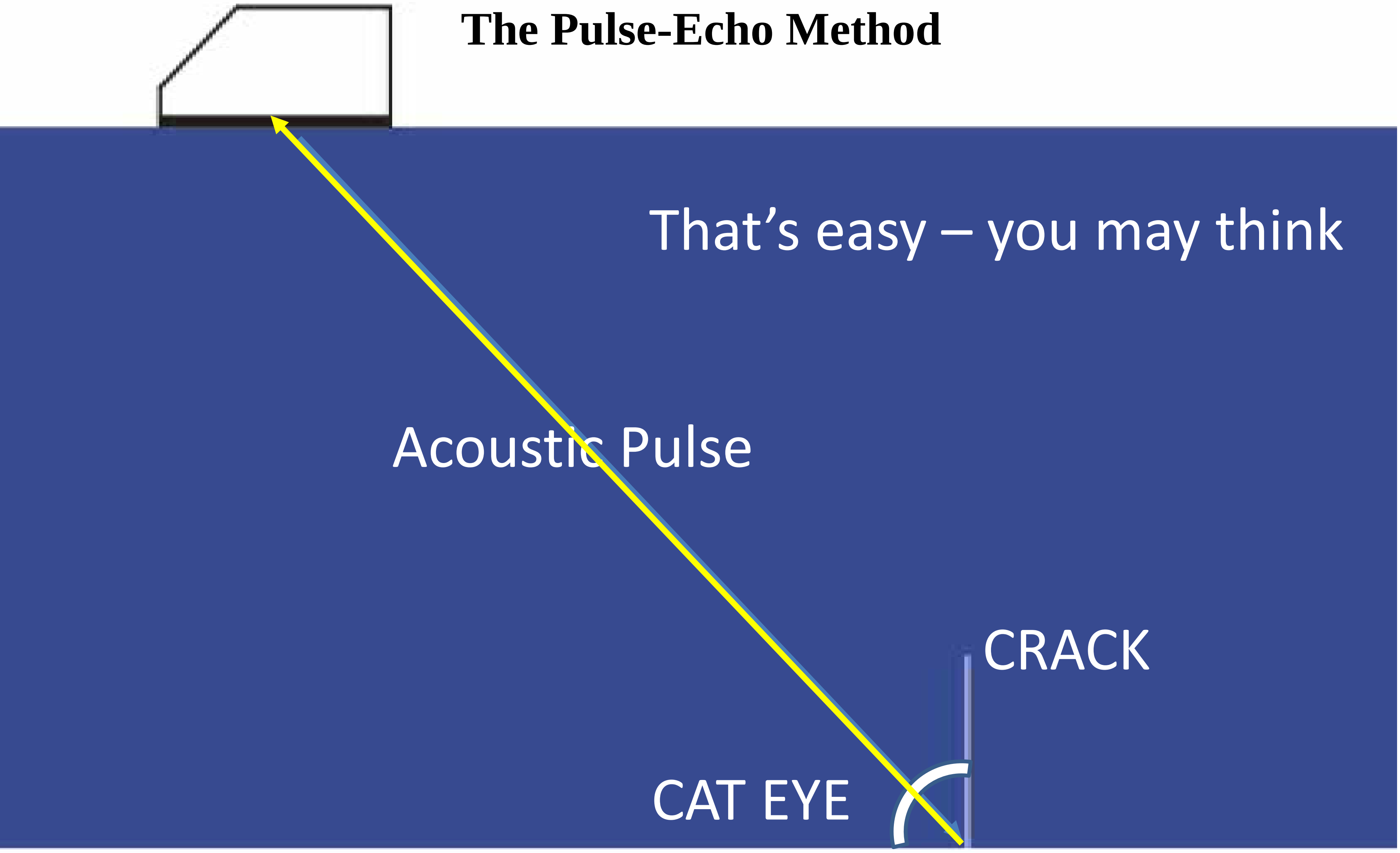
NDT&E Methods: UT

ULTRASOUND –

An Exciting Technology not just for NDT

NDT&E Methods: UT

The Pulse-Echo Method



NDT&E Methods: UT

6.	NDT&E: Introduction to Methods
6.1.	Ultrasonic Testing: Basics of Elasto-Dynamics
6.2.	Ultrasonic Testing: Ultrasound Generation
6.3.	The Pulse-Echo Method
6.4.	UT-Systems: Transducer, Instrument, Manipulator
6.5.	Current Developments
6.6.	Case Studies by Movies

NDT&E Methods: UT

The Pulse-Echo Method

STRUCTURE OF CHARACTERISTICS
for

FLAW

DETECTION | EVALUATION

MATERIAL CHARACTERIZATION

SURFACE

WAVE FIELD

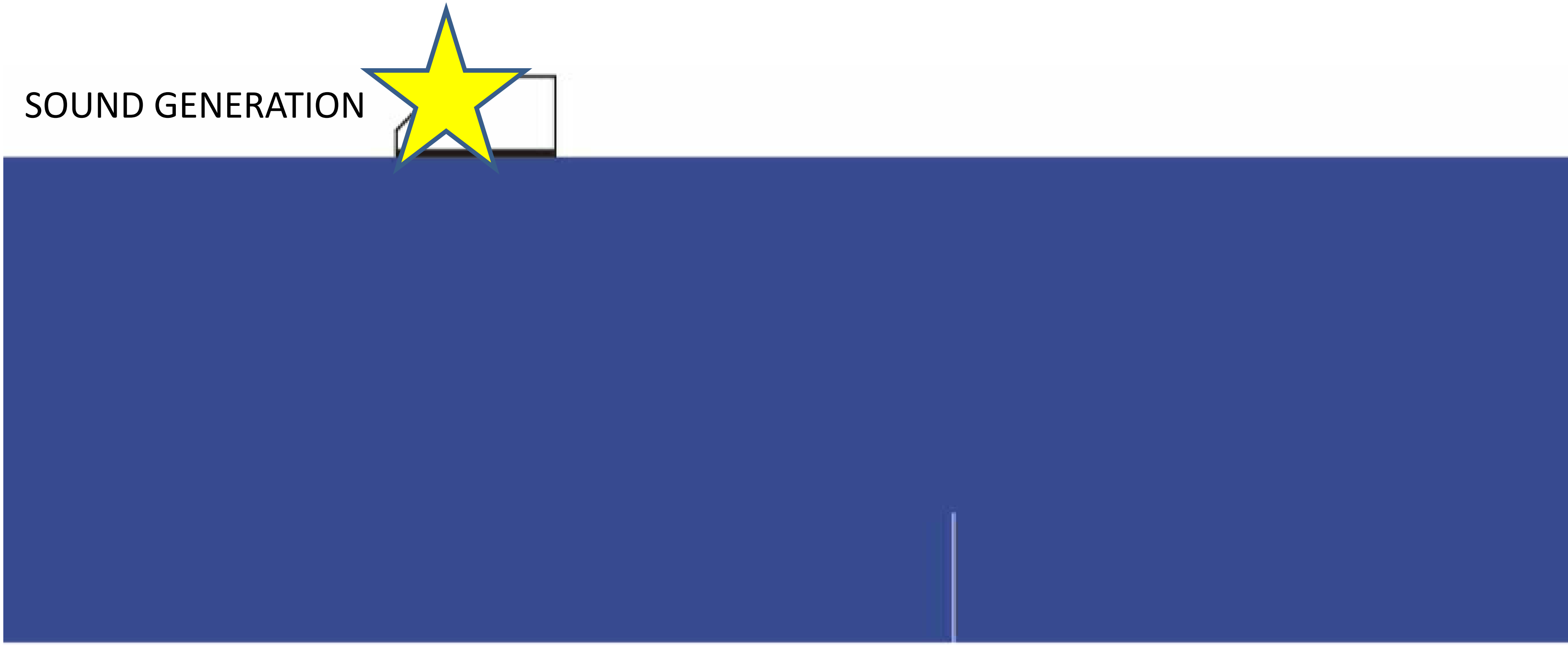
WAVE PROPAGATION

WAVE (BACK)SCATTERING

SIGNAL PROCESSING & EVALUATION

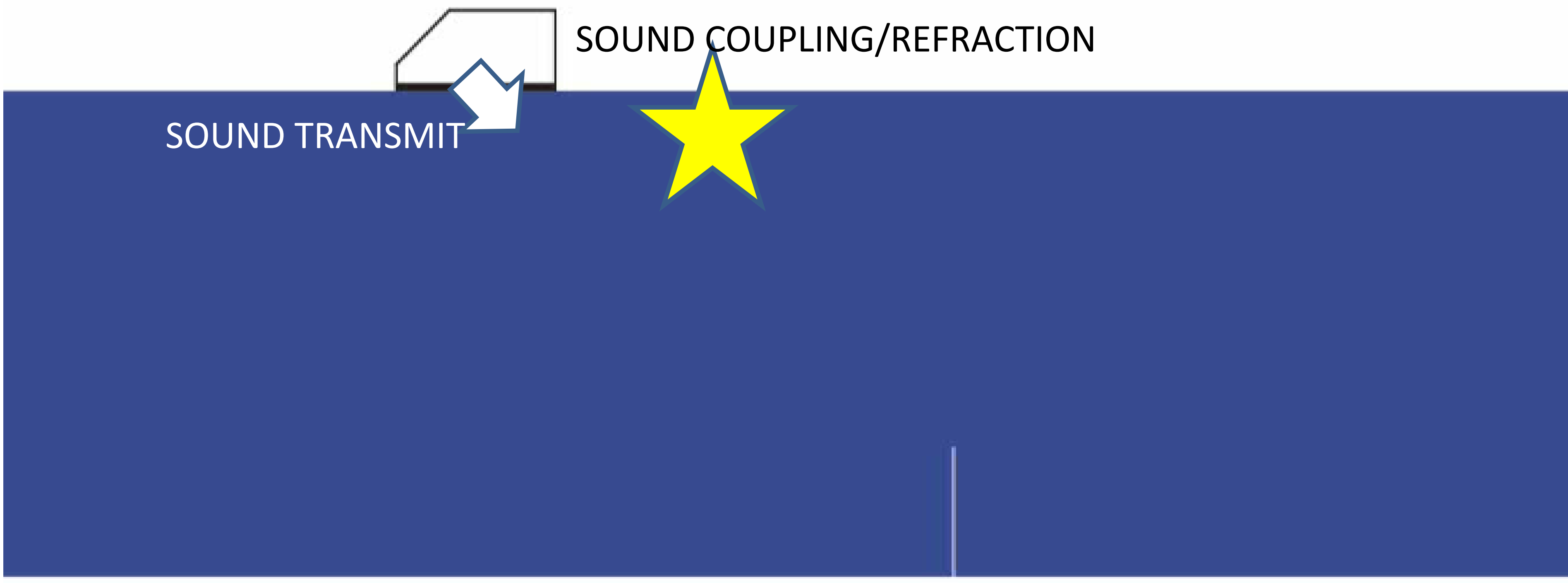
NDT&E Methods: UT

The Pulse-Echo Method



NDT&E Methods: UT

The Pulse-Echo Method



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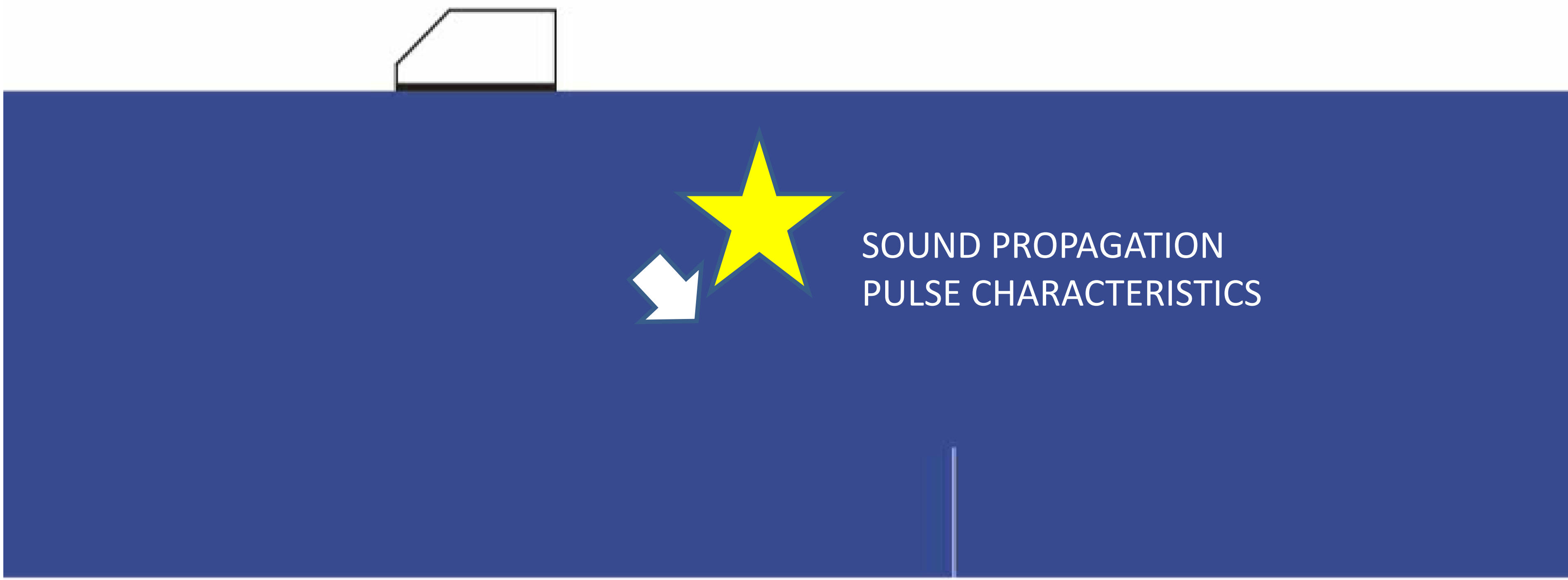
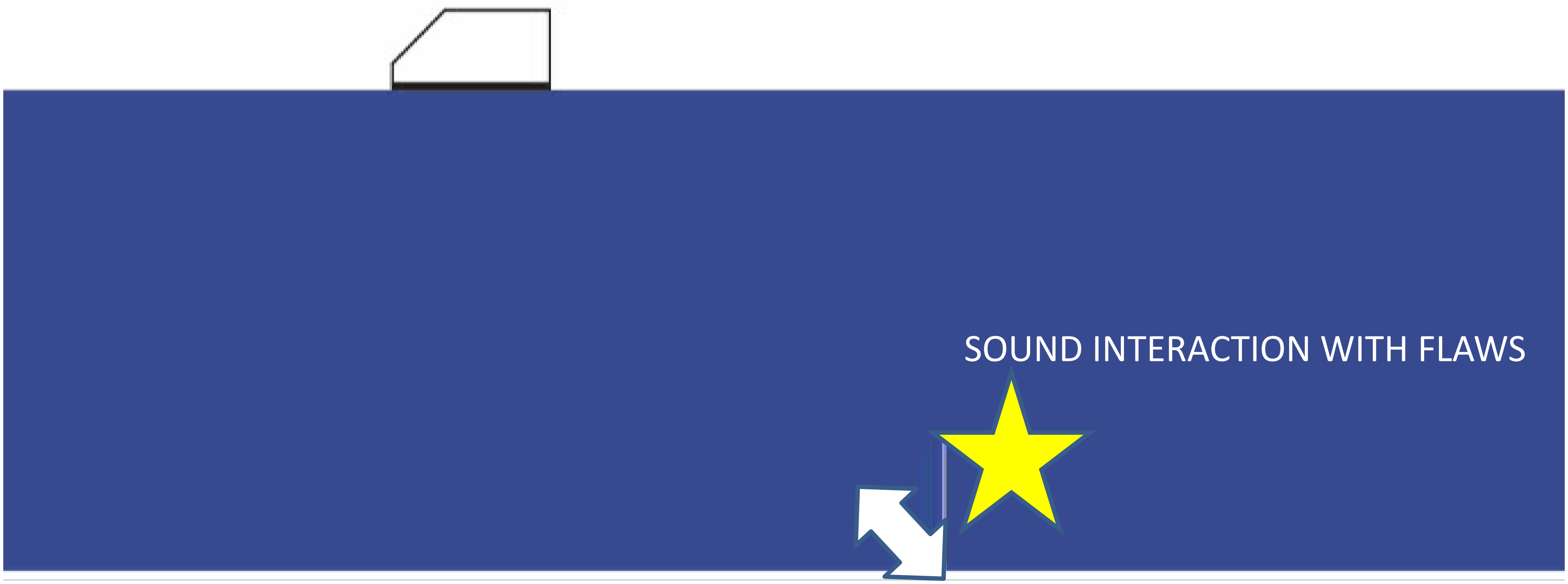
The Pulse-Echo Method



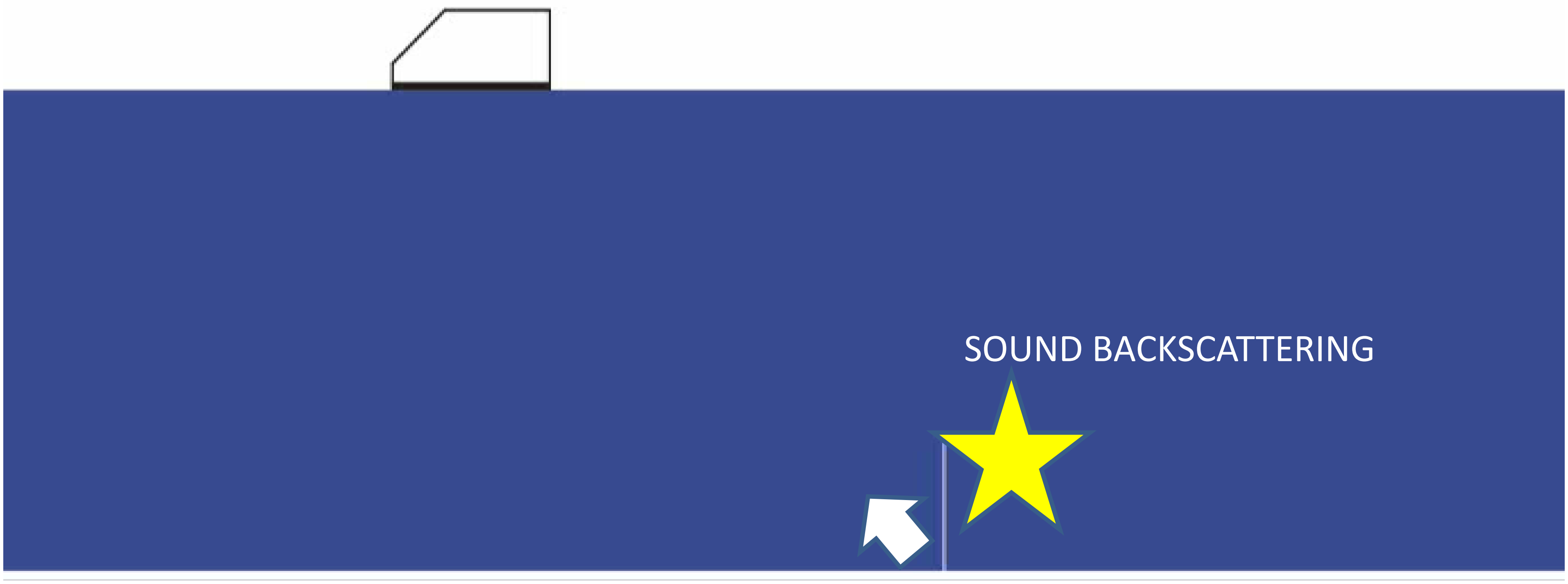
NDT&E Methods: UT

The Pulse-Echo Method



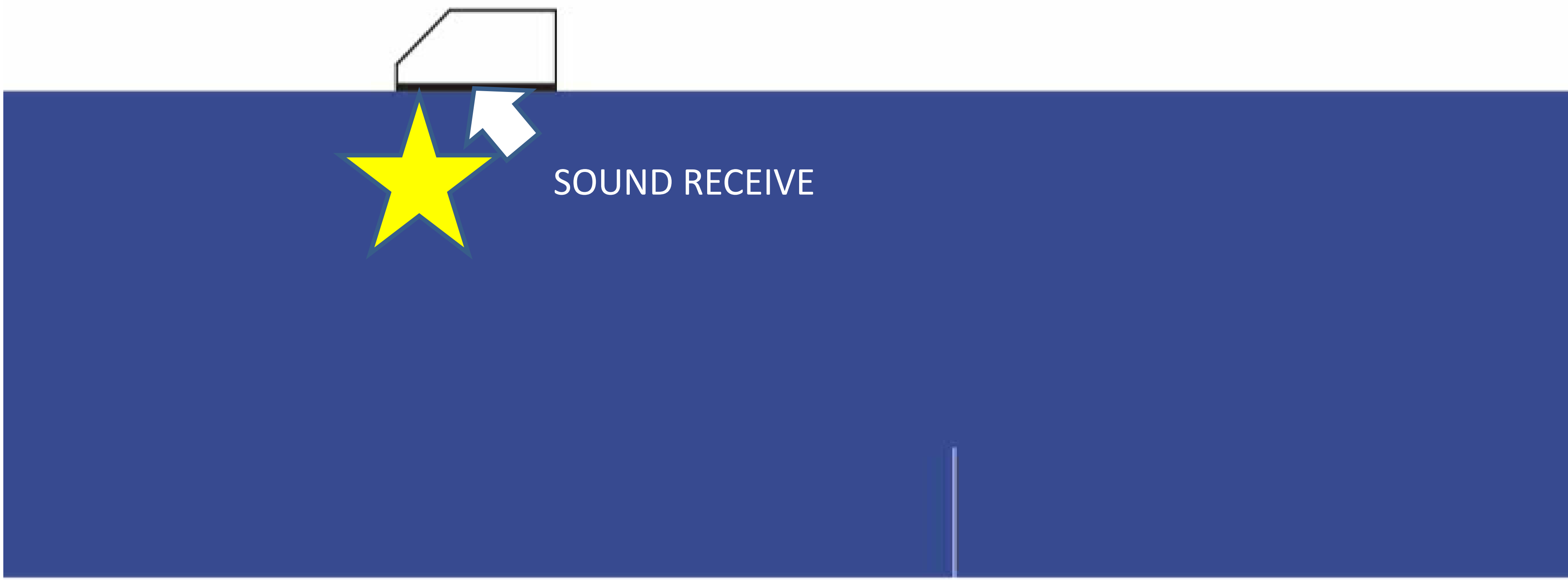
NDT&E Methods: UT

The Pulse-Echo Method



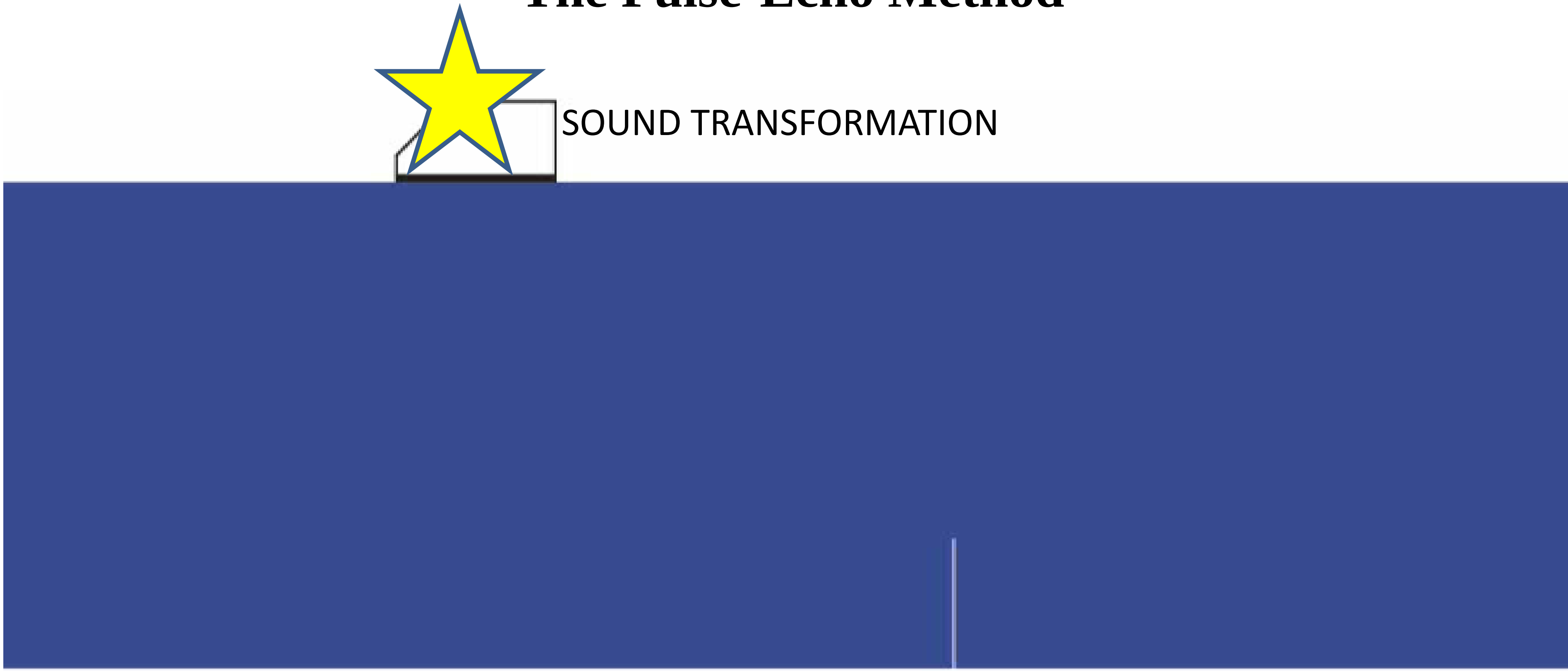
NDT&E Methods: UT

The Pulse-Echo Method



NDT&E Methods: UT

The Pulse-Echo Method



COUPLING

A SIMPLE BUT MOST PRACTICAL ISSUE:

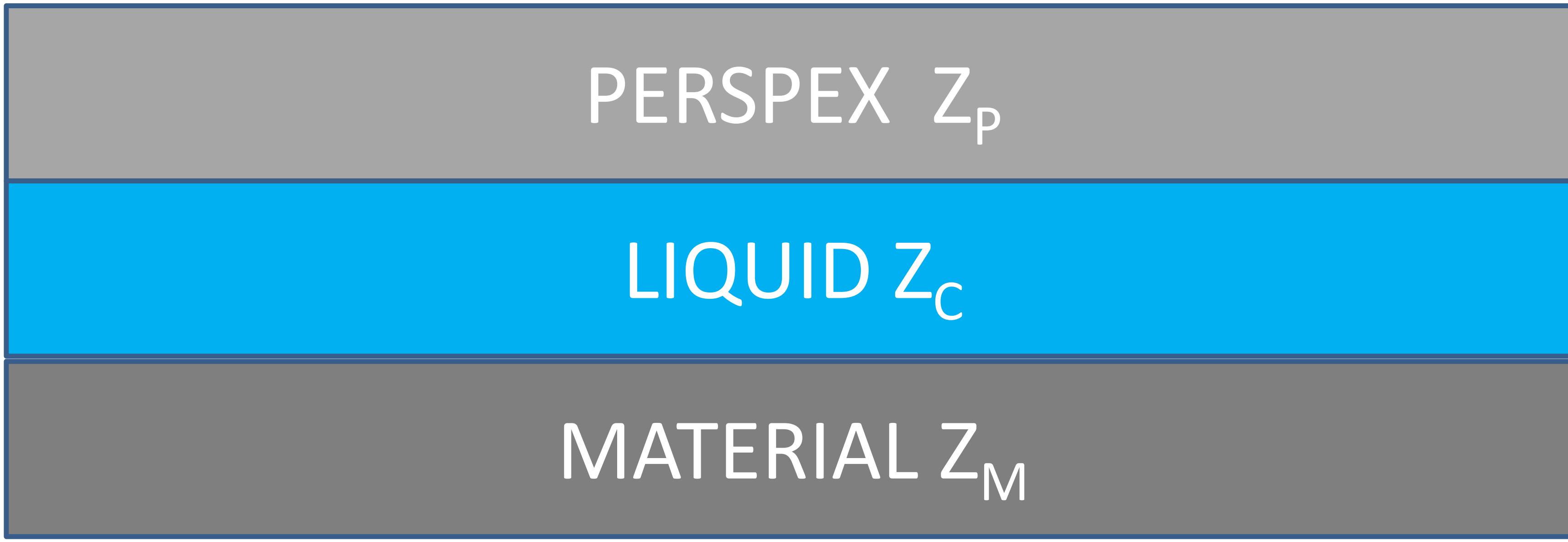
WHY DO WE USE LIQUIDS FOR COUPLING?

A MORE SOPHISTICATED ISSUE:

ARE THERE OPTIMAL LIQUID CHARACTERISTICS?

NDT&E Methods: UT

COUPLING



Coupling Sound into the Material

It is a multi-layer problem of different acoustic impedances

COUPLING

A Problem of two Interfaces or How much of the ultrasound will cross the interfaces?

For simplification we consider a plane wave and remember:

Acoustic Impedance $Z = \rho_o c = \sqrt{\rho_o / \kappa}$

ρ: density; c: sound velocity; κ: compressibility

Reflection Coefficient: $R = \frac{P_r}{P_i} = \frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t}$

$P_{i,r}$: Amplitude of incident, reflected wave

NOTE **$-1 \leq R \leq +1$:**

A negative value of R implies that the reflected wave is inverted with respect to the incident wave

COUPLING

A Problem of two Interfaces or How much of the ultrasound will cross the interfaces?

For simplification we consider a plane wave and remember:

Transmission Coefficient T:

$P_{i,r}$: Amplitude of incident, reflected wave

$$T = \frac{P_t}{P_i} = \begin{cases} \dfrac{2Z_2 \cos\theta_i}{Z_2 \cos\theta_i + Z_1 \cos\theta_t} & c_1 \geq c_2 \text{ or } \theta_i \leq \sin^{-1}(c_1/c_2) \\ 0 & c_1 < c_2 \text{ and } \theta_i > \sin^{-1}(c_1/c_2) \end{cases}$$

COUPLING

A Problem of two Interfaces or How much of the ultrasound will cross the interfaces?

For normal incidence:

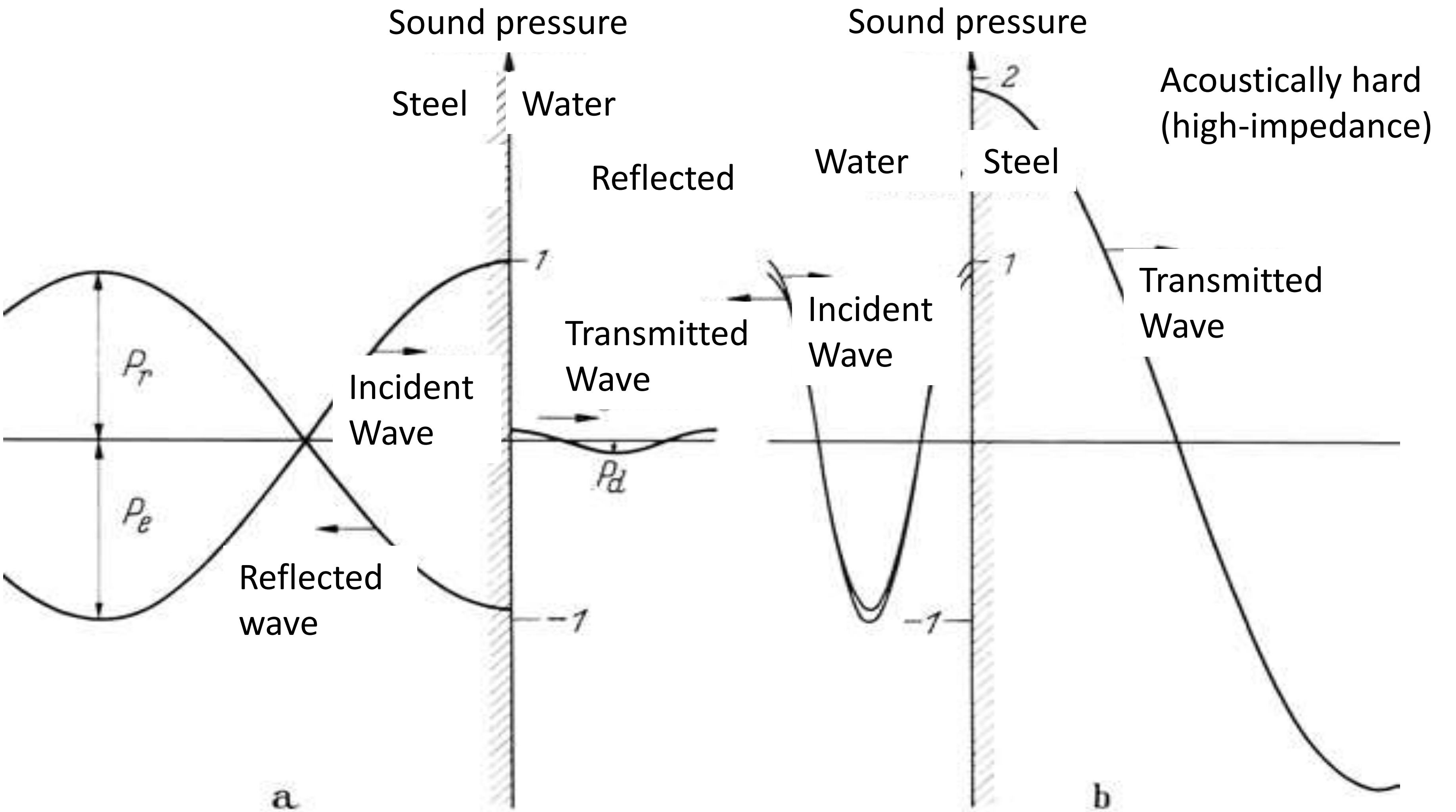
Reflection Coefficient $R = (Z_2 - Z_1)/ (Z_2 + Z_1)$

Transmission Coefficient $T = 2Z_2 / (Z_2 + Z_1)$

With: $1 + R = T$

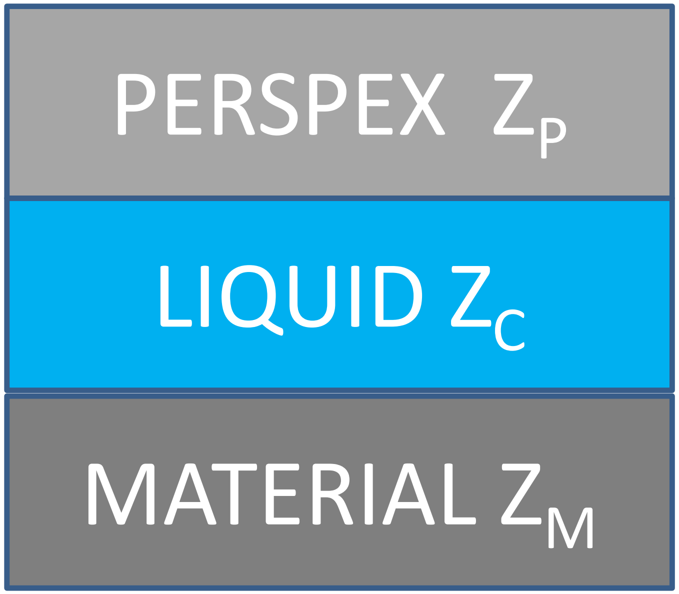
NDT&E Methods: UT

COUPLING



NDT&E Methods: UT

COUPLING



***Optimized Coupling Impedance*:**

$$Z_C \sim \sqrt[2]{Z_P Z_M}$$

Geometric Mean

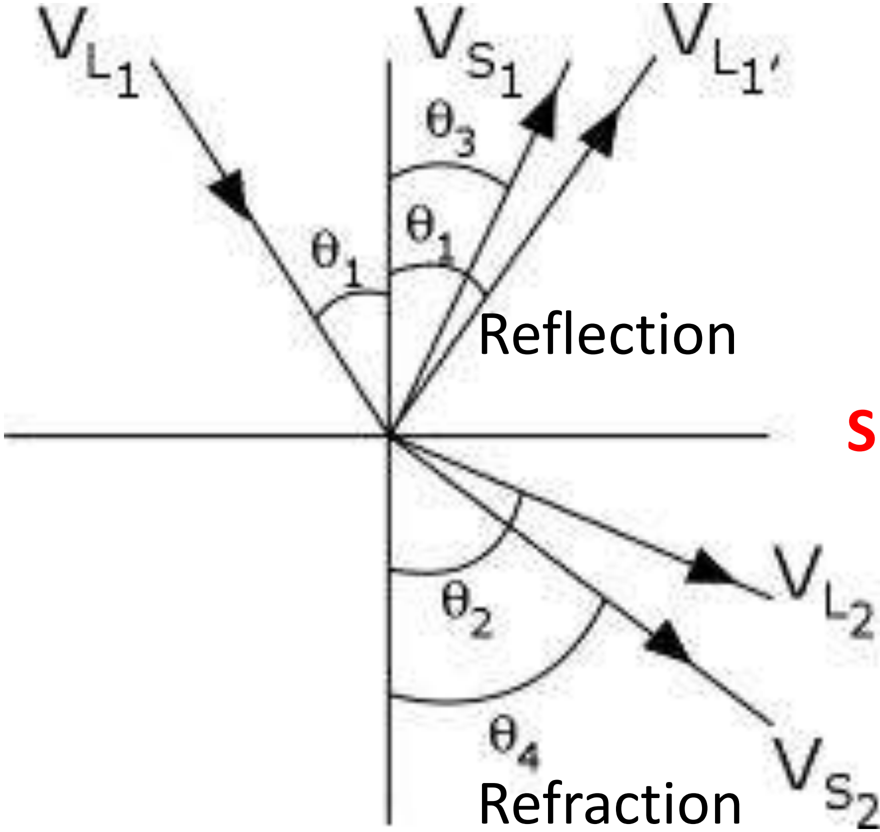
For a set of numbers $\{x_i\}_{i=1}^{N}$

the geometric mean is defined as $\left(\prod_{i=1}^{N} x_i\right)^{1/N}$

NDT&E Methods: UT

COUPLING

Coupling is Angle Dependent



SNELL'S LAW OF REFRACTION

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$

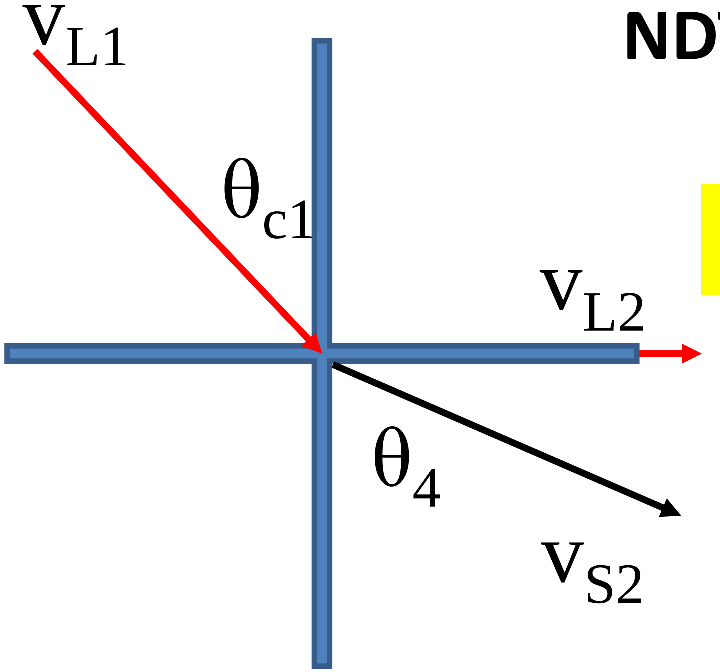
&

MODE CONVERSION

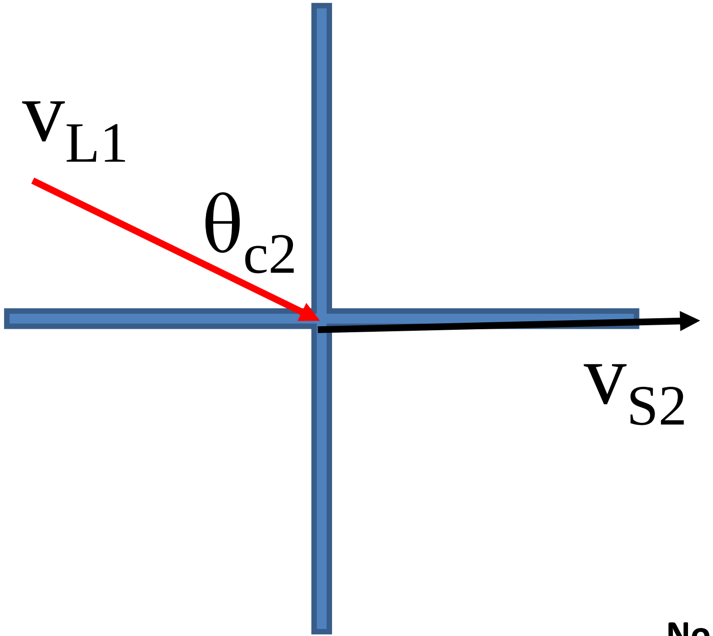
NDT&E Methods: UT

COUPLING

Critical Angles



Beyond the **first critical** angle θ_{c1} , only the **shear wave** propagates into the material.



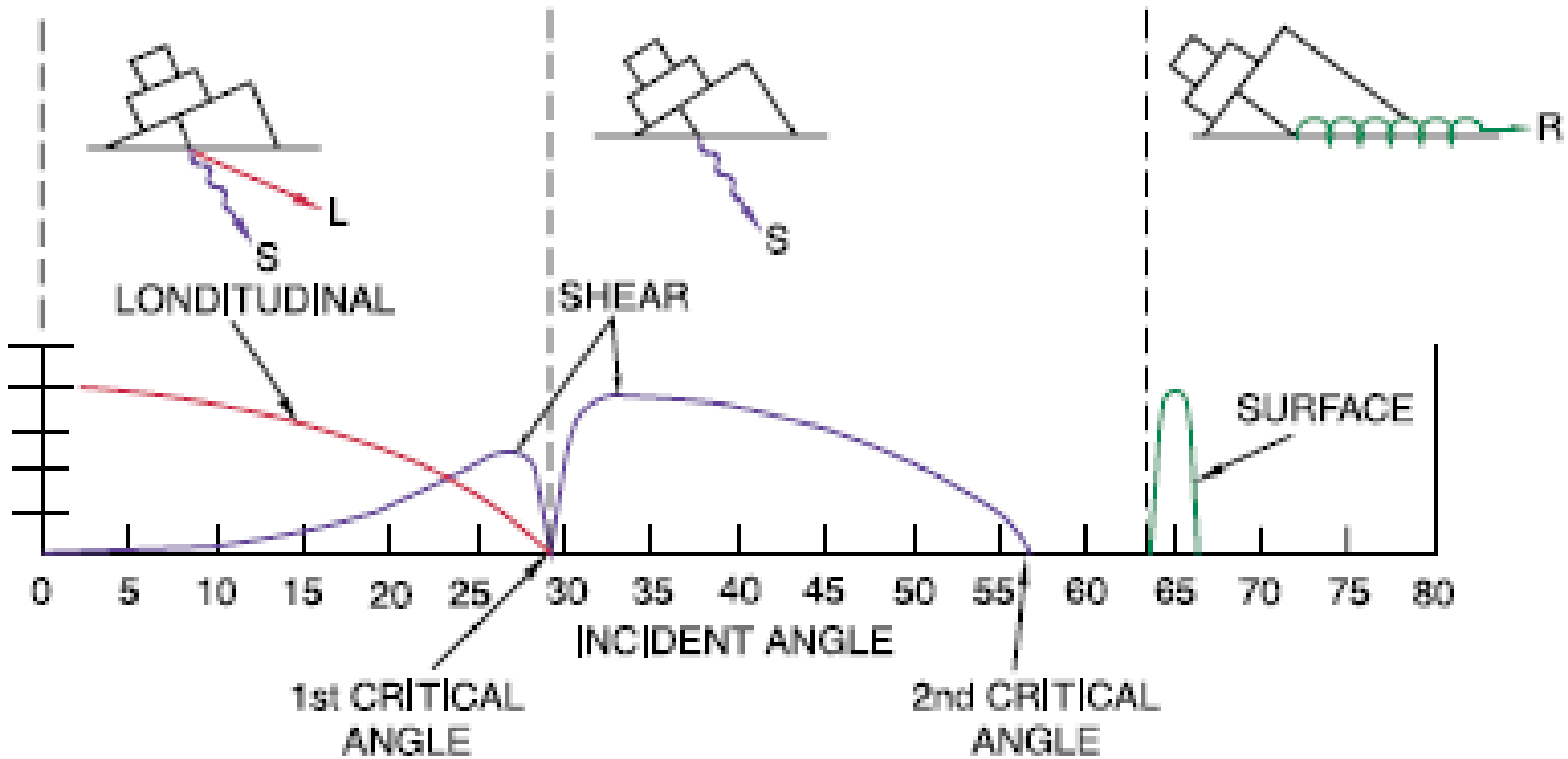
In many cases there is also an incident angle 90 degrees for the refracted shear wave. This is known as the **second critical angle**.

All of the wave energy is reflected or refracted into a surface (shear creep wave) Slightly beyond the second critical angle, surface waves will be generated.

NDT&E Methods: UT

COUPLING

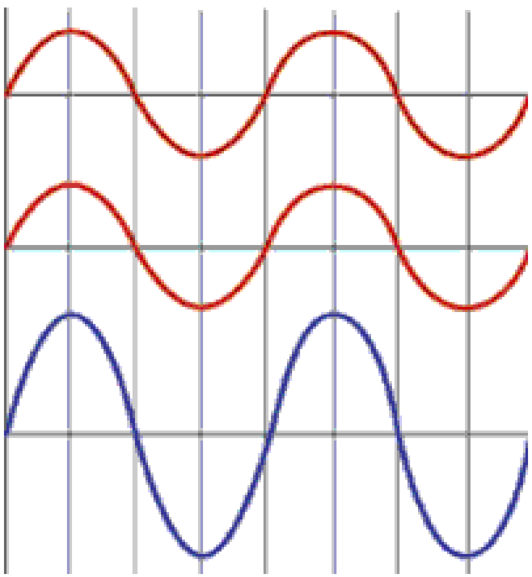
Coupling is Angle Dependent



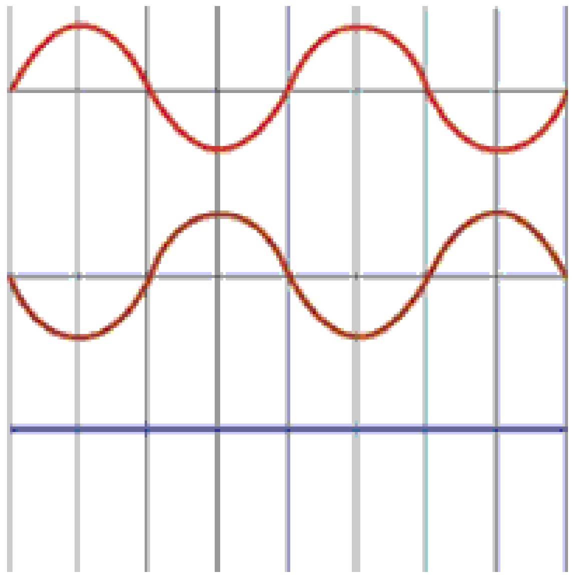
NDT&E Methods: UT

COUPLING

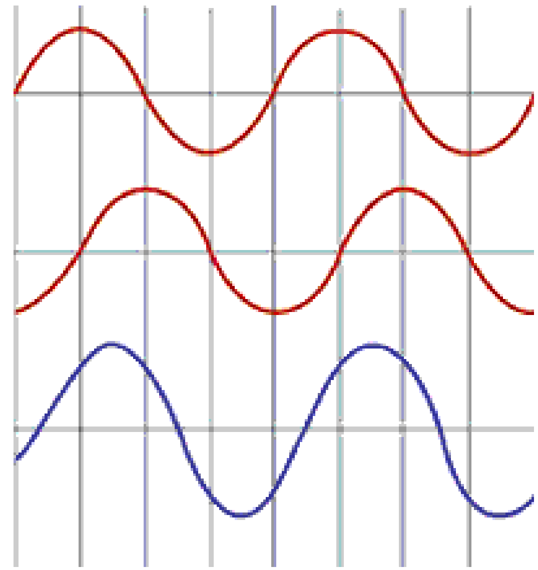
Wave Interference



In Phase



Out of Phase



Superposition

Reflected and primary wave pulse interact in the coupling

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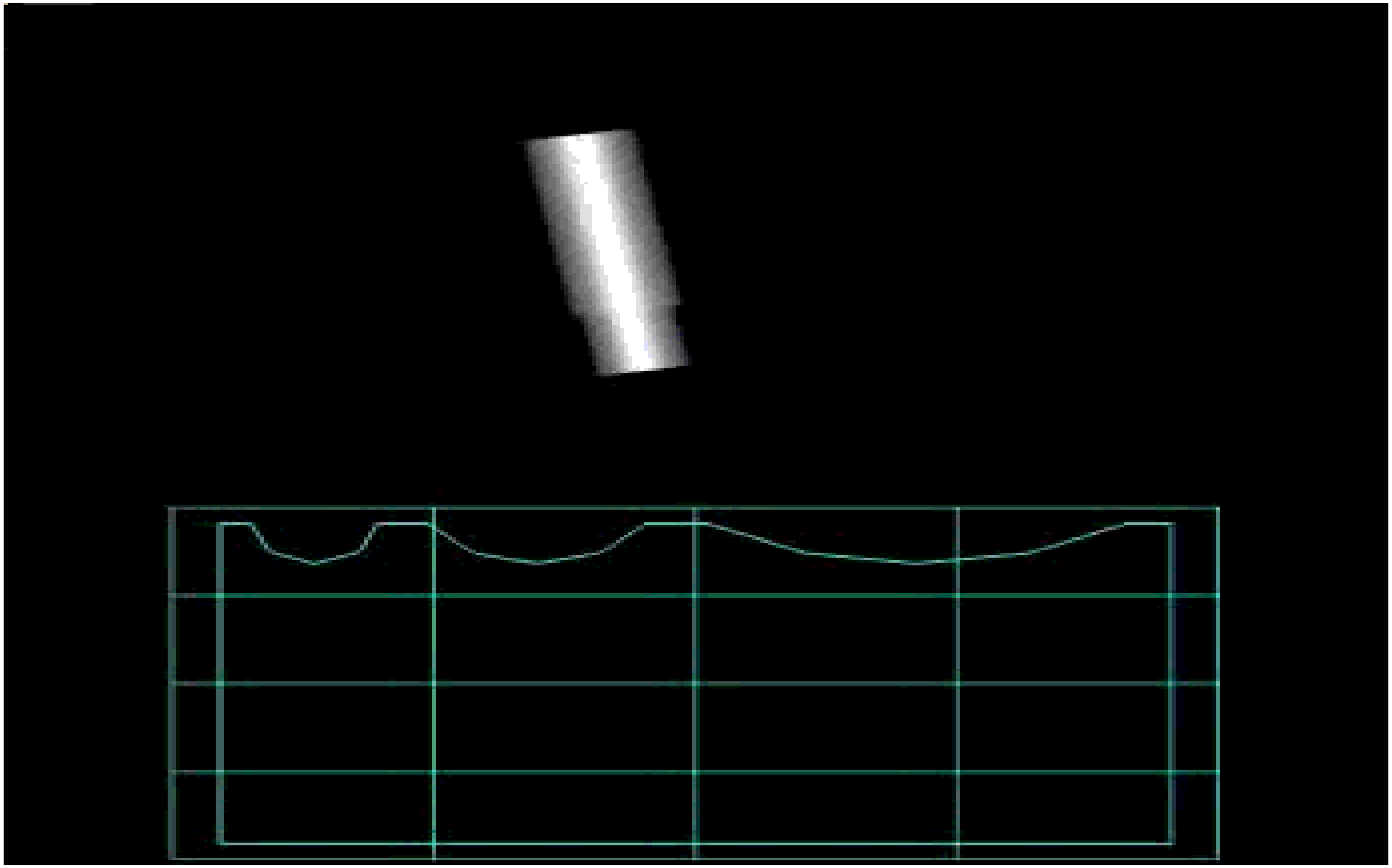
SURFACE REQUIREMENTS



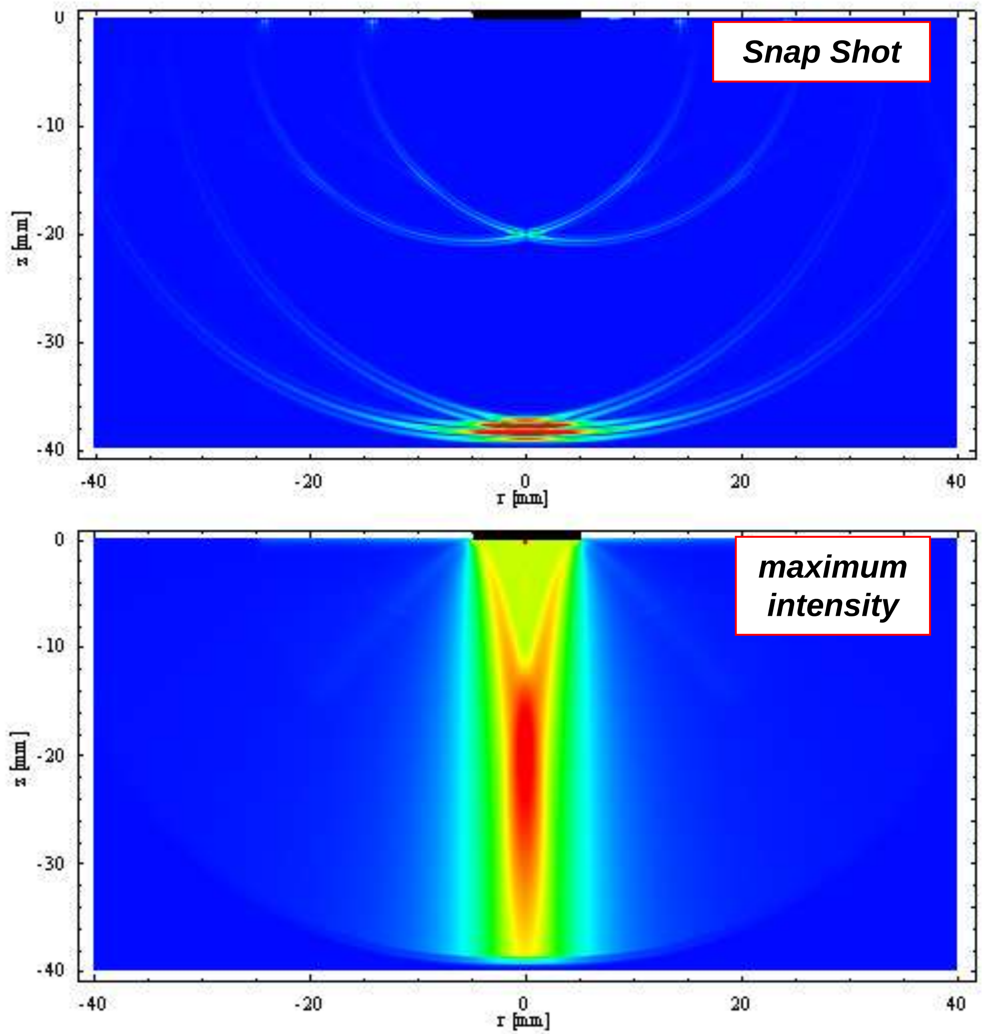
NDT&E Methods: UT

SURFACE REQUIREMENTS

Case Studies: Surfaces

Simulation by Dr. Schubert
Fraunhofer IZFP-D

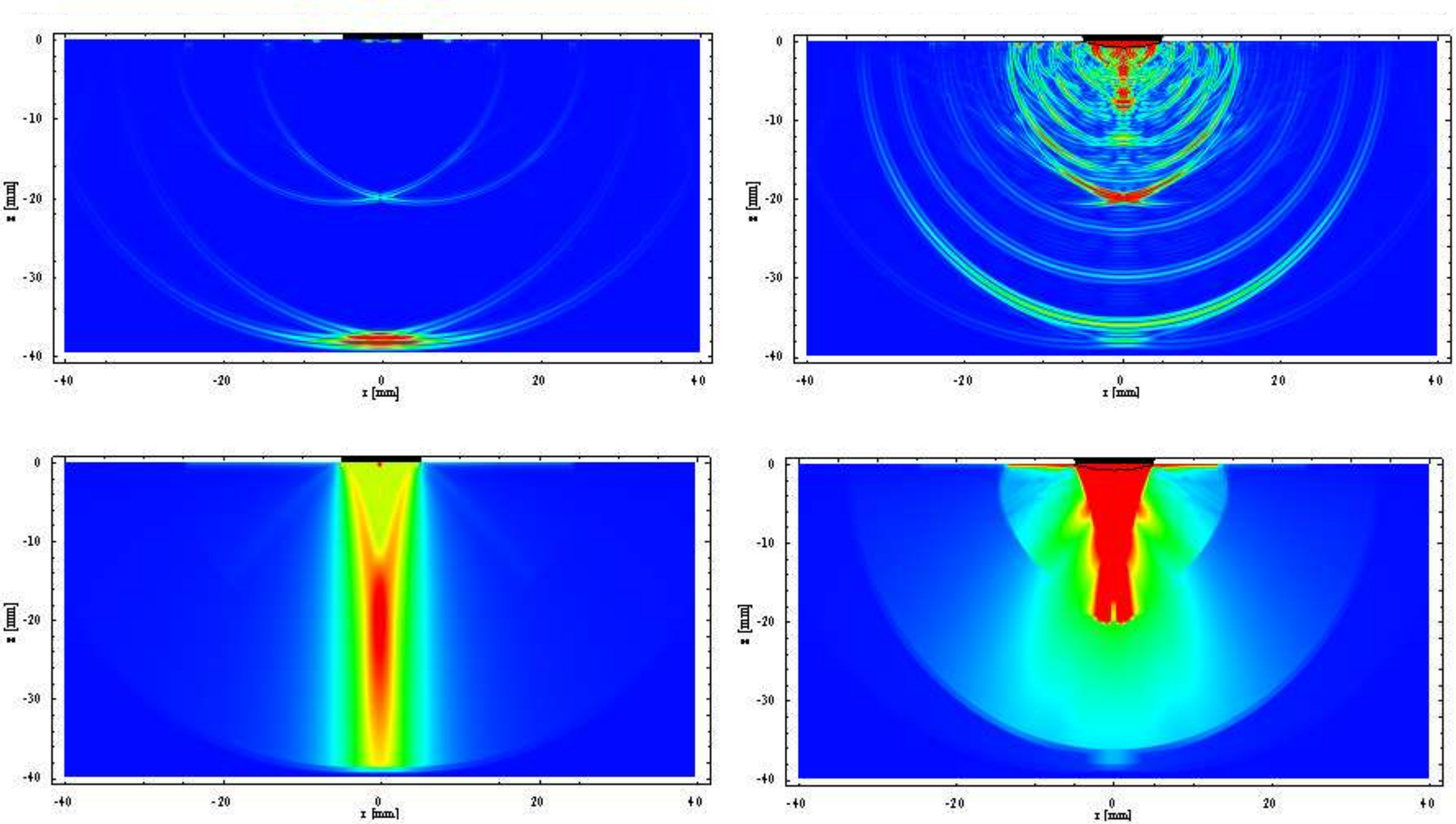
Transducer:	normal probe f = 4 MHz
Aperture:	A = 10 mm
Surface:	flat



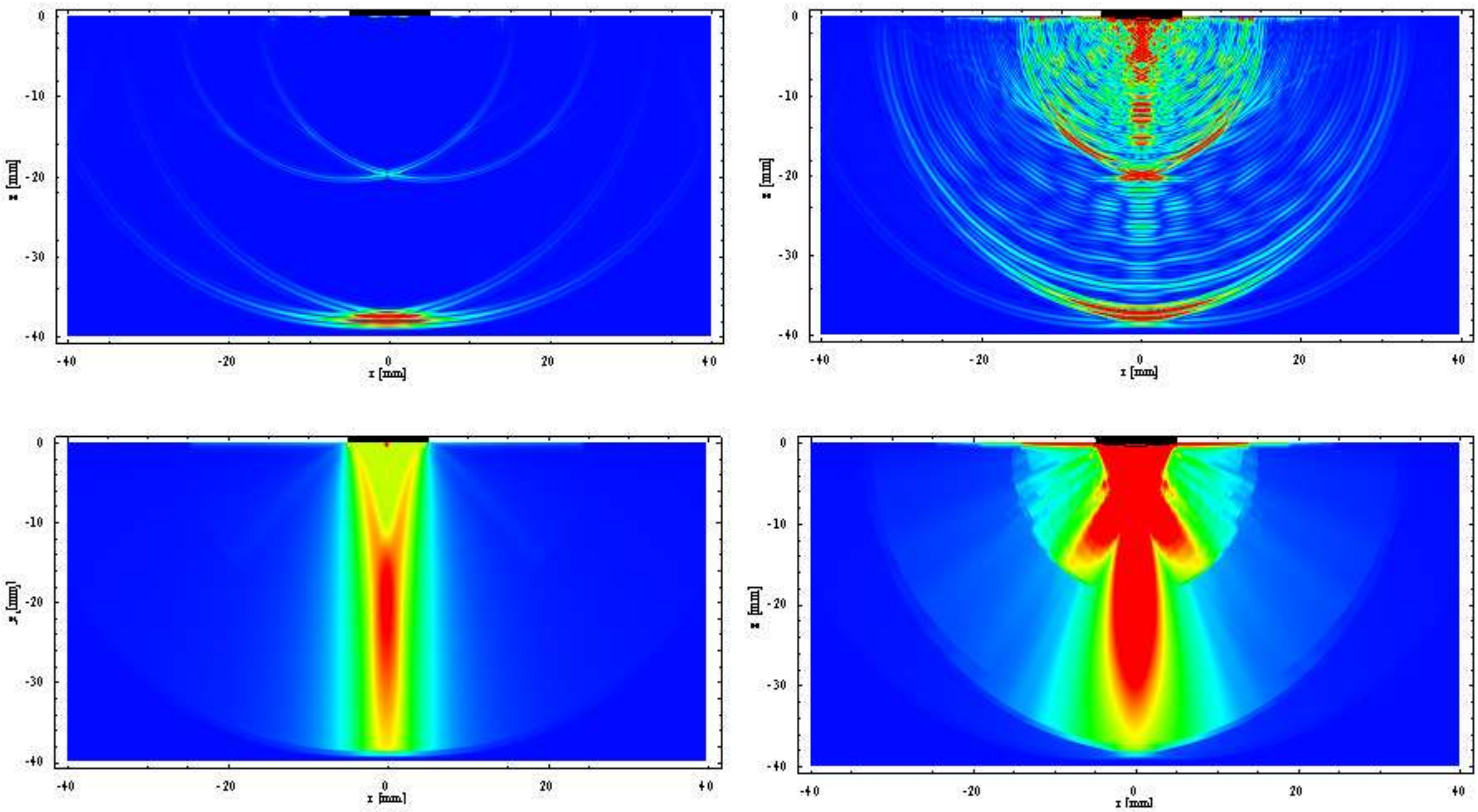
NDT&E Methods: UT

SURFACE REQUIREMENTS

Water gap depth (lense shaped):
0.74 mm ($\lambda/2$ in steel, 2λ in water)

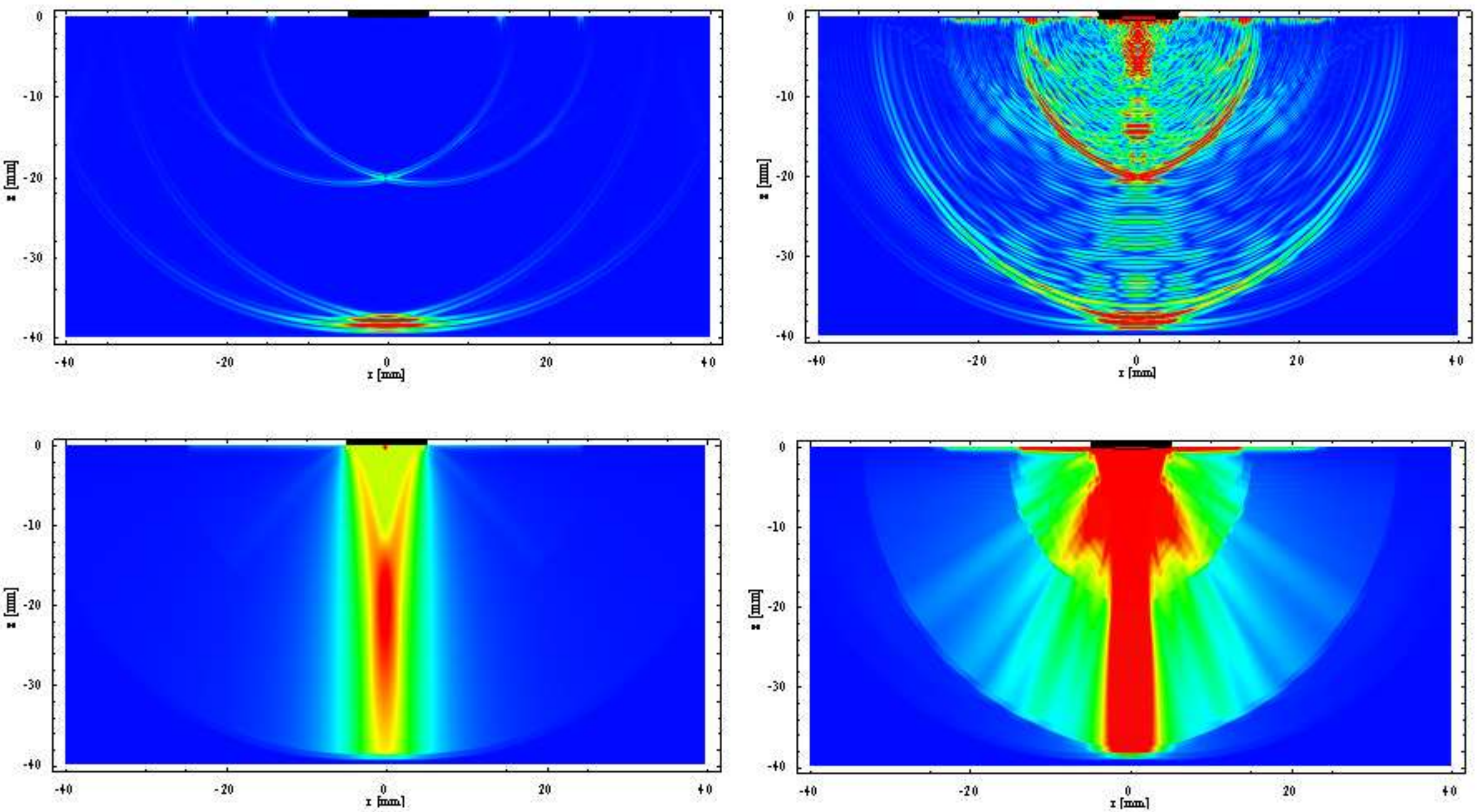


Water gap depth (lense shaped): 0.37 mm (λ/4 in steel, λ in water)



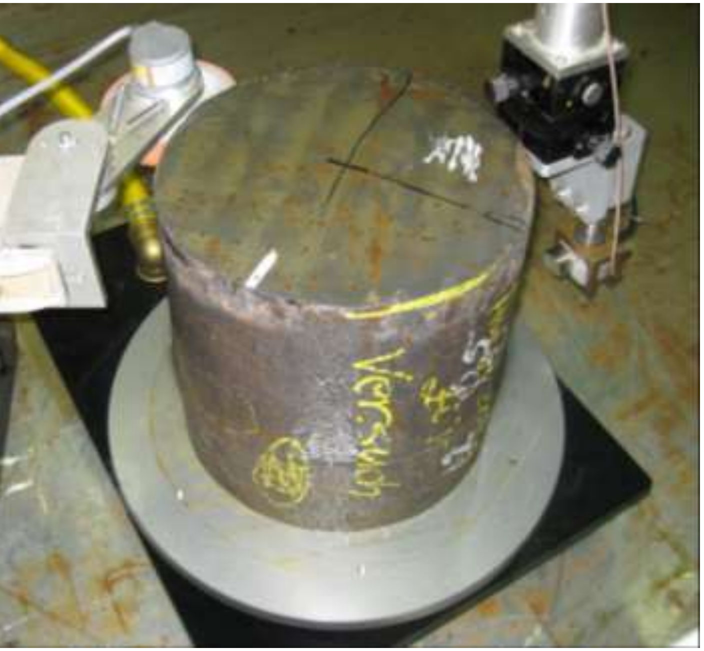
Michael Kröning

Water gap depth (lense shaped):
0.18 mm (λ/8 in steel, λ/2 in water)



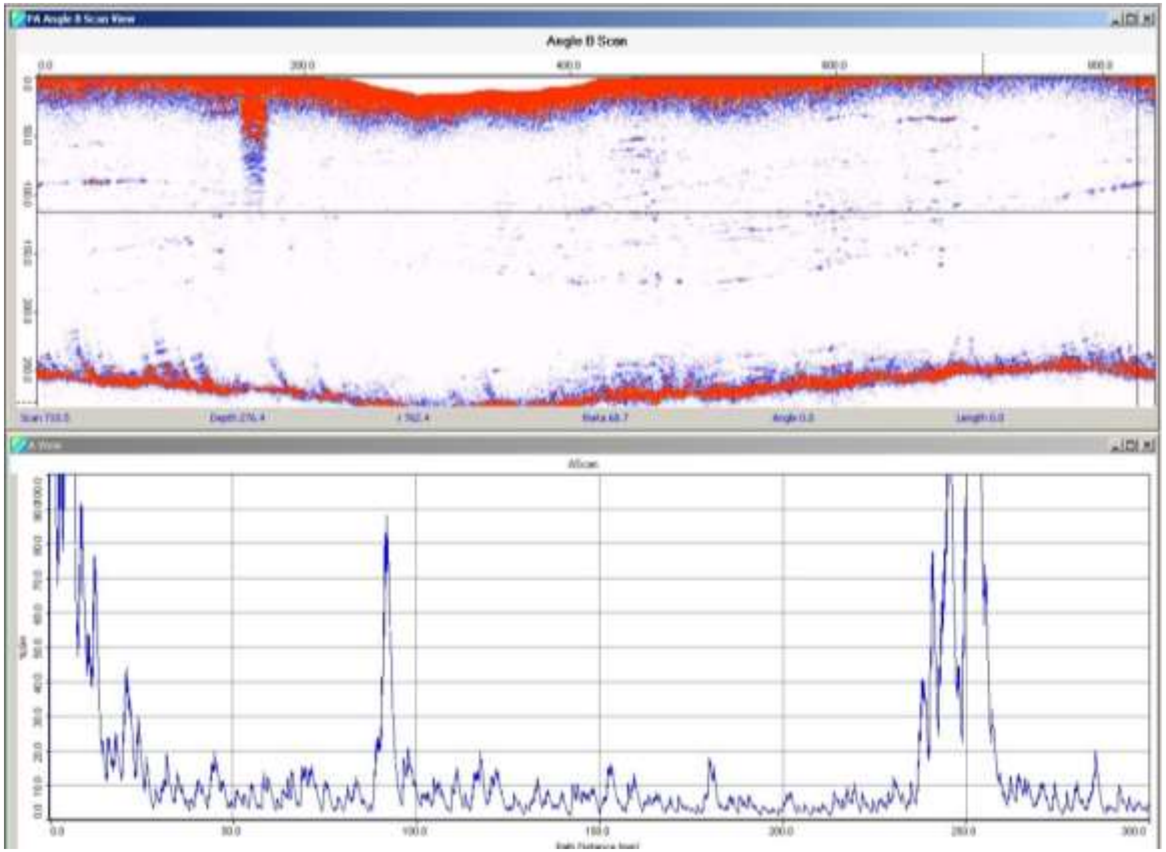
NDT&E Methods: UT

SURFACE REQUIREMENTS



Raw-forged steel bar

with artificial flaws

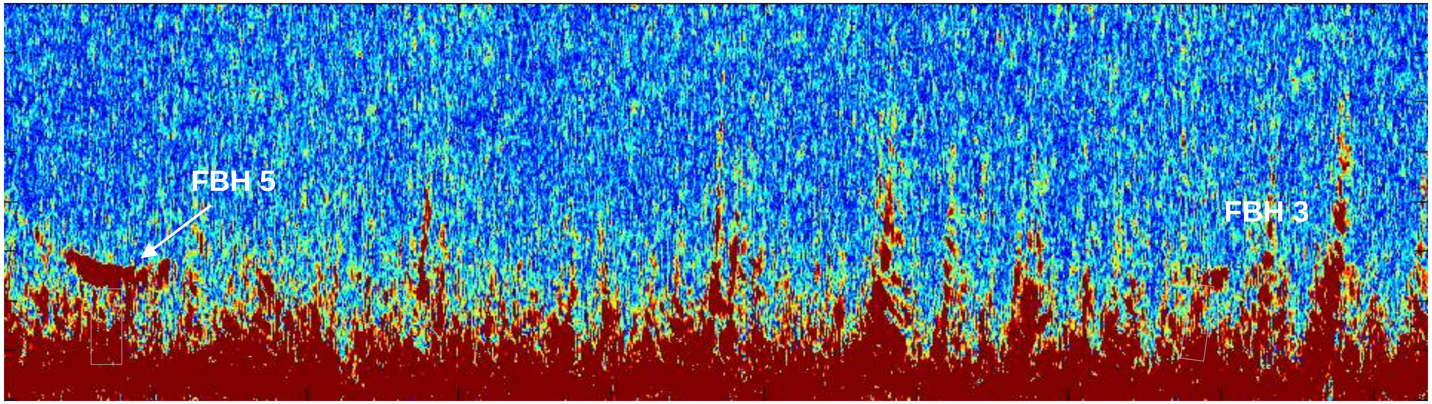


Phase Aberration Correction (Inspection on Rough Surfaces)

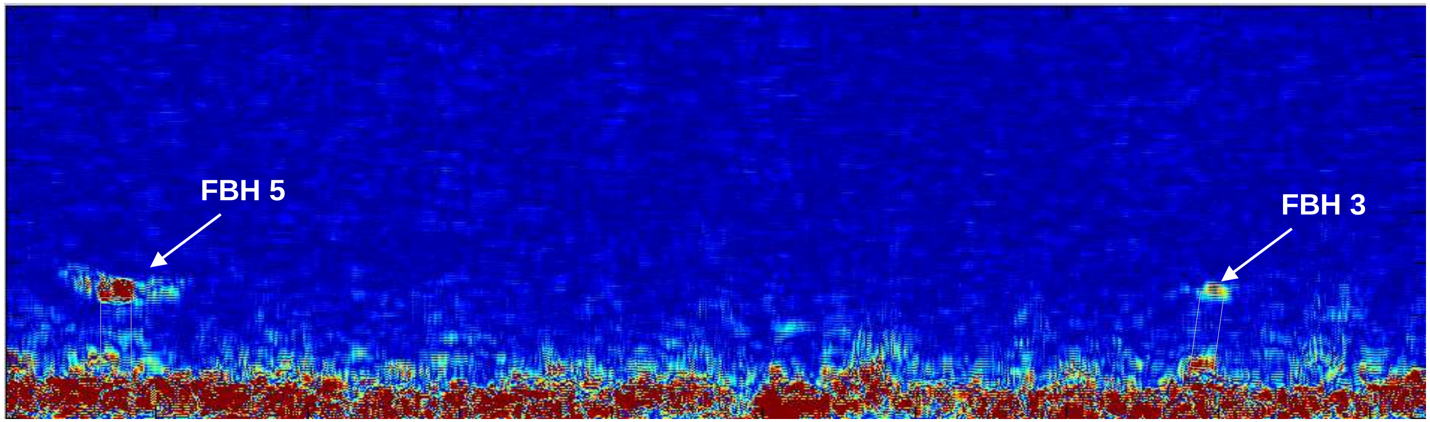
NDT&E Methods: UT

SURFACE REQUIREMENTS

Virgin Image



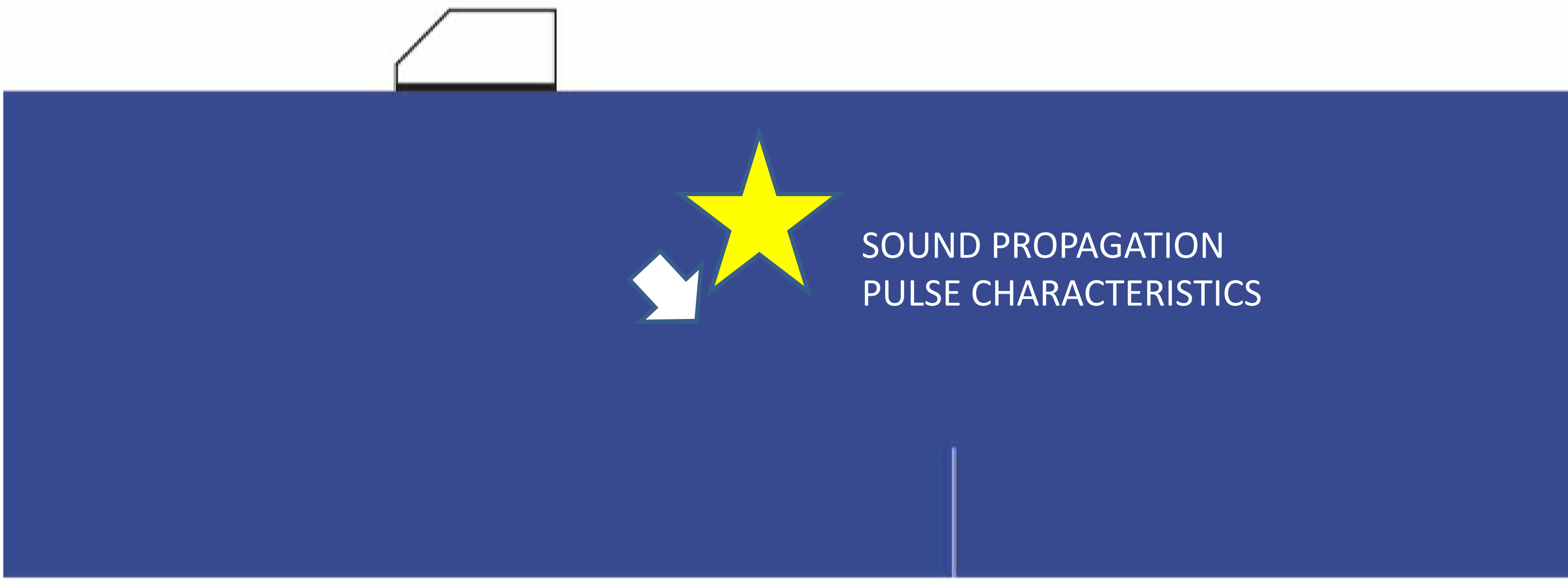
Denoised Image



Phase Aberration Correction

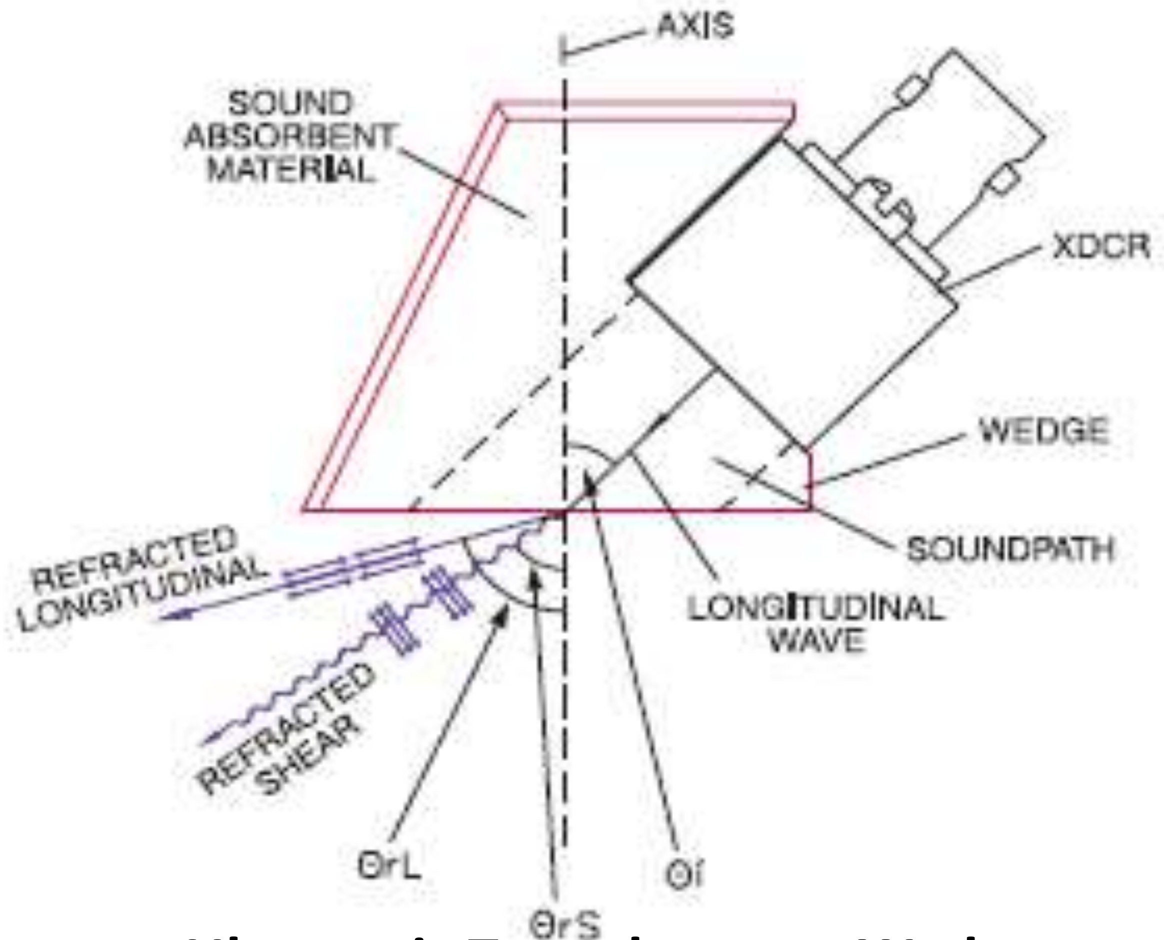
NDT&E Methods: UT

Sound Propagation



NDT&E Methods: UT

Sound Propagation

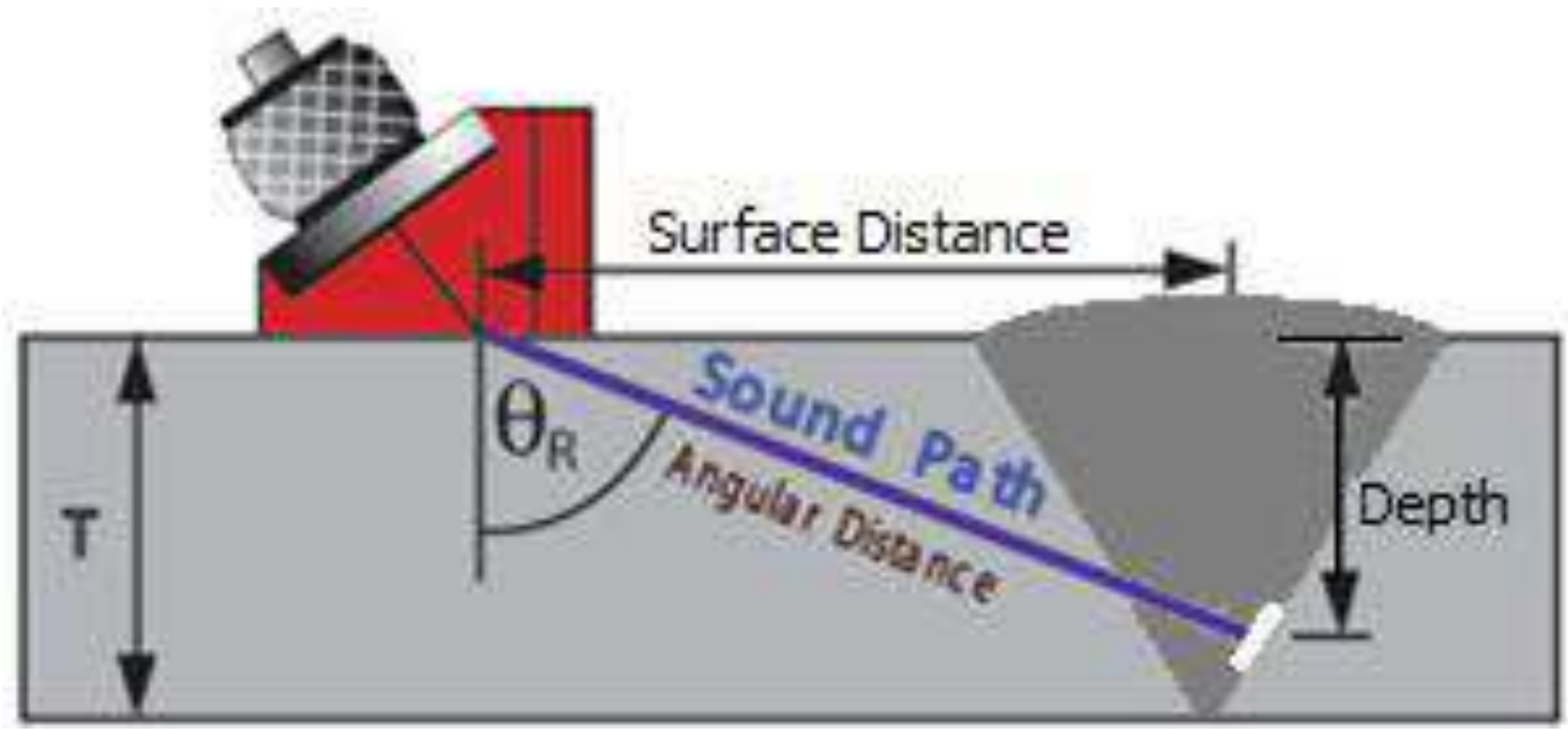


Ultrasonic Transducer on Wedge (Olympus, 2011)

NDT&E Methods: UT

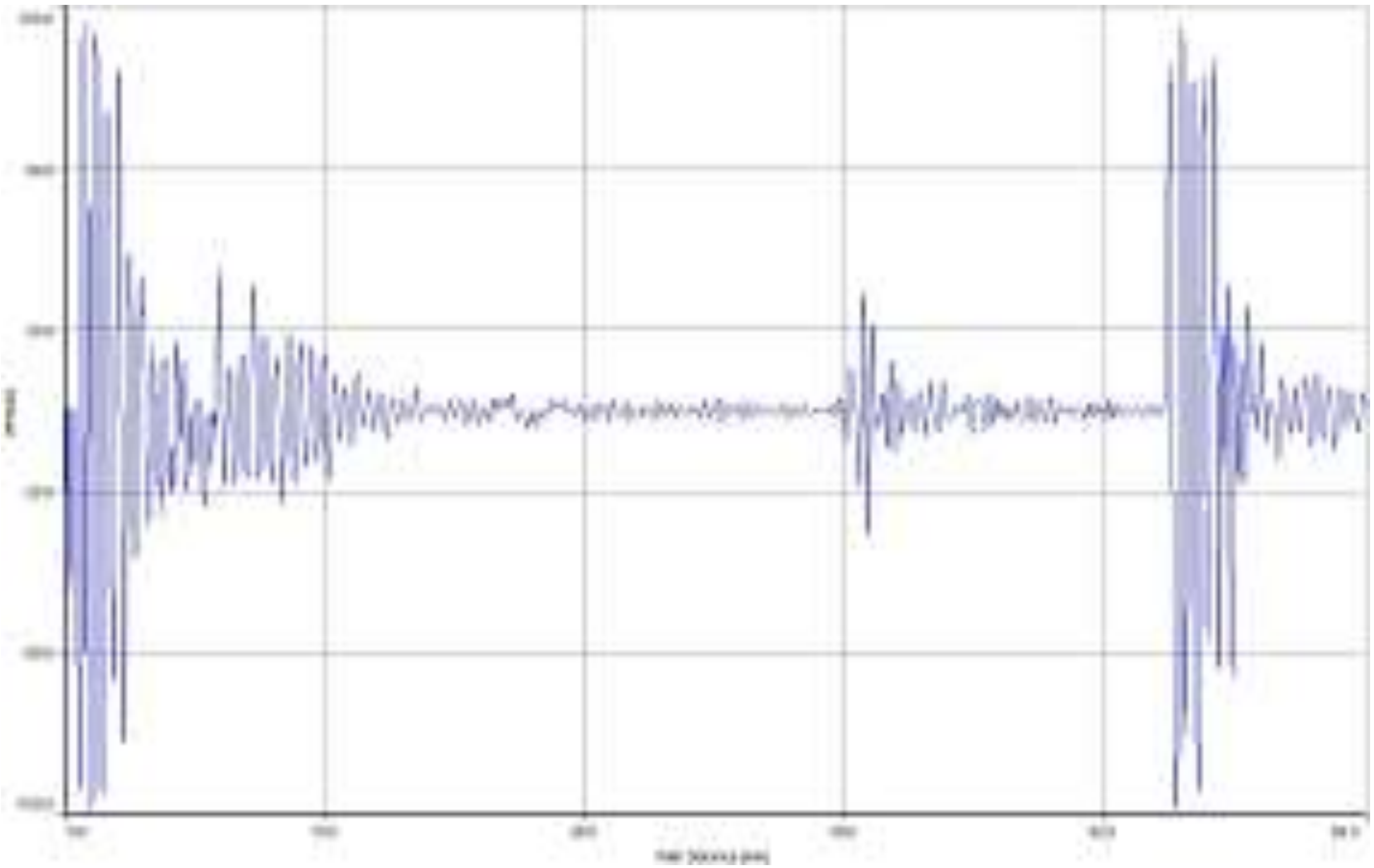
Sound Propagation

FLAW DETECTION BY PULSE-ECHO METHOD



NDT&E Methods: UT

Sound Propagation



RF-Reflectogram (A-SCAN)

Mr. Delano, Sperry Inc., USA termed the reflectogram A-scan (amplitude scan)

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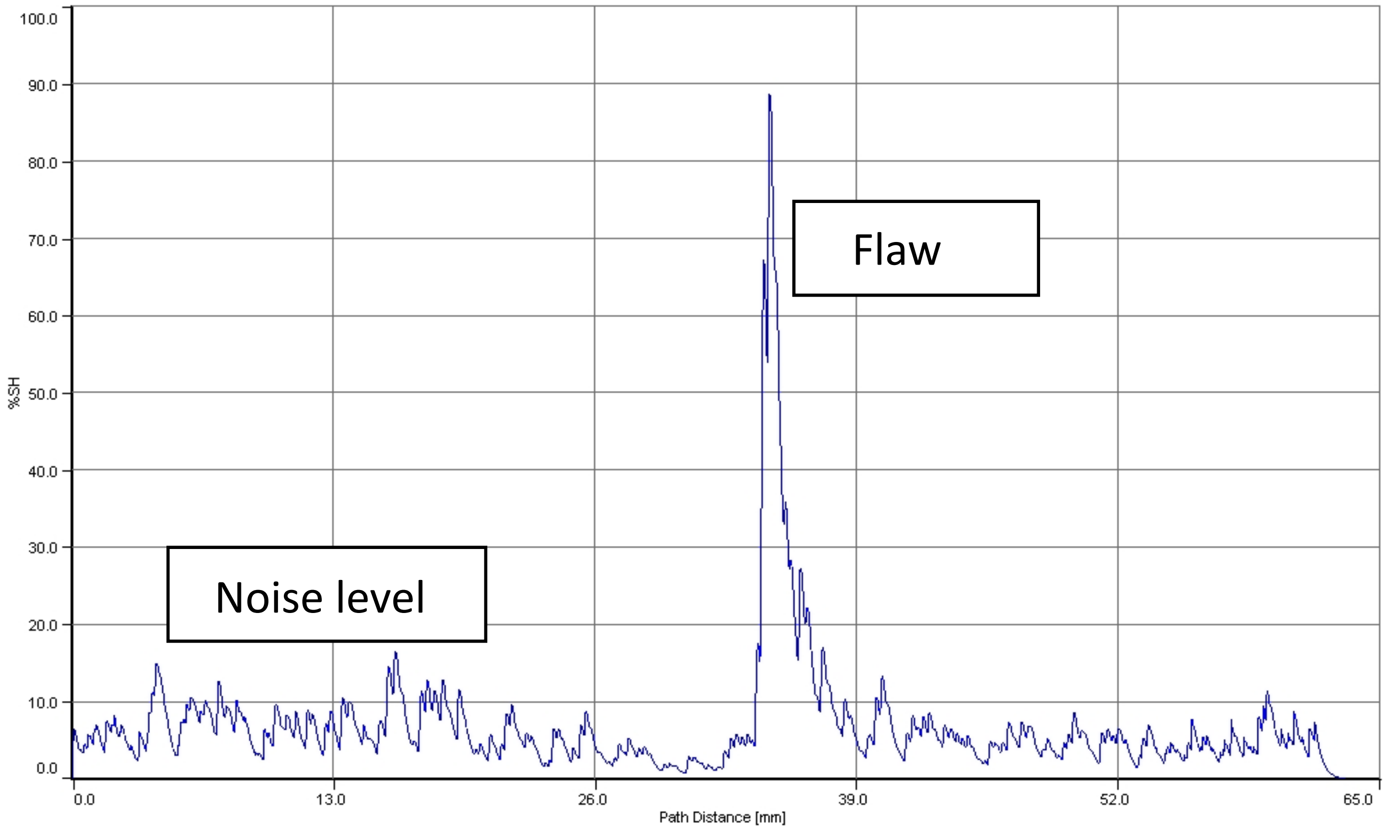
Sound Propagation



Rectified A-Scan

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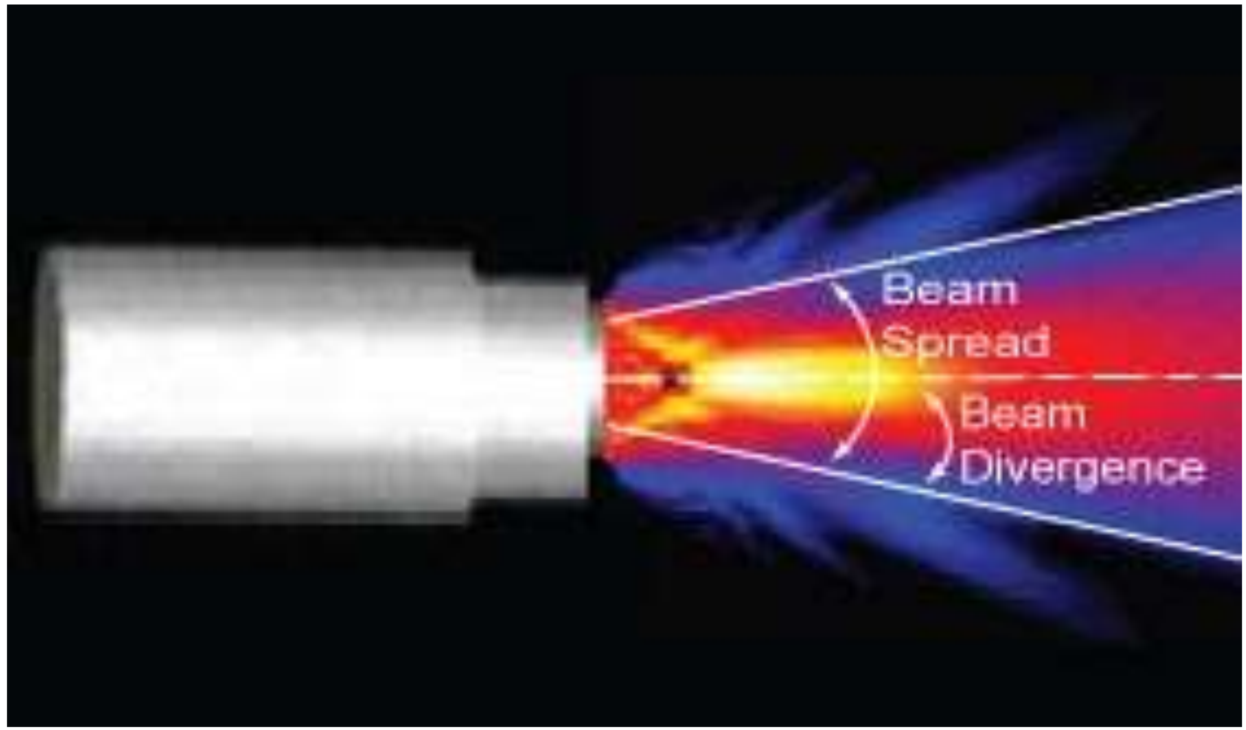
Sound Propagation

FREQUENCY f
APERTURE   A

Beam Spread:

Beam Divergence:

$$\sin\frac{\theta}{2} = \frac{0.514v}{2Af}$$

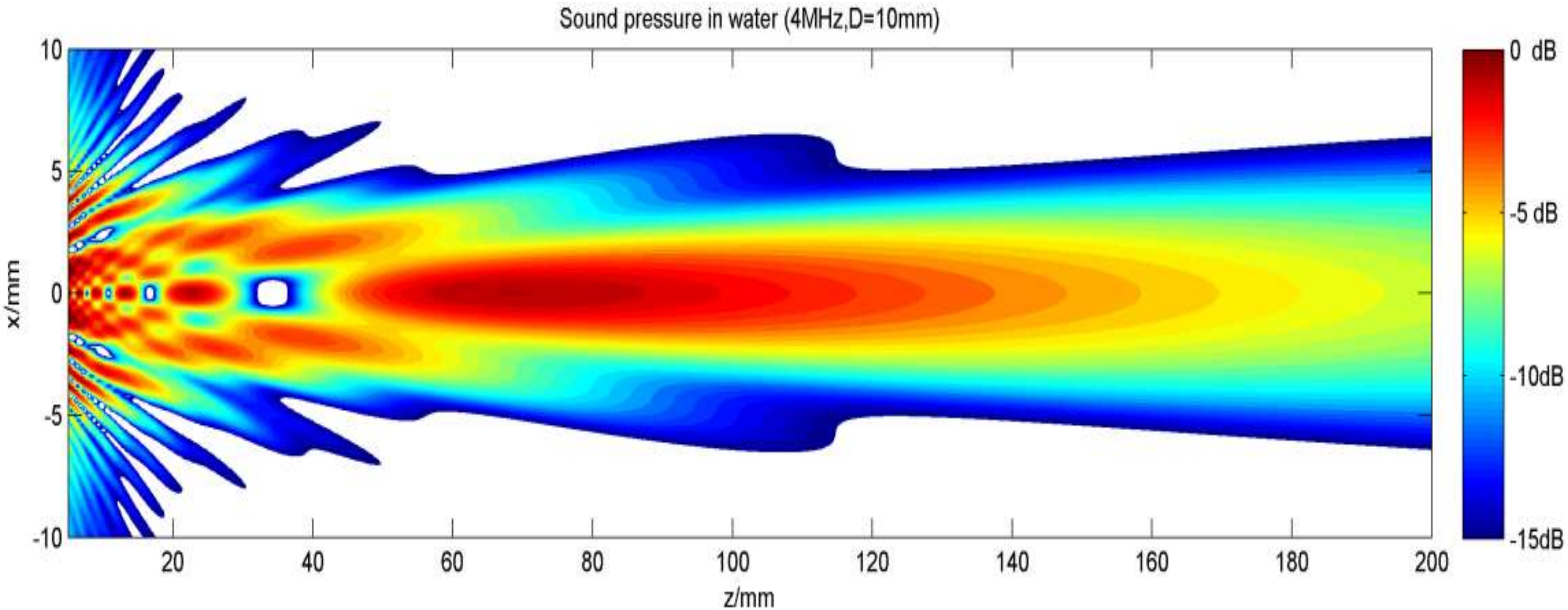


Beam divergence of a plane circular transducer (shown is a harmonic acoustic field)

NDT&E Methods: UT

Sound Propagation

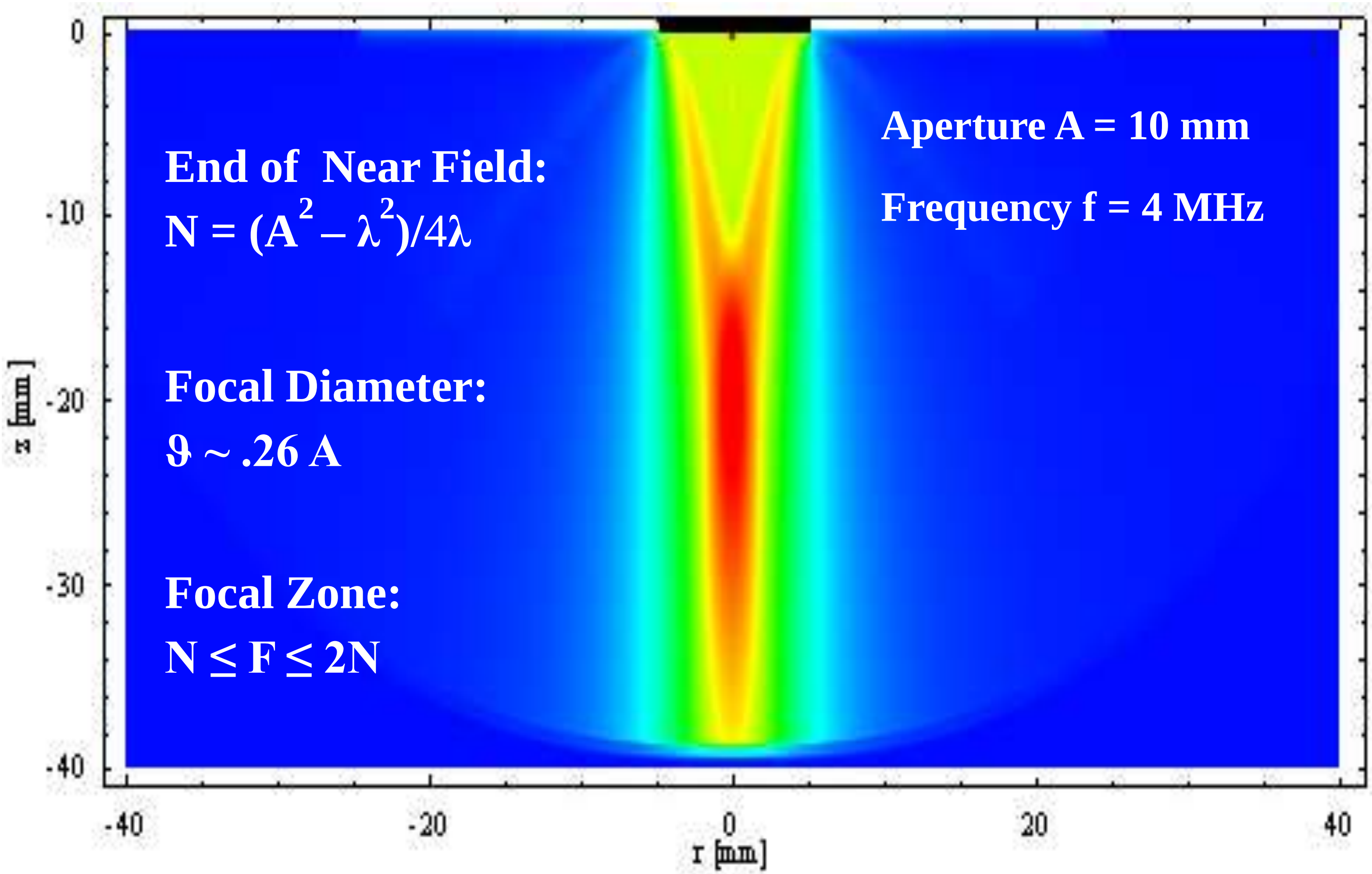
Near Field NF, Focal Zone F, Far Field FF



Harmonic Sound Field with Focal Zone and Far Field

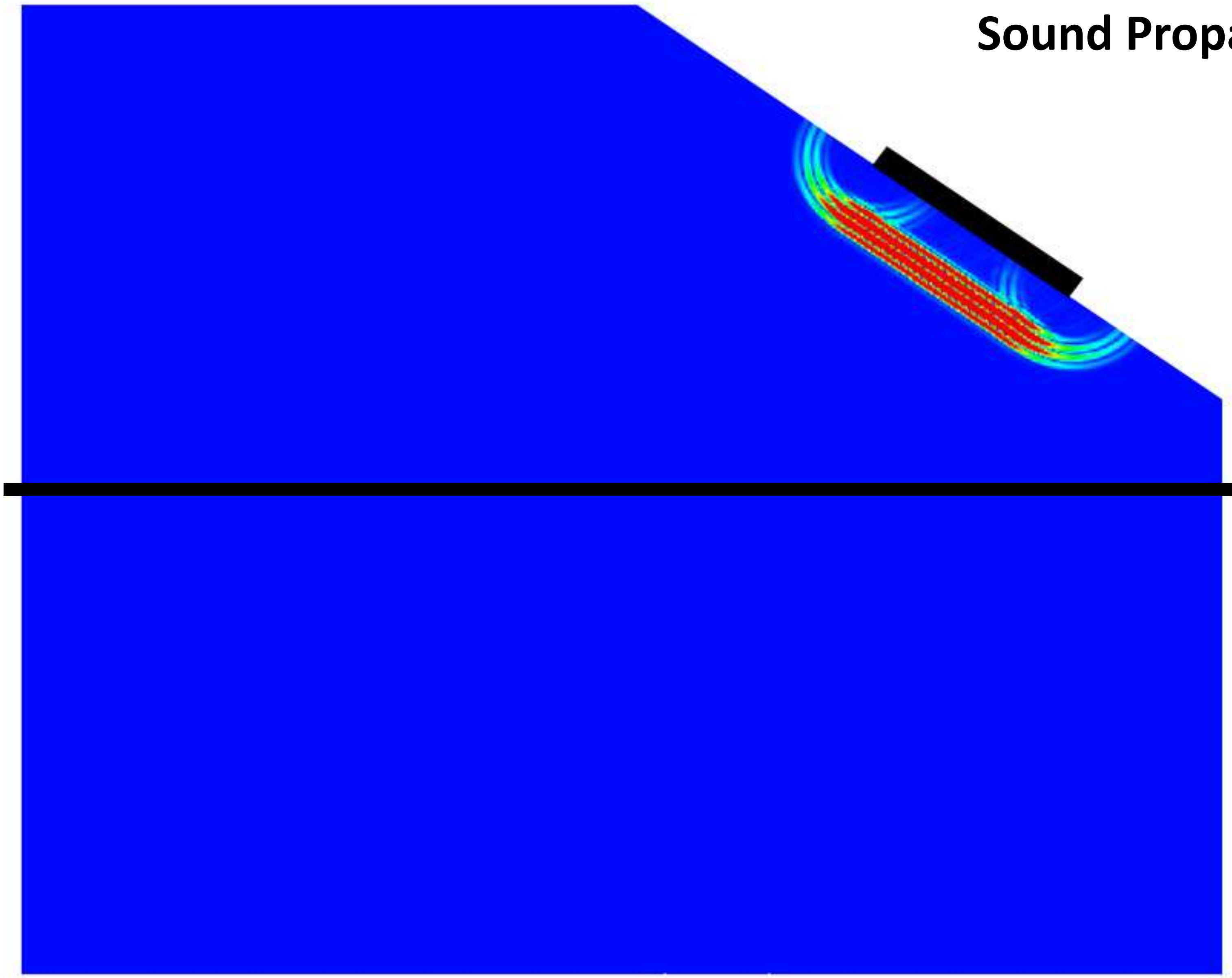
NDT&E Methods: UT

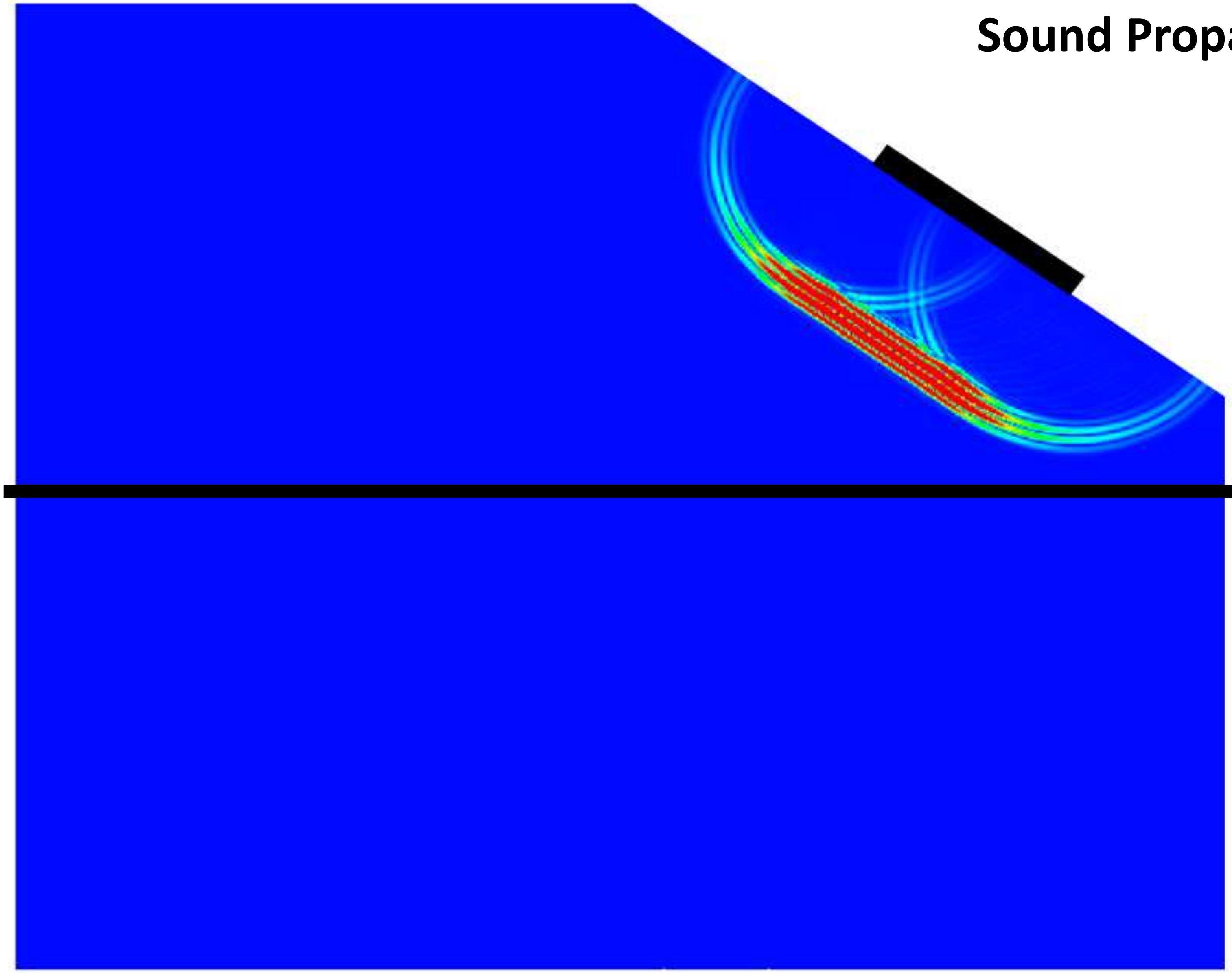
Sound Propagation

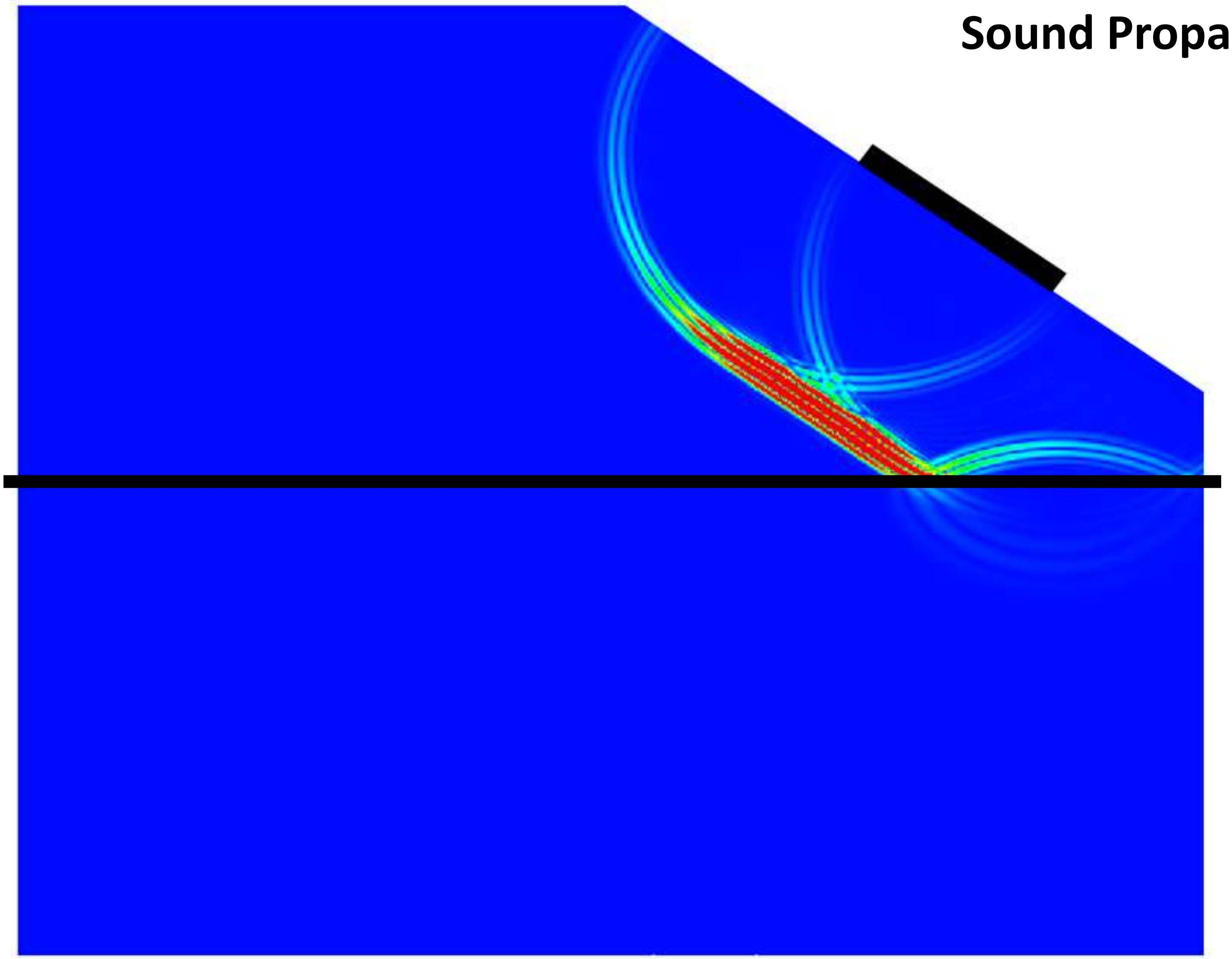


Intensity Profile (Broad Band Transducer)

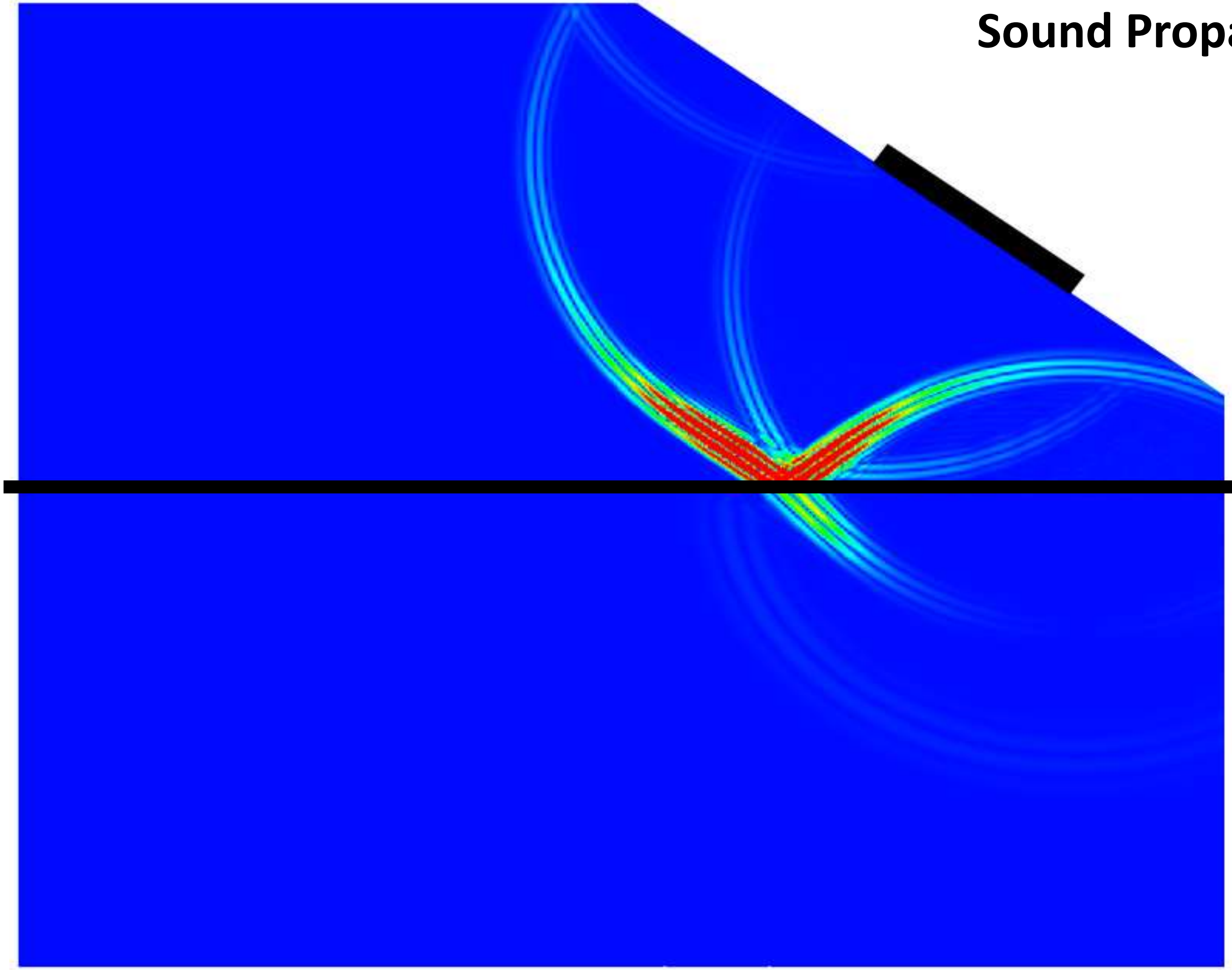
Sound Propagation

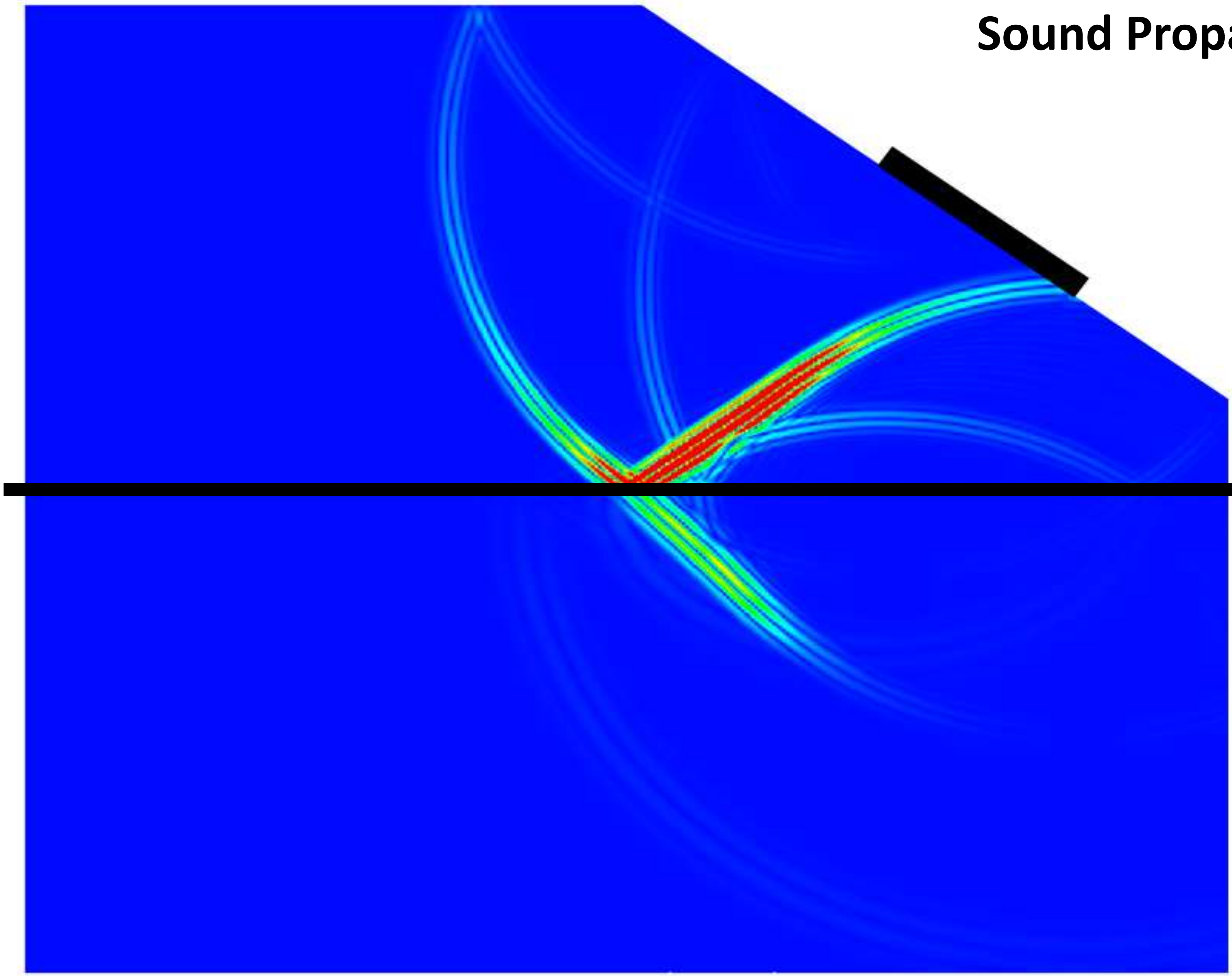


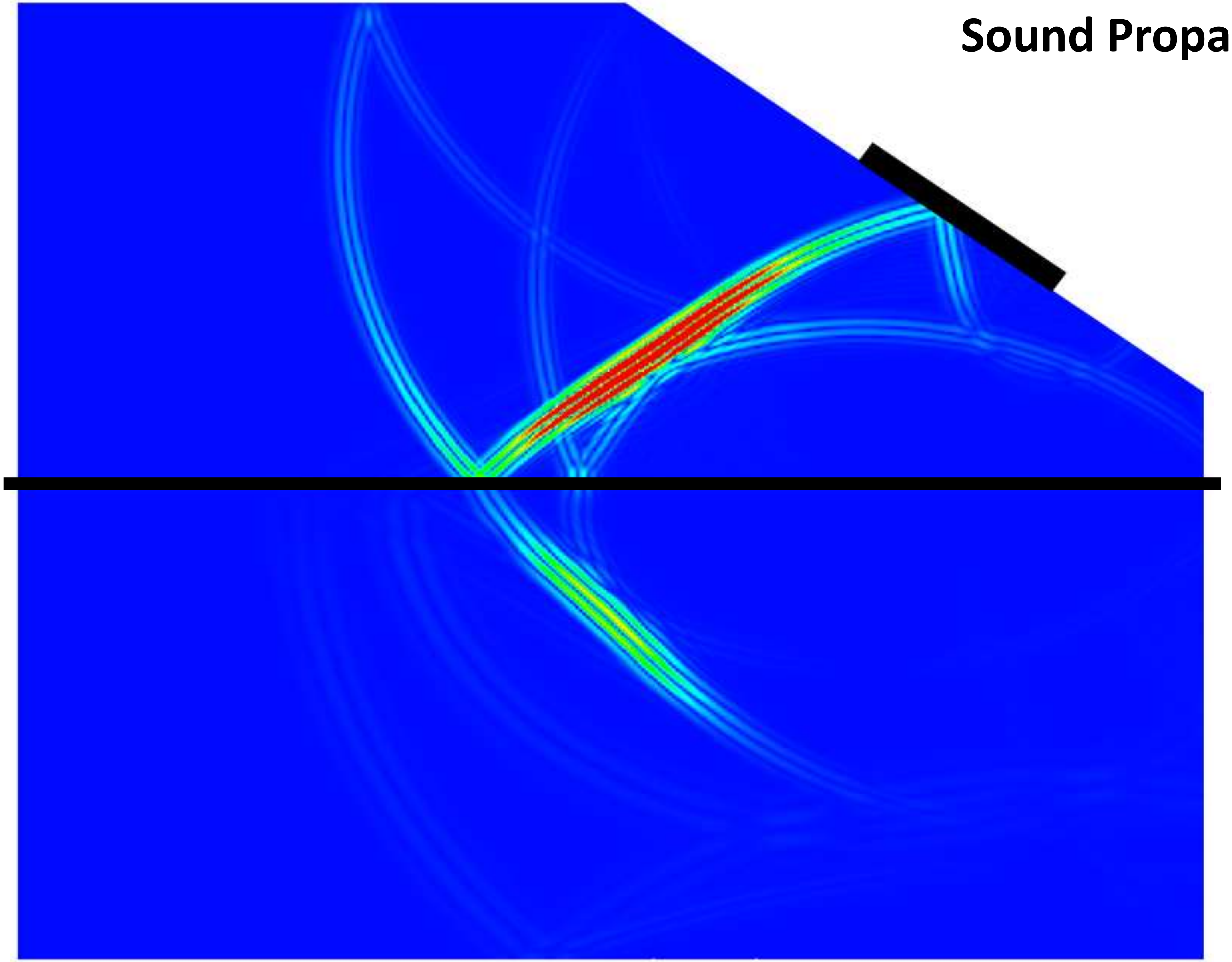




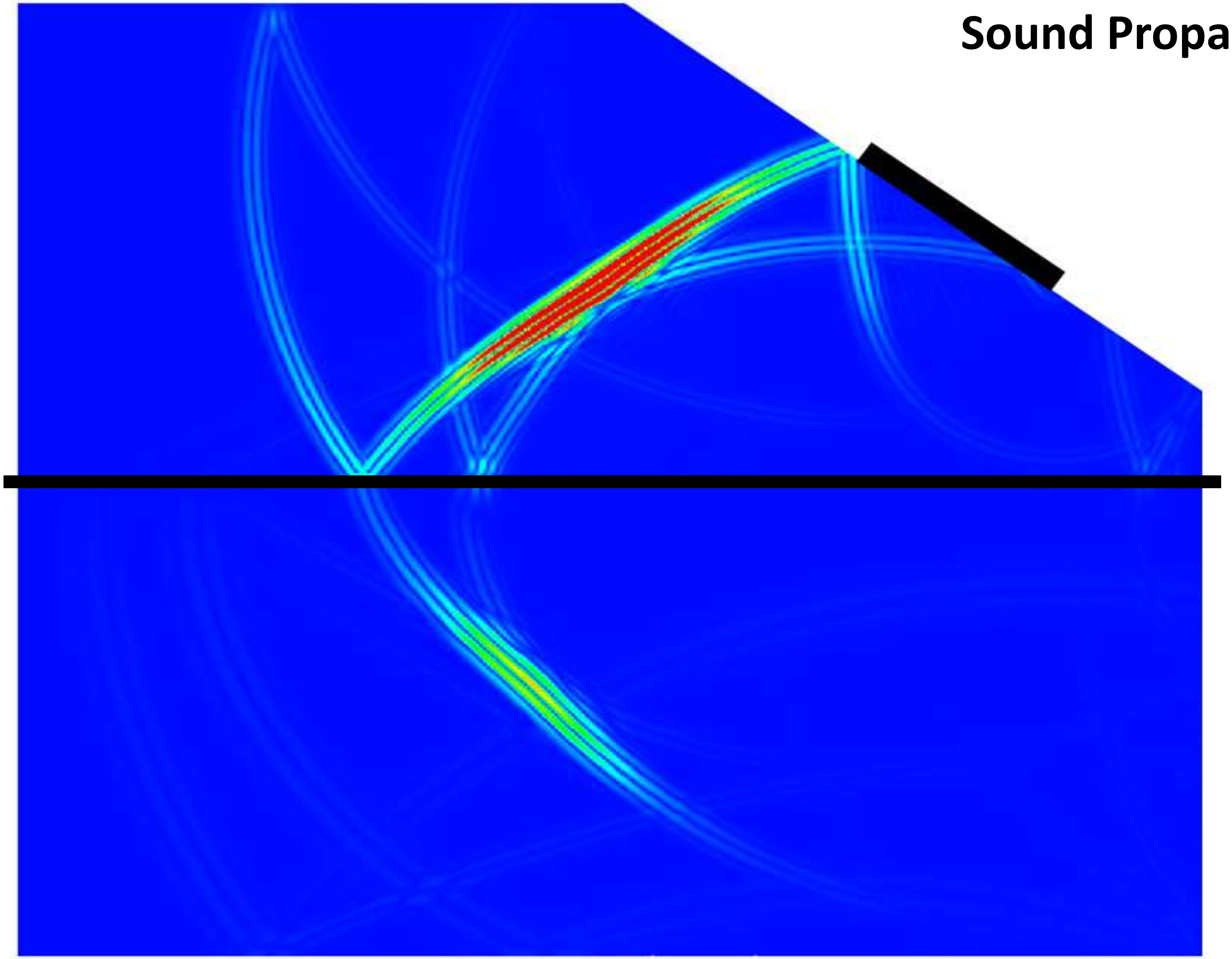
Sound Propagation



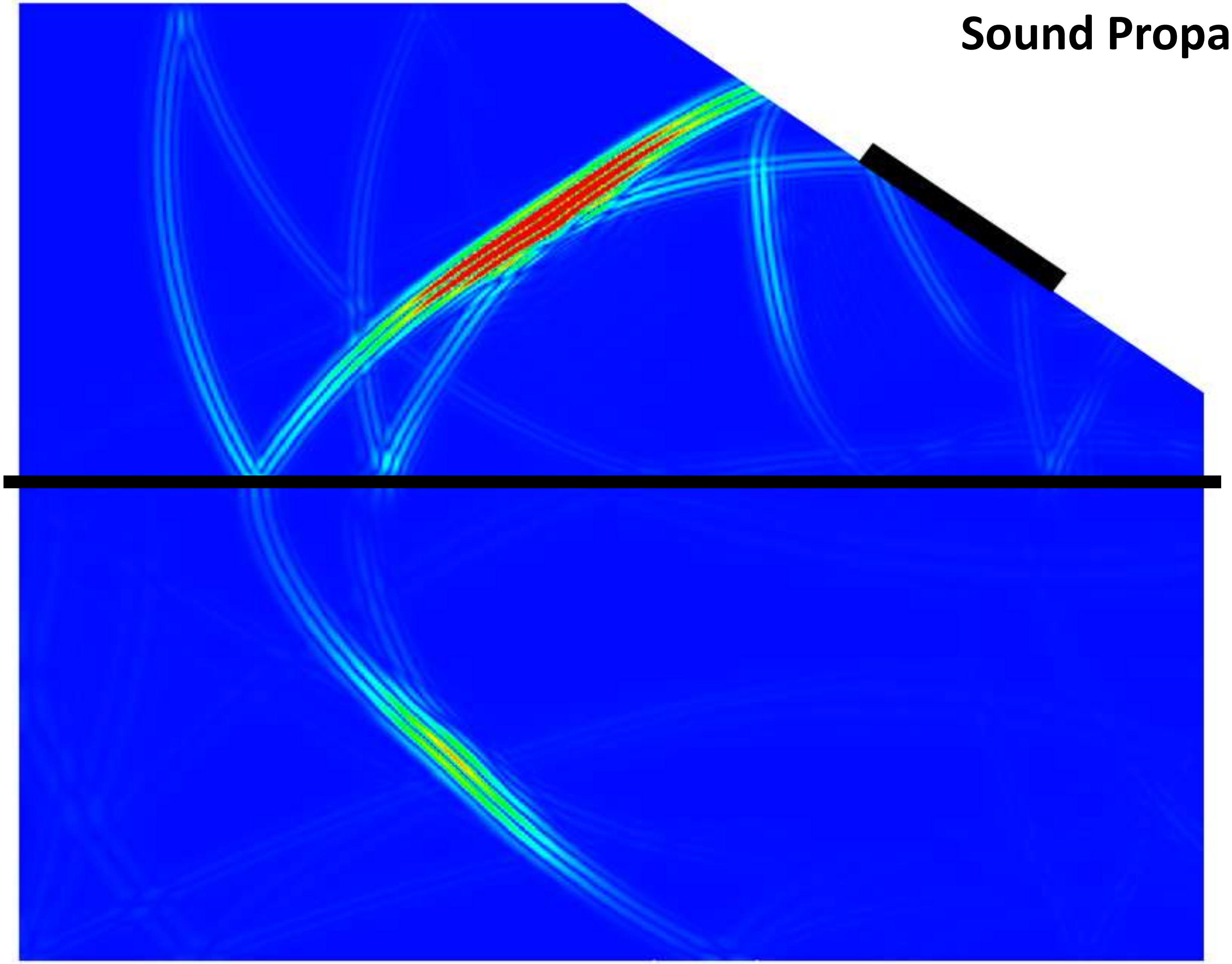




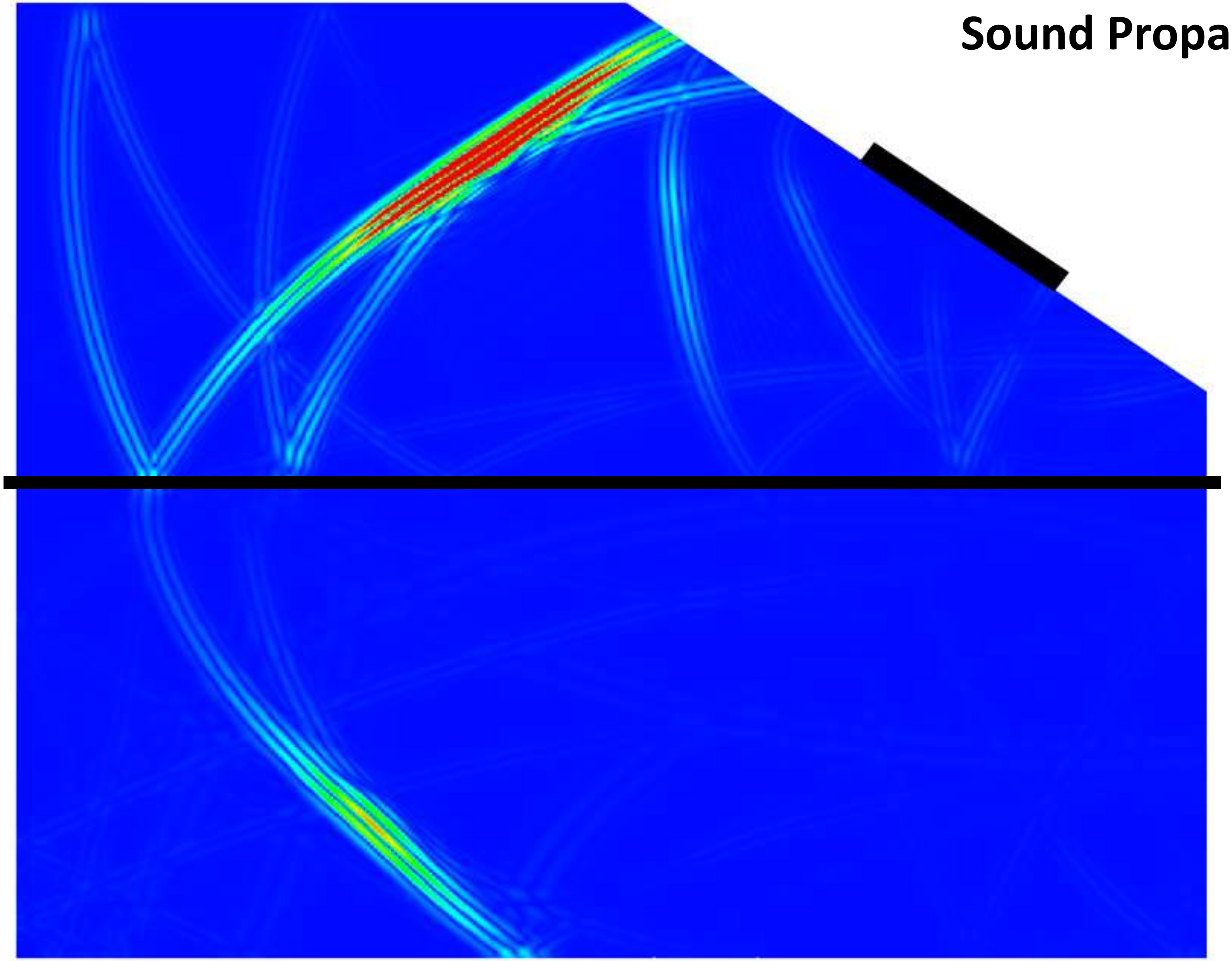
Sound Propagation



Sound Propagation

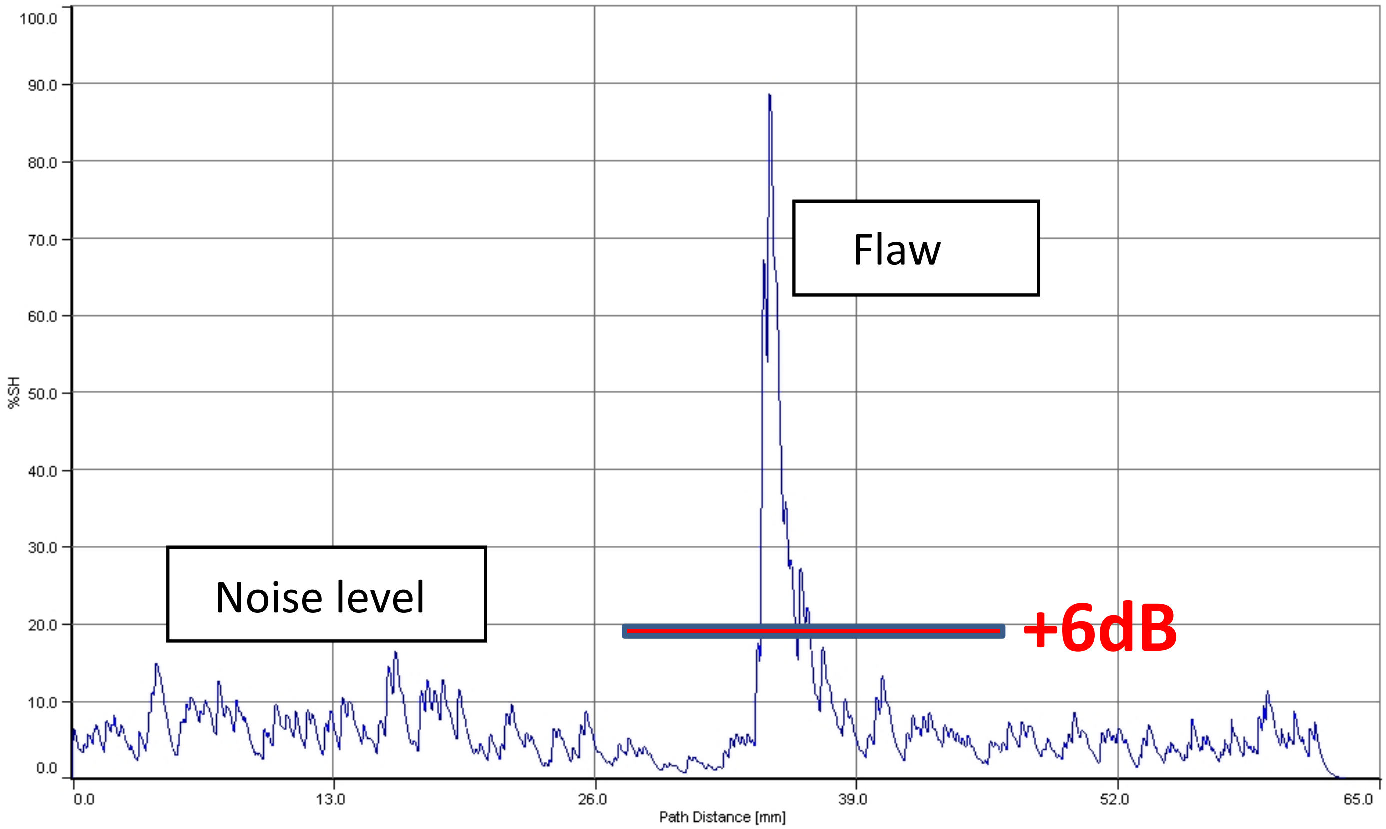


Sound Propagation



NDT&E Methods: UT

Sound Propagation



Required Minimal Sensitivity for Flaw Signal Detection

NDT&E Methods: UT

Sound Propagation

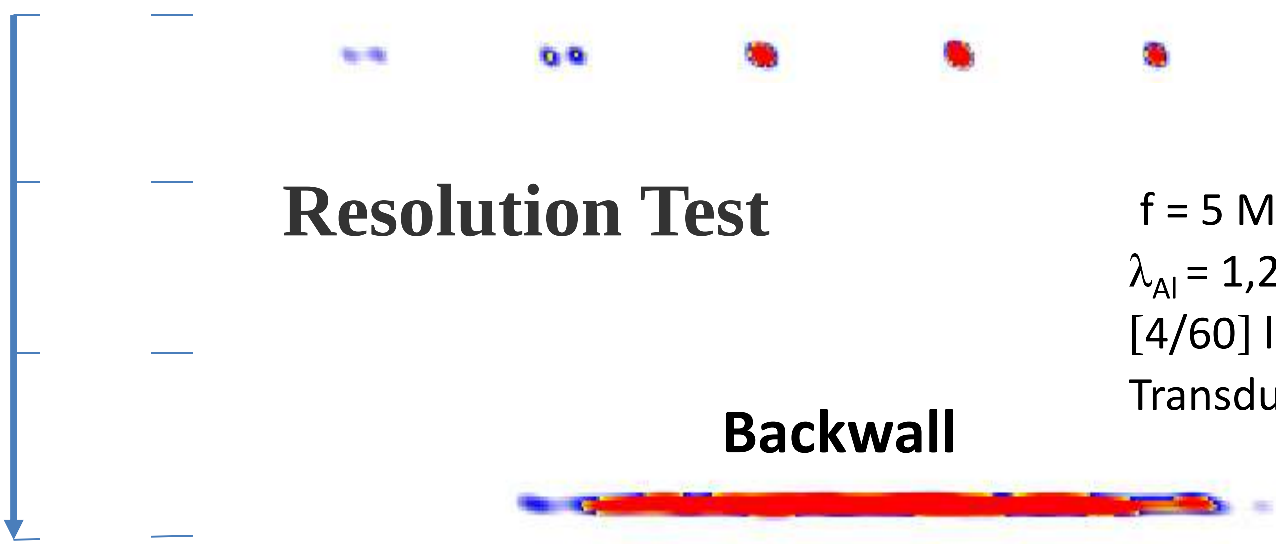
A Statement by Common Sense:

The longer the distance the less we can sense details,
We loose contrast and resolution sensitivity

DEPTH/mm

Center-Center Separation/mm
0.5mm Diameter SDH Pairs

D: 0.4 mm



f = 5 MHz
λ_{Al} = 1,26 mm
[4/60] linear array
Transducer: Olympus 5L60

Sound Attenuation

Attenuation of Ultrasound in a Media is due to:

- **Specular reflections**
- **Scattering from Inhomogeneity**
- **Beam Divergence**
- **Absorption**

Sound Attenuation

Acoustic Intensity I_{db} expressed in decibels

$$I_{dB}(\mathrm{dB}) = 10\log\left(I/I_{ref}\right)$$

I_{ref} is the reference intensity

$$I(\mathrm{W/m^2}) = \frac{P^2}{2\rho_0 c}$$

P is the pressure amplitude of the wave;
ρ_0 is the undisturbed mass density of the medium;
c is the speed of sound

0,1 – 4,0 MPa for diagnostic imaging

NDT&E Methods: UT

Attenuation

$$p(x,t) = Pe^{-\alpha x}\cos(\omega t - kx)$$

P: Amplitude of the Wave

$$\alpha = (\alpha_S + \alpha_R) + \alpha_D + \alpha_A$$

α [Np/m] is the frequency dependent amplitude attenuation coefficient

$$L_{\mathrm{Np}} = \ln\frac{x_1}{x_2} = \ln x_1 - \ln x_2.$$

The **neper** (unit symbol **Np**) is a logarithmic unit for ratios of measurements of physical field and power quantities, such as gain and loss of electronic signals.
The unit's name is derived from the name of John Napier, the inventor of logarithms.

NDT&E Methods: Attenuation

$$I = I_0 \exp(\alpha x)$$

I_0 : initial intensity, x: distance of wave propagation

α: attenuation coefficient - a function of frequency f

$$\boldsymbol{\alpha = \alpha_G + \alpha_A + \alpha_S}$$

α_G: geometric attenuation coefficient ($\sim 1.7\ \lambda/A^2$)

α_A: absorption coefficient

α_S: scattering coefficient

Any variation in a medium's density or sound speed will produce acoustic scattering.

Scatter depends primarily upon the size of the scatterer, the acoustic wavelength of the sound source, and the wave mode.

NDT&E Methods: Attenuation

The Scattering Coefficient

Diffuse (geometric) Scattering: Scattering cross section is large compared with the wavelength. The sound diffuses into various directions or will be absorbed by large coarse grains:

$$\boldsymbol{\alpha_D = C_D d^{-1}} \qquad \lambda \ll \pi d$$

Stochastic Scattering: Scattering cross section is about the wave length; It can be assessed by the cross section per scattering element:

$$\boldsymbol{\alpha_S = C_S d f^2} \qquad \lambda \cong \pi d$$

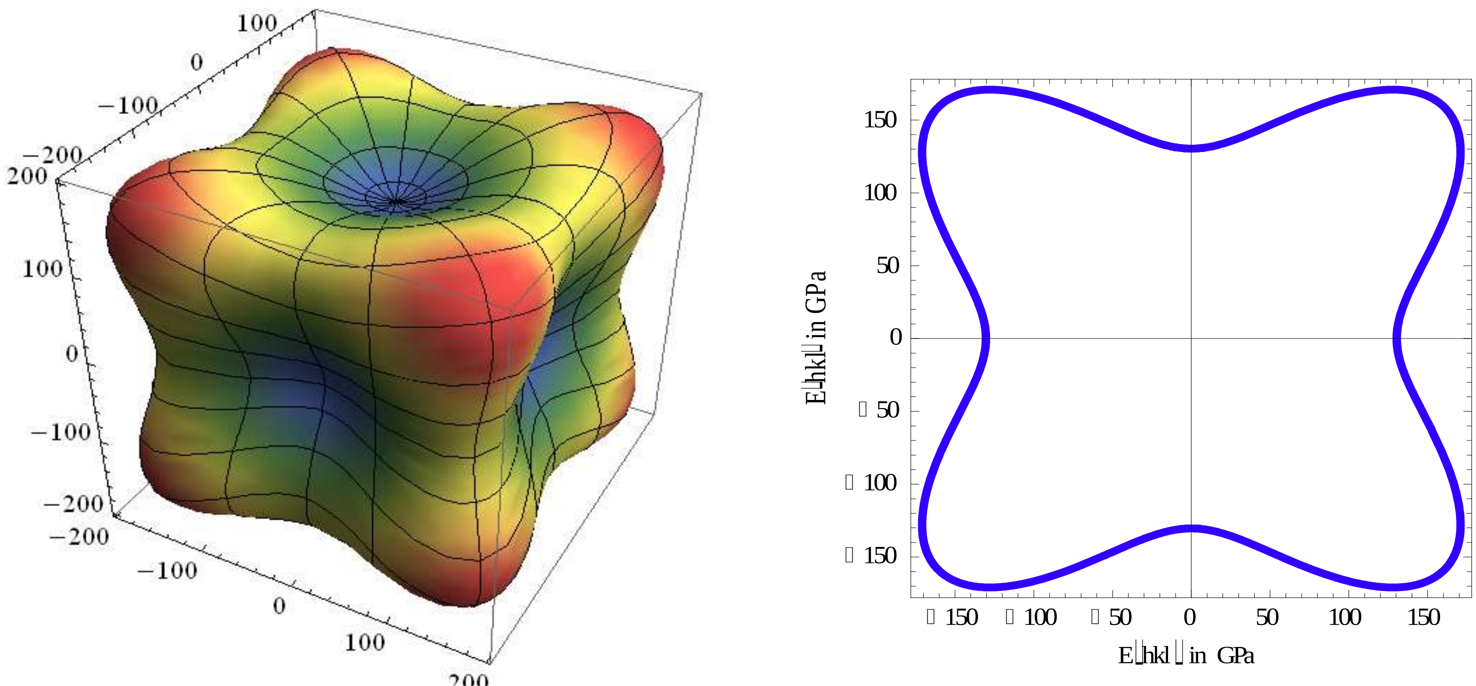
Rayleigh Scattering: Scattering cross sections are significantly smaller than the wave length; acoustic noise observable when scanning results from Raleigh scattering:

$$\boldsymbol{\alpha_r = C_r d^3 f^4} \qquad \lambda \gg \pi d$$

C_D, C_S and C_r are constants denoting material density, elastic anisotropy, sound velocity, and geometry factors.

NDT&E Methods: Rayleigh Scattering

NDT&E Methods: Attenuation



Elastic Constants of Ferrite as a Function of Crystallographic Axes

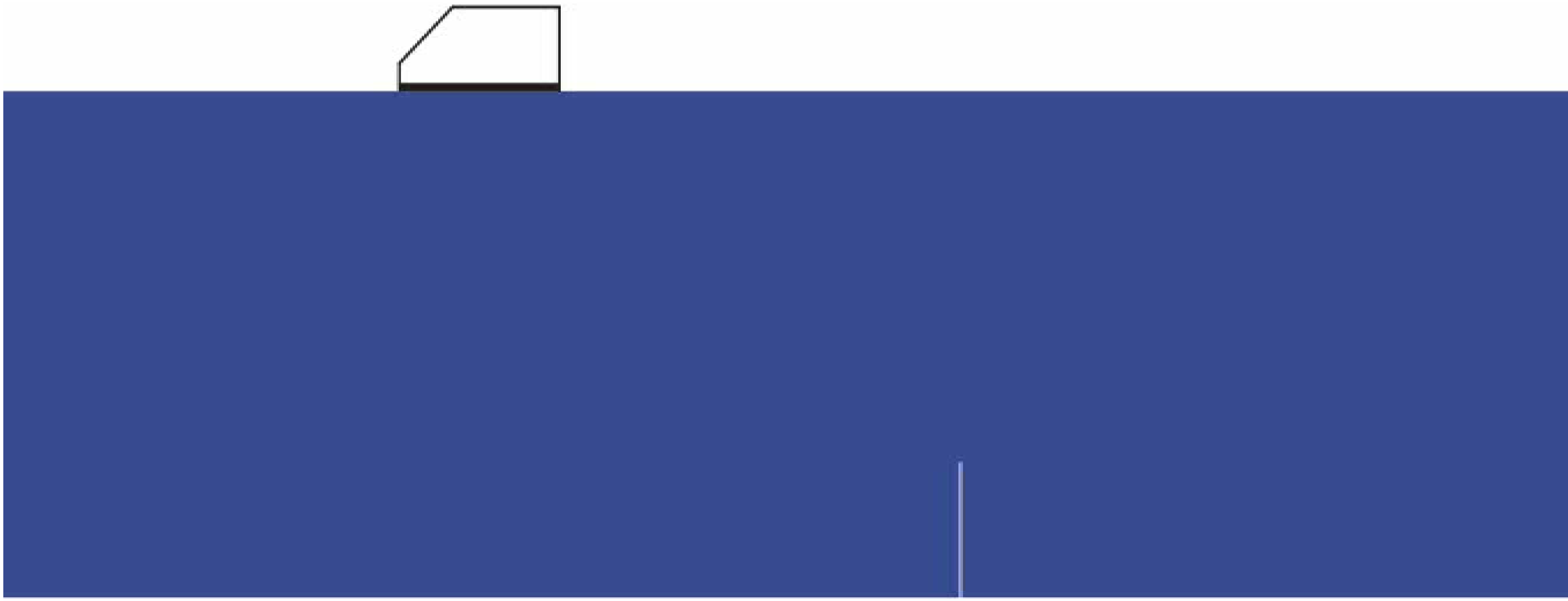
	S_{11} [1/TPa]	S_{12} [1/Tpa]	S_{44} [1/Tpa]	C_{11} [Gpa]	C_{12} [Gpa]	C_{44} [Gpa]	Anisotropy Factor A
Aluminium	16	-5.8	35.3	108	62	28.3	1.2
Iron	7.67	-2.83	8.57	230	117	135	2.5
Copper	15	-6.3	13.3	169	122	75.3	3.2

Elastic Properties of Cubic Systems

Technical Principles
for
Improving Sensitivity and Resolution

NDT&E Methods: UT

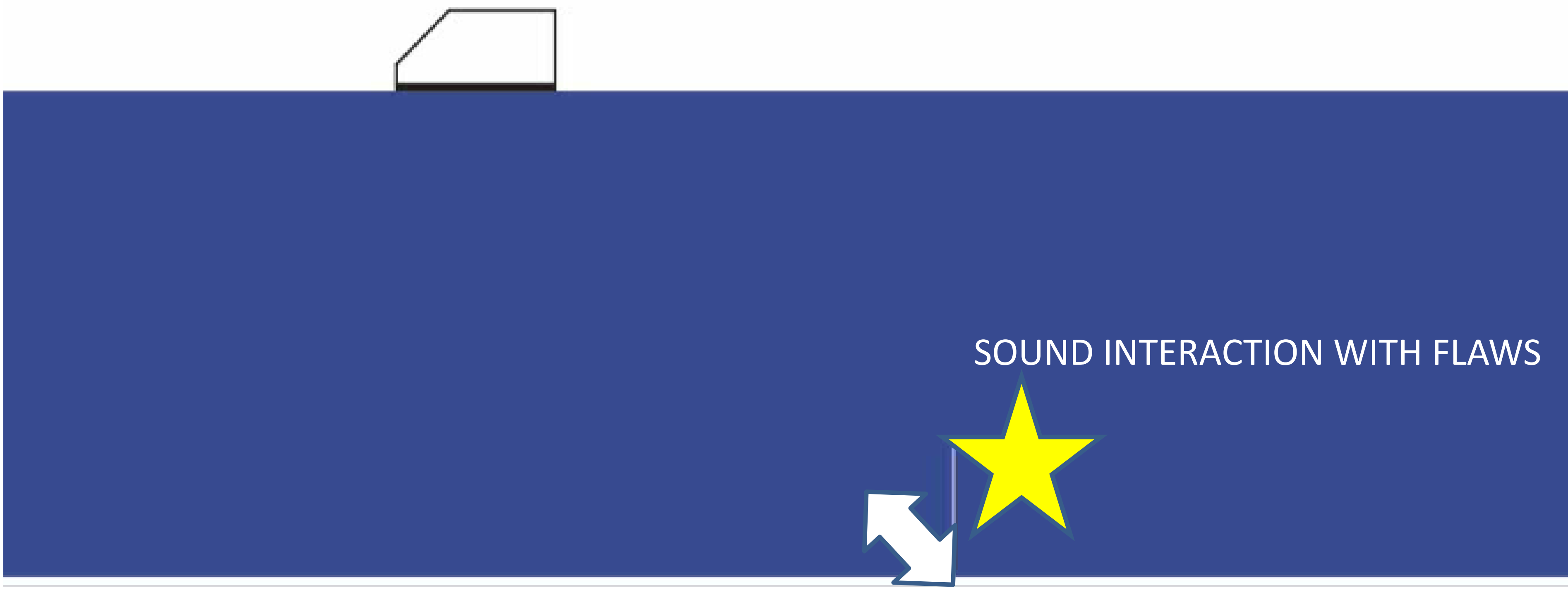
There is a must until now: ACOUSTIC ISOTRPY



There are no standards for the consideration of acoustic anisotropy but promising research results

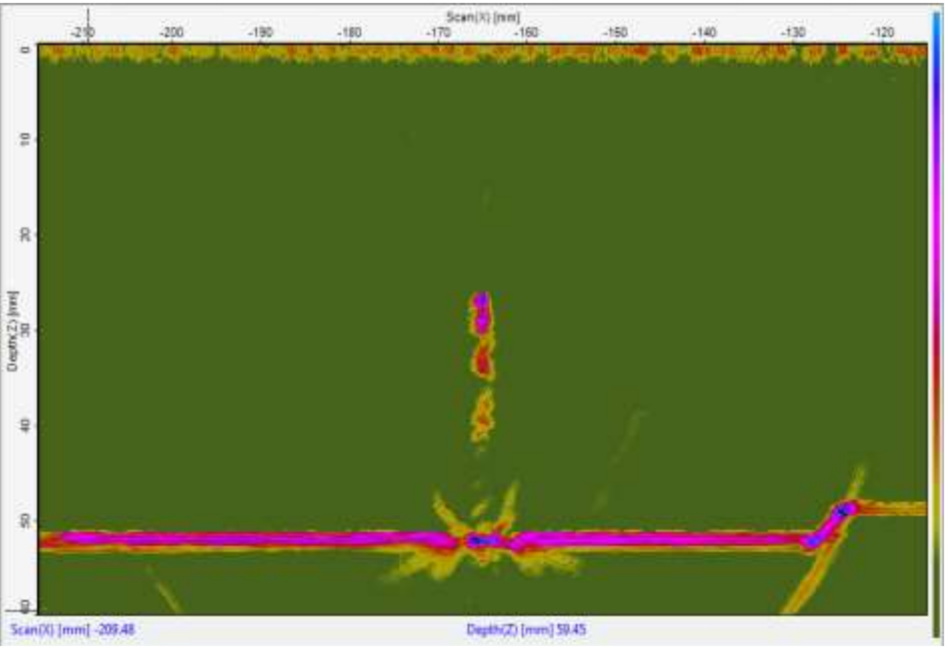
NDT&E Methods: UT

The Pulse-Echo Method

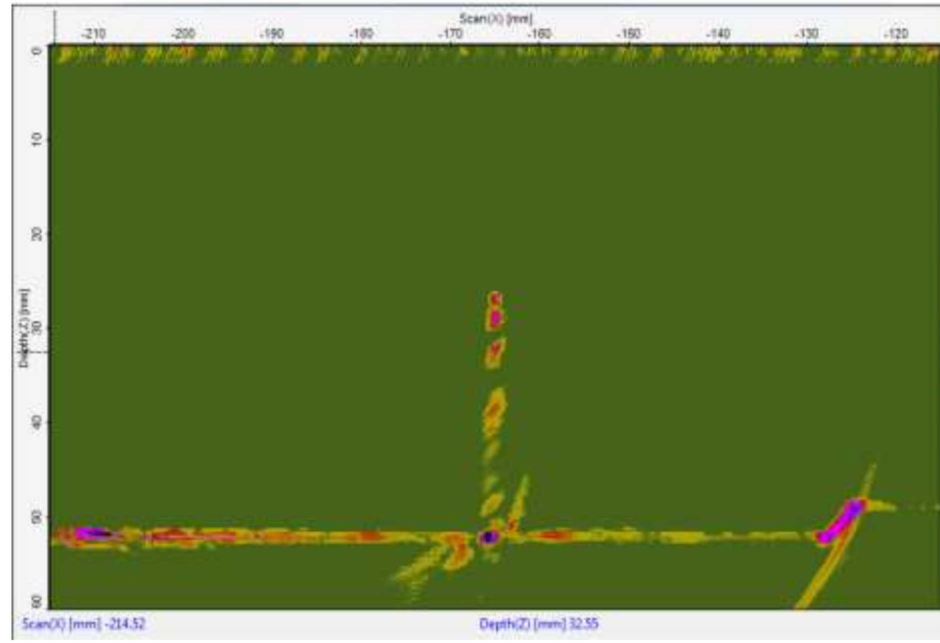


NDT&E Methods: UT

Sound Propagation



a) Complete Compound Scan



b) Limited Compound Scan

(Transducer: Olympus 60L5; 4 Transmit Elements; L-Mode)

Crack Imaging

Literature

1.