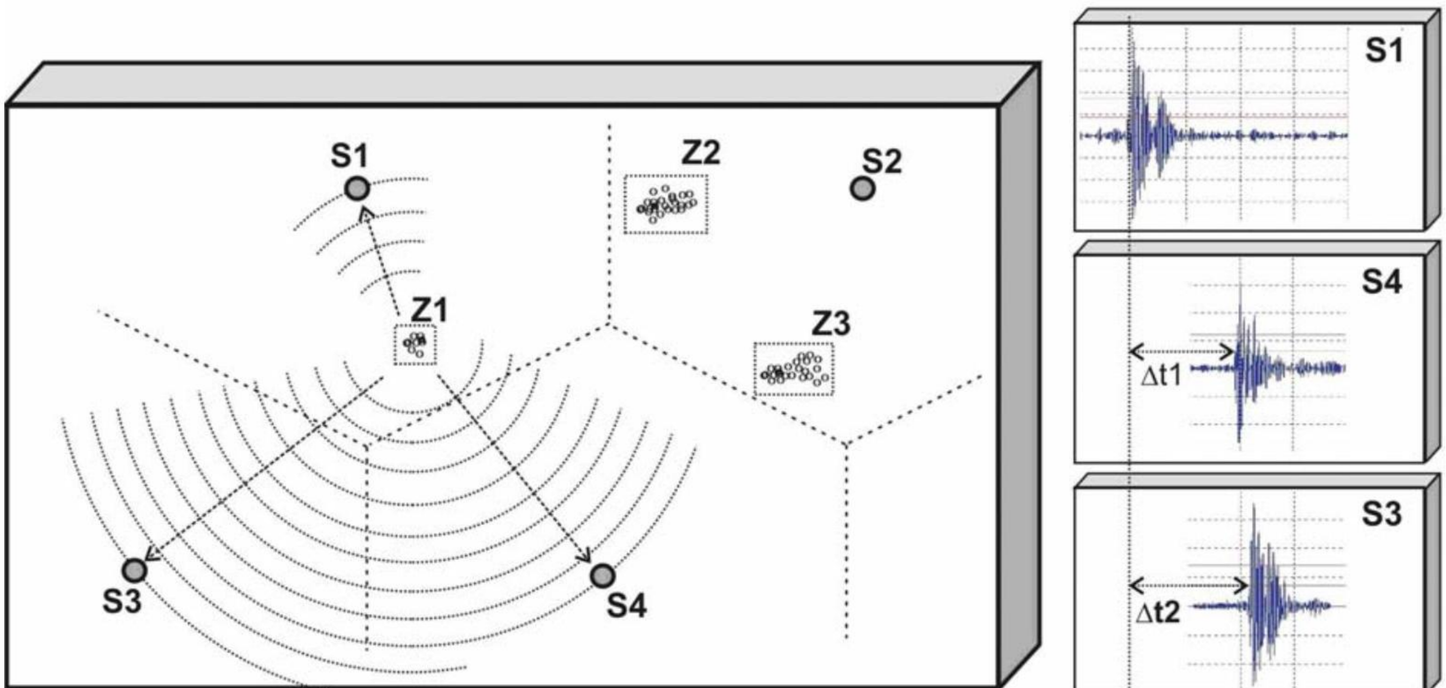


EXPERIMENTAL SETUP

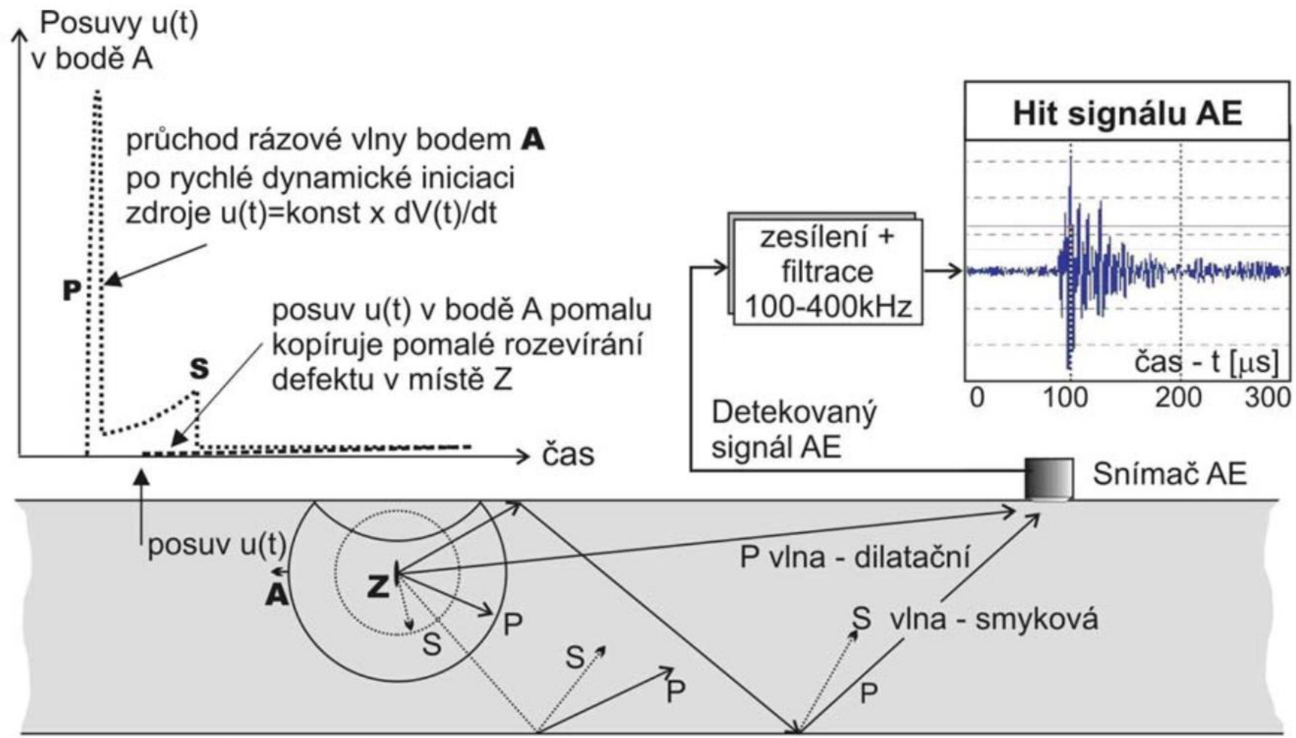




UČEBNICE AE



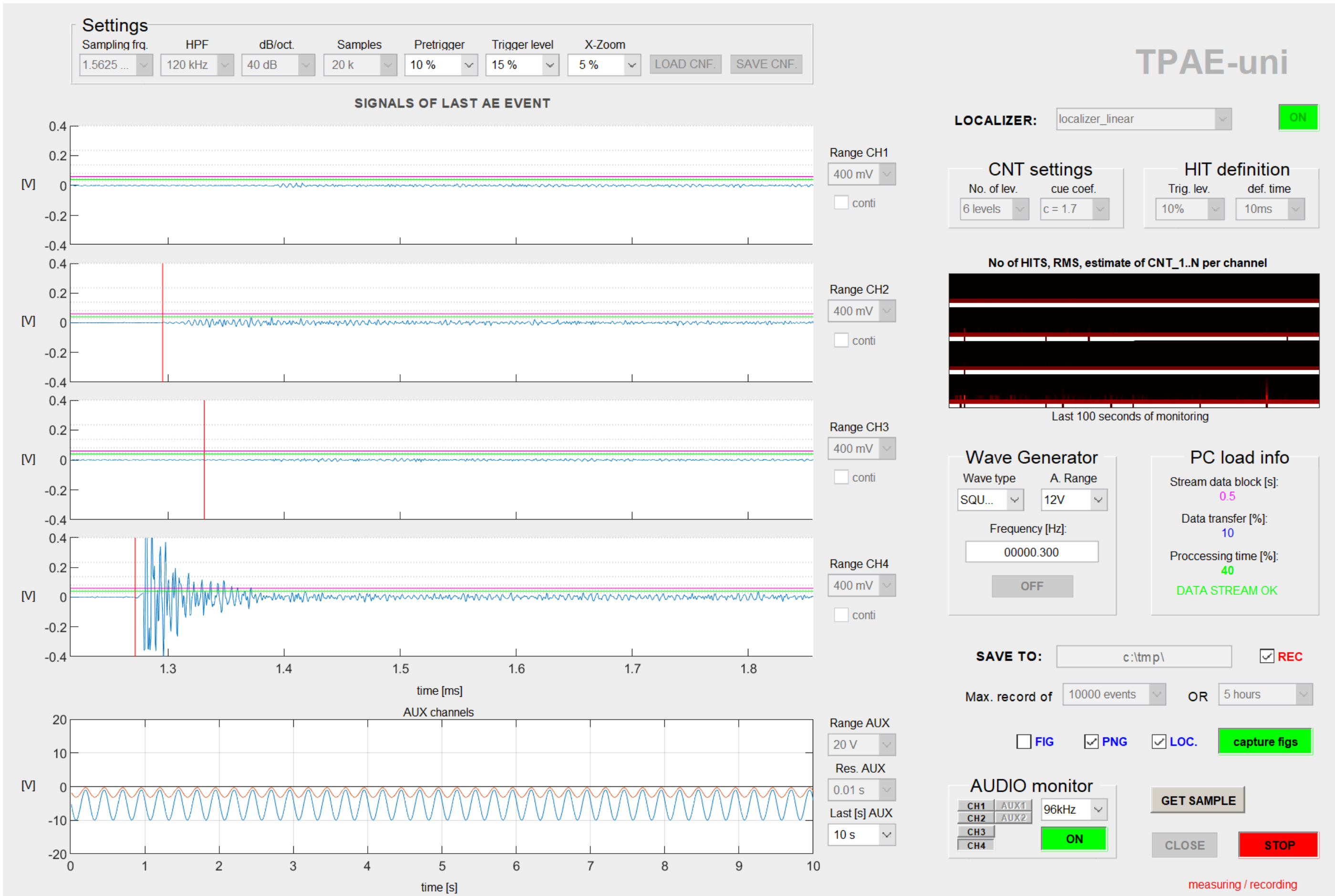
Obr.1.3: Měřicí síť AE a princip planární (rovinné) Δt lokalizace událostí zdroje akustické emise Z1



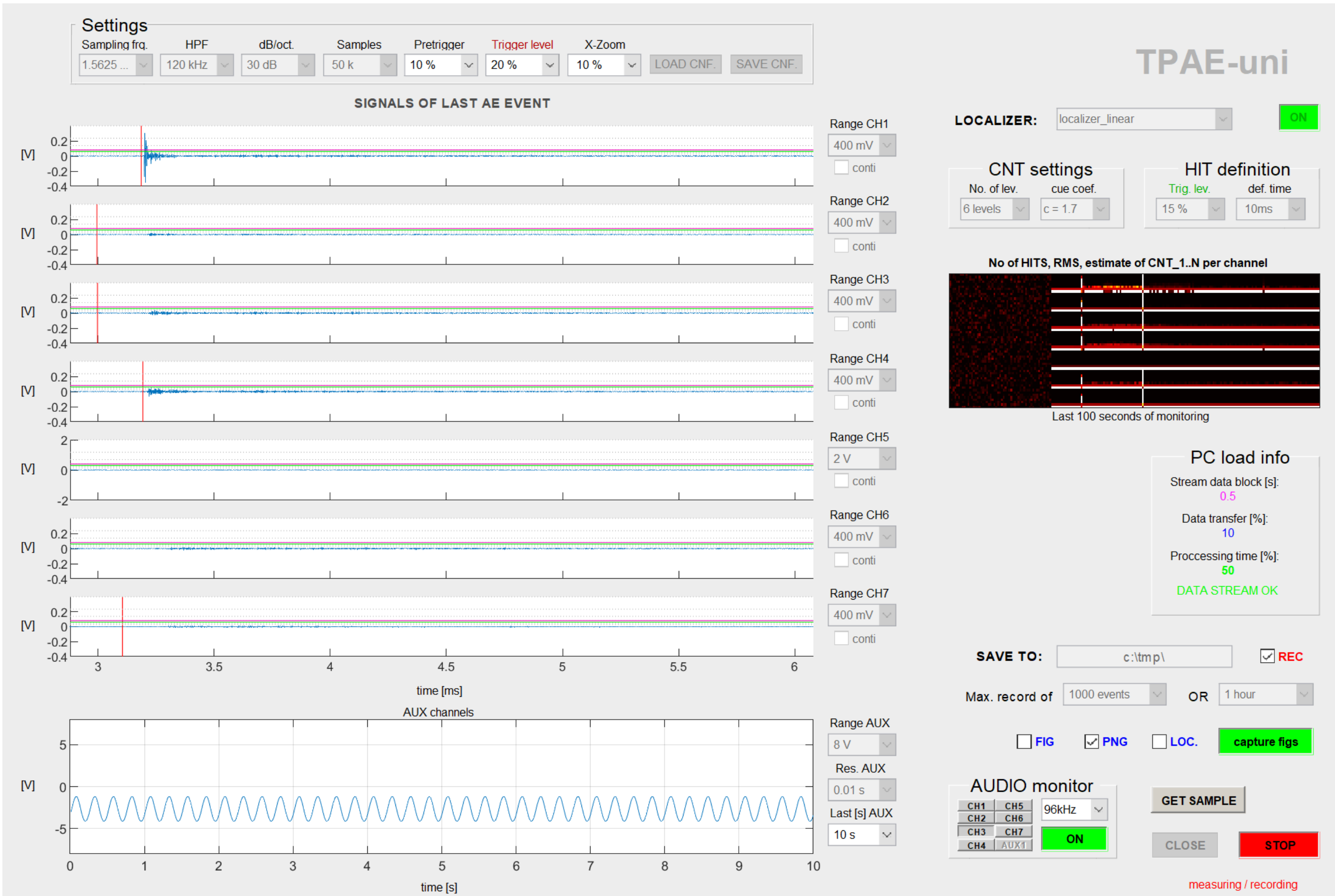
Obr.1.4: Princip jevu a citlivosti detekce akustické emise

Ze zdroje AE (Z) se šíří počáteční kulové vlnoplochy dilatační P a smykové S vlny, které můžeme zobrazit jako svazek paprsků, jež se následně v tělese šíří, odrážejí a rozpadají. Vytváří tak výslednou odezvu zdroje Z detekovaného v místě snímače AE.

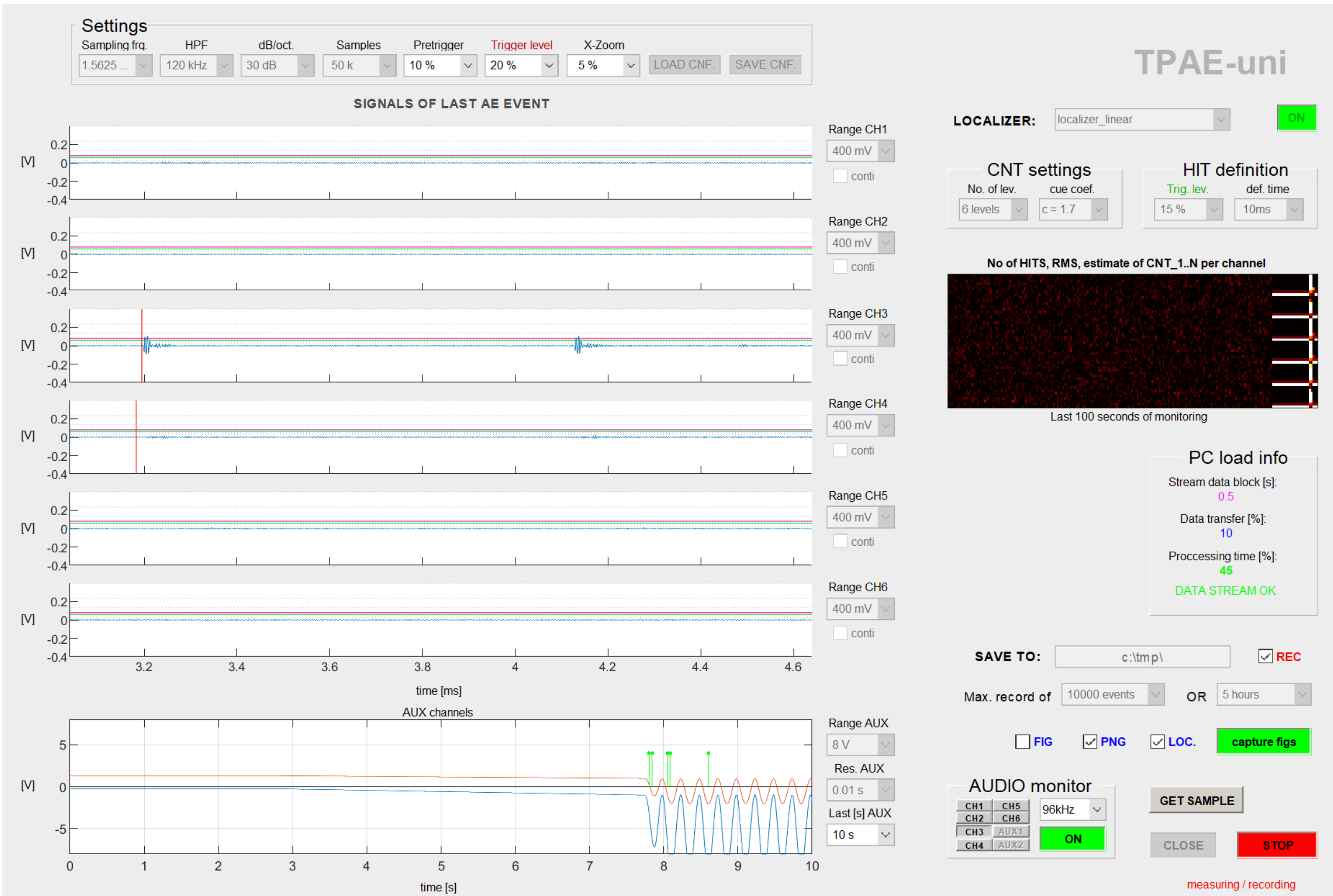
REAL AE SIGNALS



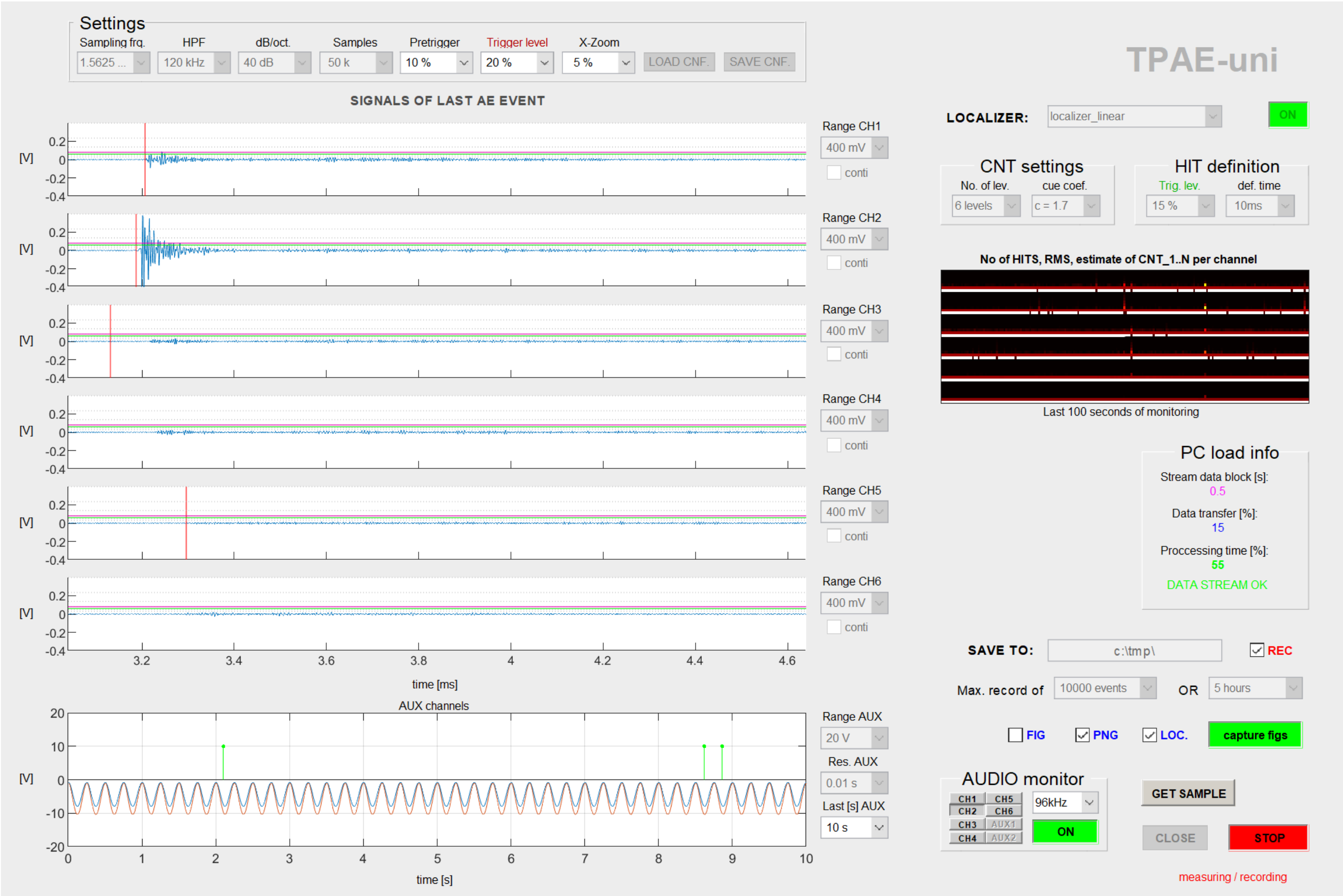
REAL AE SIGNALS



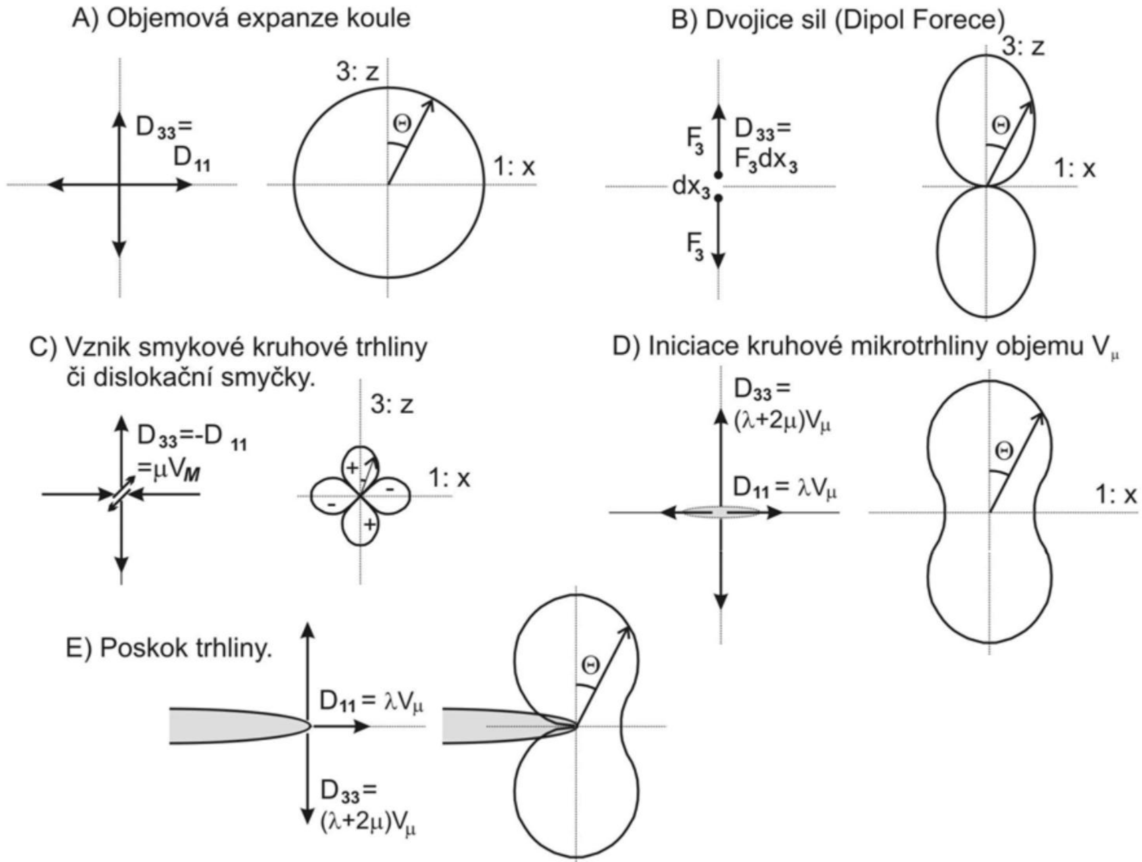
REAL AE SIGNALS



REAL AE SIGNALS

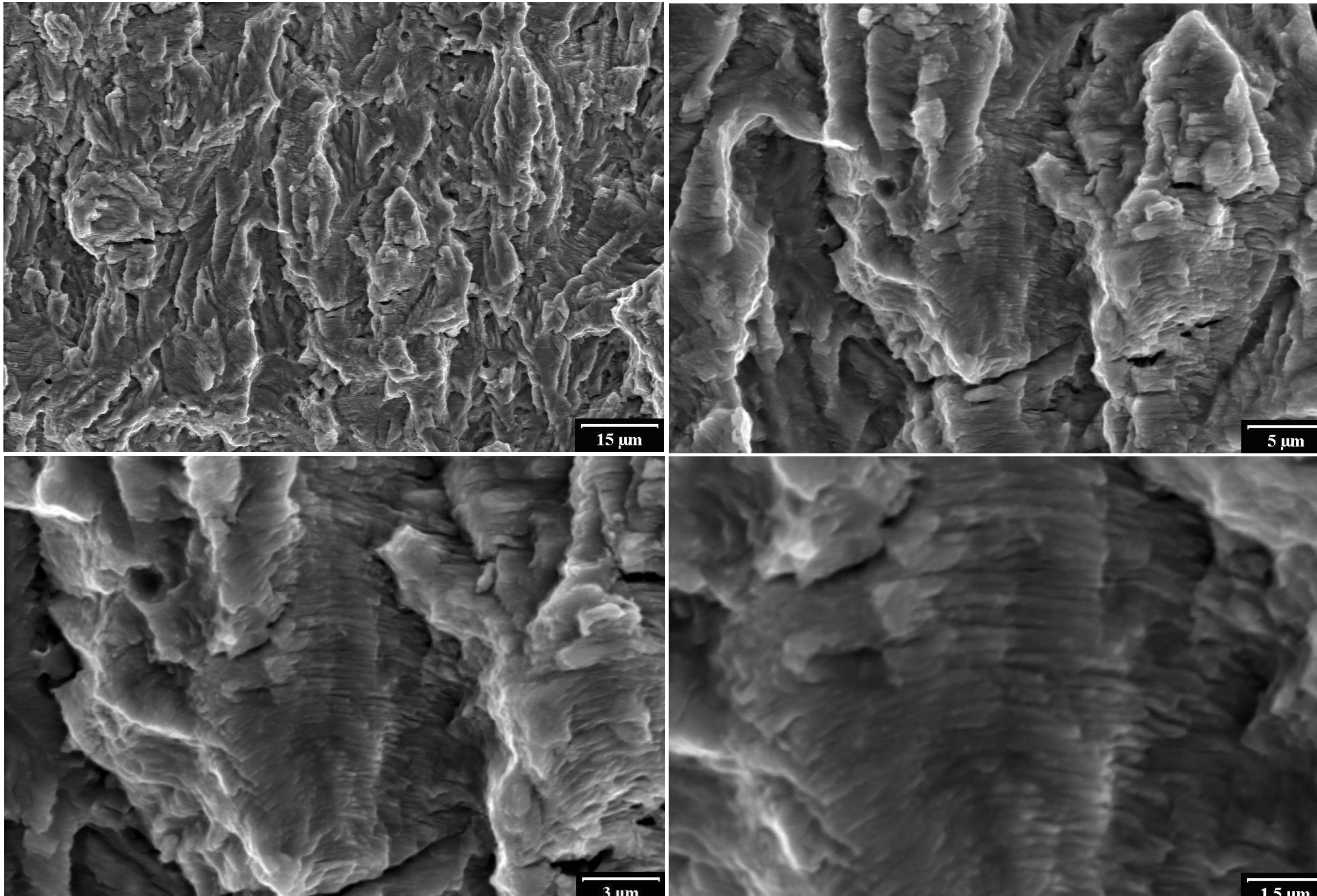


UČEBNICE AE



Obr. 2.4 Směrové vyzařovací charakteristiky vybraných typů zdrojů AE. Rozložení velikosti posuvů ve směru paprsků na kulové vlnoploše v závislosti na směru (úhlu Θ).

Images of the fracture surface



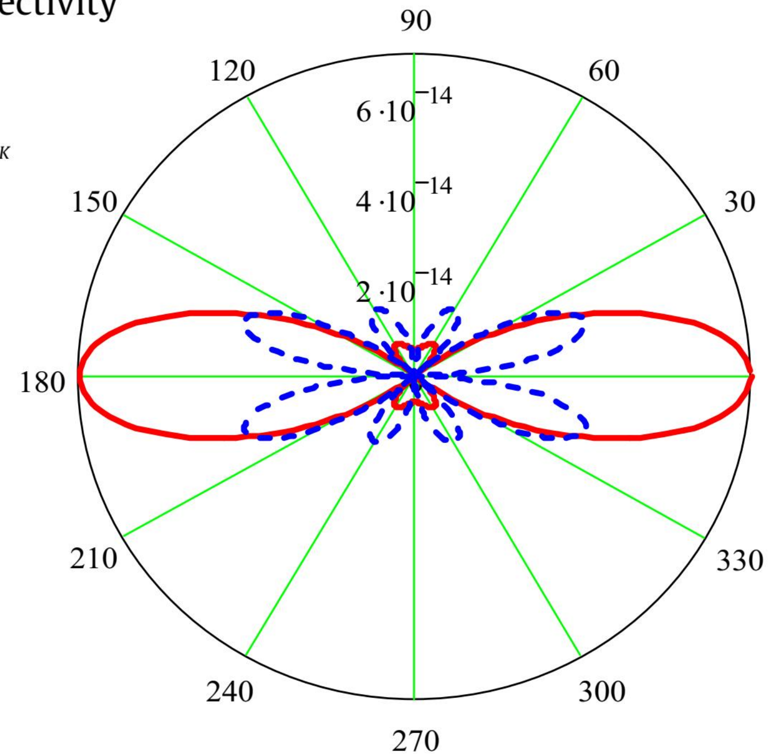
Acoustic emission from finite two-dimensional cracks: Directivity functions and frequency spectra

Victor V. Krylov

Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

Variable directivity?

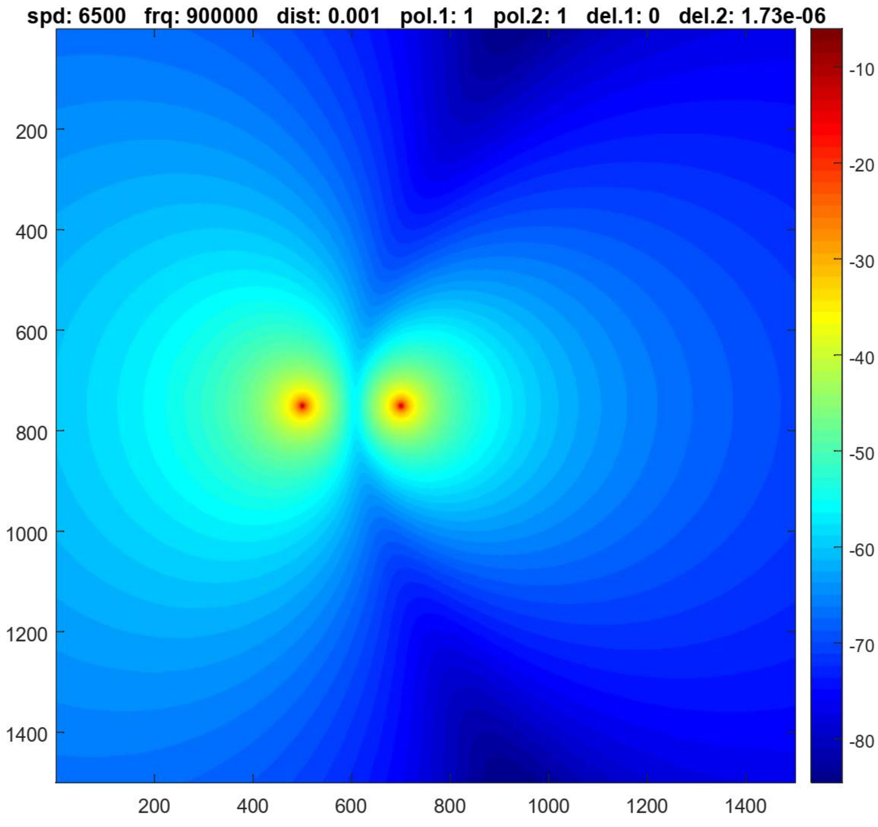
Theoretical model?

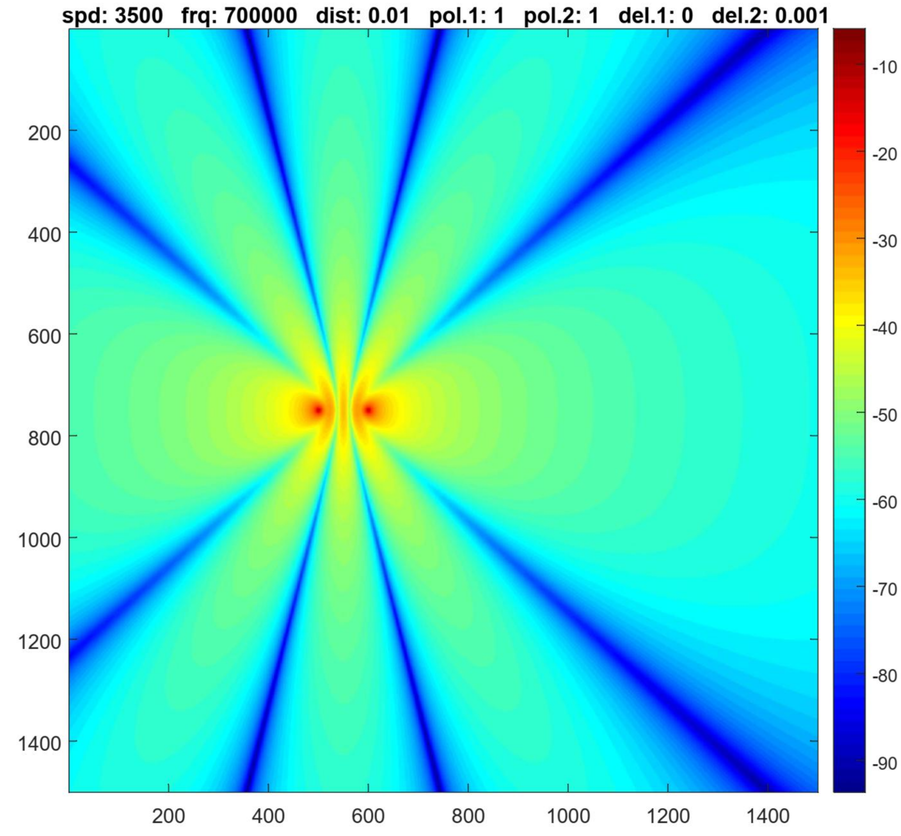


Angular dependence of crack radiation

Fig. 5. Angular dependencies of longitudinal waves (solid curve) and shear waves (dashed curve) radiated by an opening crack at frequency $f = 450$ kHz.

Model of two sinusoidal sources





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Thank you for your attention...