GUIDED WAVE RADIATION FROM A POINT SOURCE IN THE PROXIMITY OF A PIPE BEND

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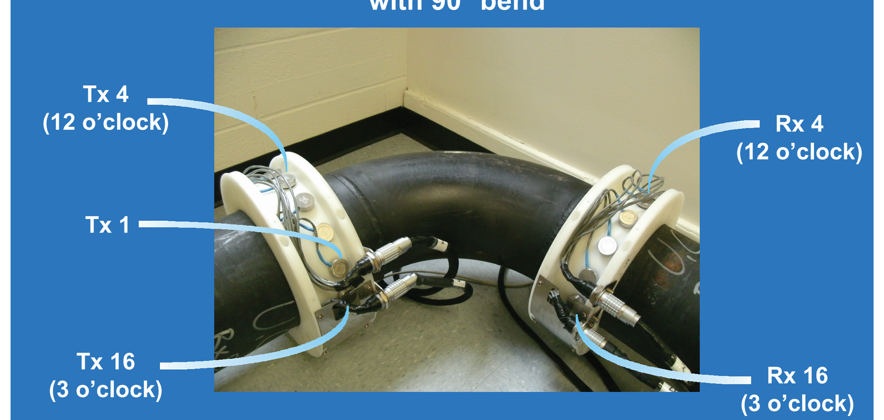
INTRODUCTION

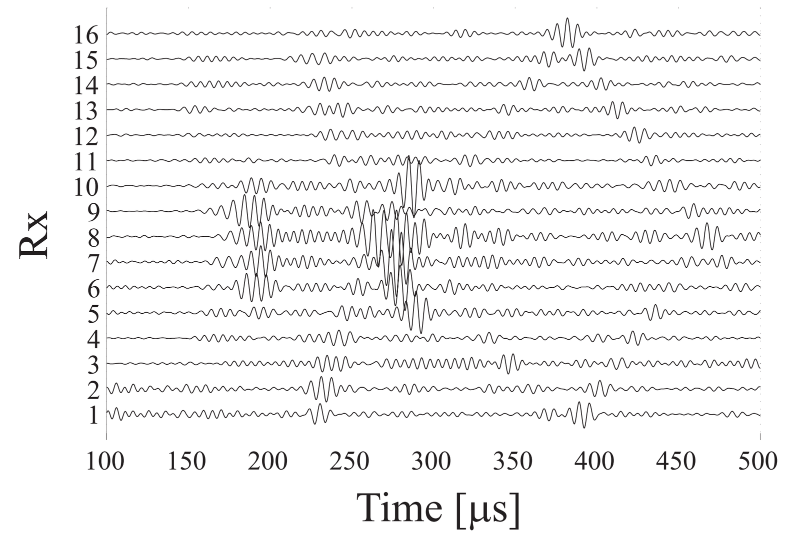
Throughout the oil and gas industry corrosion and erosion damage monitoring play a central role in managing asset integrity. Recently, the use of guided wave technology in conjunction with tomography techniques has provided the possibility of obtaining point-by-point maps of wall thickness loss over the entire volume of a pipeline section between two ring arrays of ultrasonic transducers. Current research has focused on straight pipes while little work has been done on pipe bends which are also the most susceptible to developing damage. Tomography of the bend is challenging due to the complexity and computational cost of the 3-D elastic model required to accurately describe guided wave propagation. Here we reduce the 3-D elastic model to a 2-D acoustic model that simplifies the interpretation of guided wave propagation phenomena and leads to greater computational efficiency for tomographic applications.

8" Dia. Schedule 40 Pipe with 90° bend

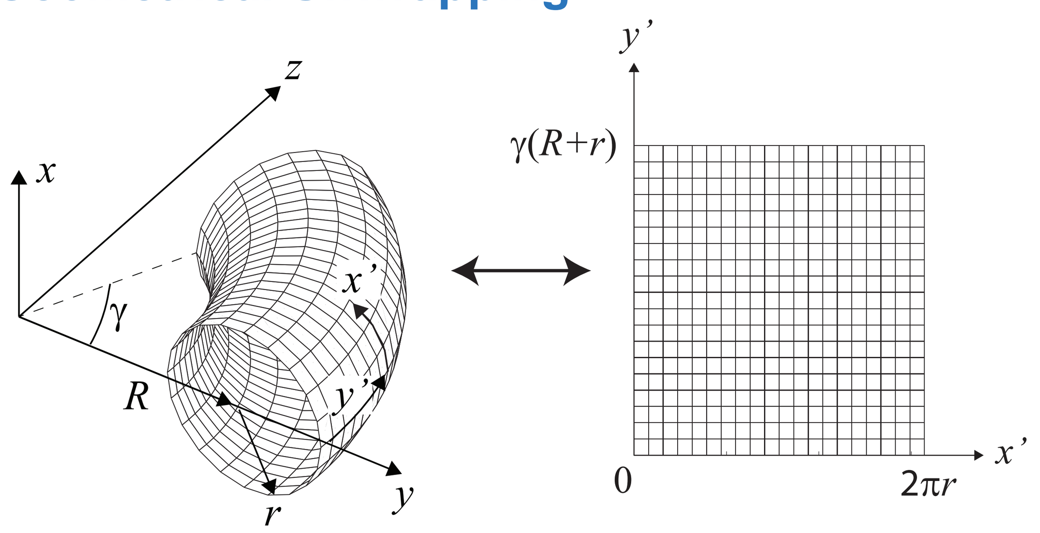


Ring arrays of EMAT transducers placed near bend, Transducers labeled in counter-couclockwise order

Cascade plot of signals received by Rx 1-16 with Tx 8 transmitting



Geometrical Unwrapping



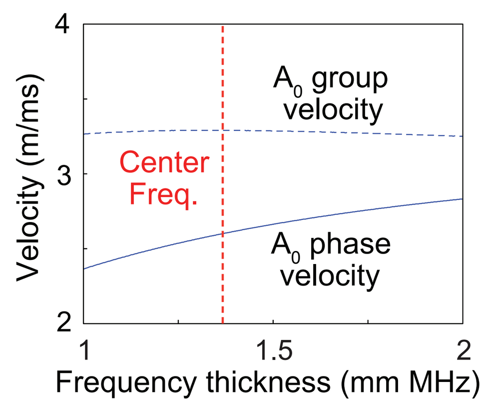
2-D Parameterization

$$x = r\sin\frac{x'}{r}$$

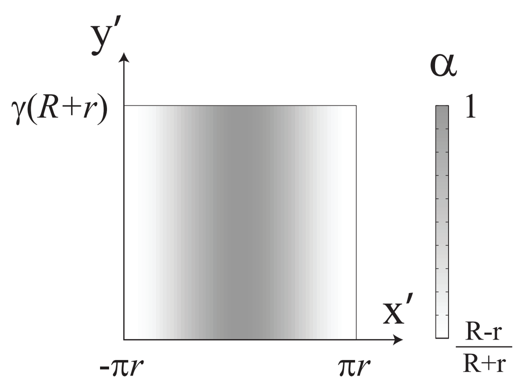
$$y = \left(R + r\cos\frac{x'}{r}\right)\cos\frac{y'}{R+r}$$

$$z = \left(R + r\cos\frac{x'}{r}\right)\sin\frac{y'}{R+r}$$

2-D Anisotropic Acoustic Model



A_0 Frequency Dependence



Map of stretching

To account for the stretching caused by the unwrapping, the 2-D acoustic model is anisotropic and inhomogeneous, with waves propagating more rapidly along the inside of the bend.

Elliptically anisotropic sound speed in the acoustic model

$$c_{ani}(x', y', \beta) = \frac{c(x', y', f)}{\sqrt{\cos^2\beta + \alpha^2\sin^2\beta}}$$

$c(x', y', f)$ - A_0 mode group velocity

$c_{ani}(x', y', \beta)$ - anisotropic acoustic velocity

β - direction of travel, angle measured from x' axis

$\alpha = \frac{R + r\cos\frac{x'}{r}}{R+r}$ - measure of anisotropy and inhomogeneity

Anisotropic Acoustic Ray Equation

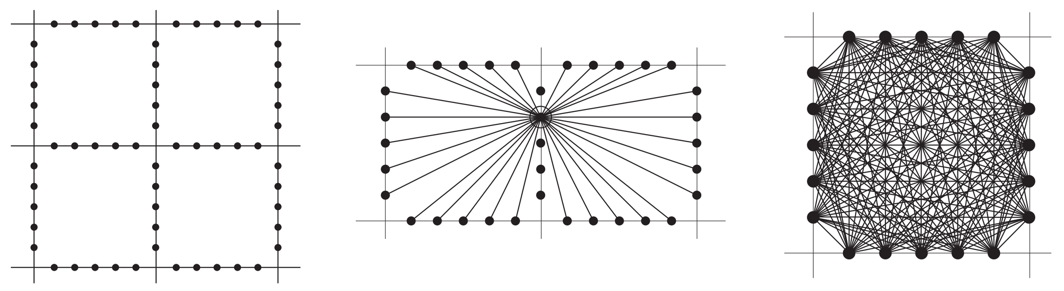
Under the short wavelength approximation, wave propagation can be described according to the ray theory of geometrical acoustics based on the Eikonal equation. Ray theory does not account for diffraction effects, but can be implemented with great computationally efficiency and leads to accurate first-arival traveltime estimations.

Anisotropic Eikonal Equation

$$c^2\left(\frac{\partial t}{\partial x'}\right)^2 + \frac{c^2}{\alpha^2}\left(\frac{\partial t}{\partial y'}\right)^2 = 1$$

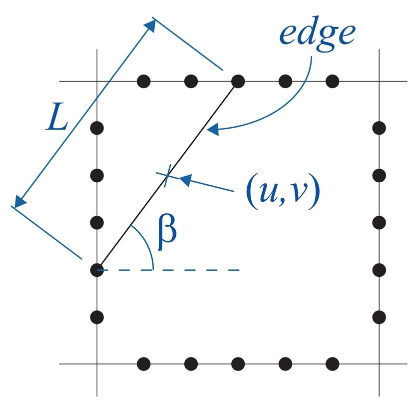
SOLVING THE EIKONAL EQ. VIA SHORTEST PATH METHOD

Shortest Path Ray tracing (SPR) represents the possible ray-paths over the 2-D domain as a weighted graph, where the edge costs correspond to traveltimes. Dijkstra's algorithm is used to determine the minimum traveltime paths, which are chosen as the true ray paths due to Fermat's principle.



Node Placement about elements — Edges per Node — Edges per Element

Calculation of Edge Costs



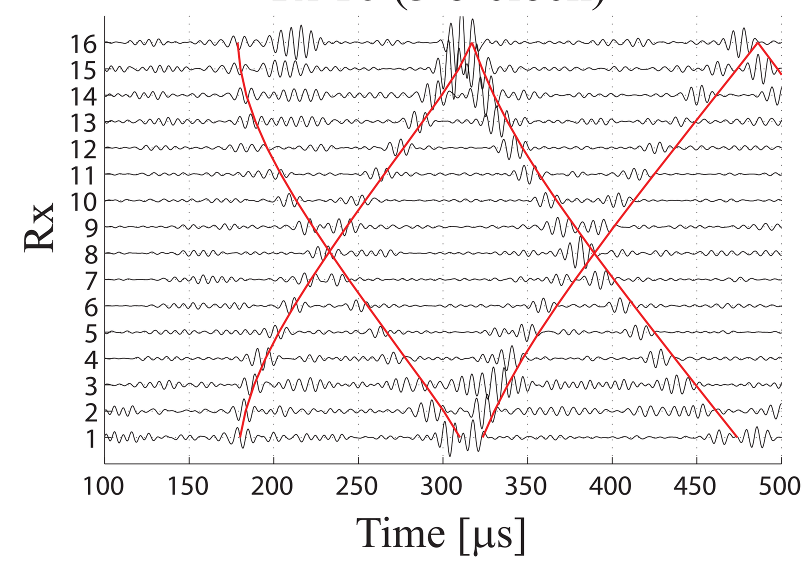
$$\mathrm{Cost}(edge) = \frac{L}{c_{ani}(u, v, \beta)}$$

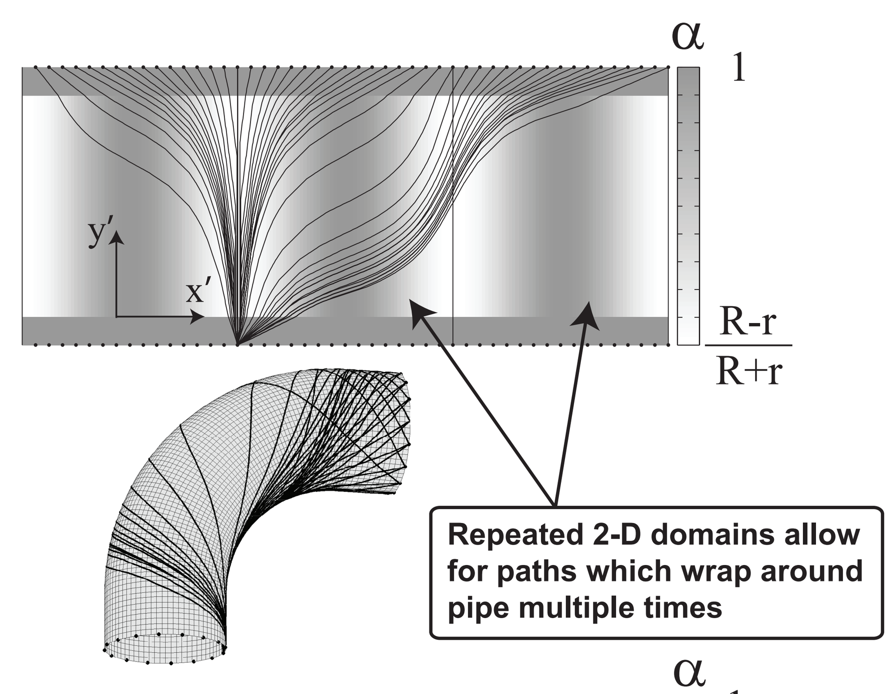
Dijkstra's algorithm is used in a wide variety of applications, including: routing network packets, giving driving directions with GPS, and much more.

EXPERIMENTAL VALIDATION

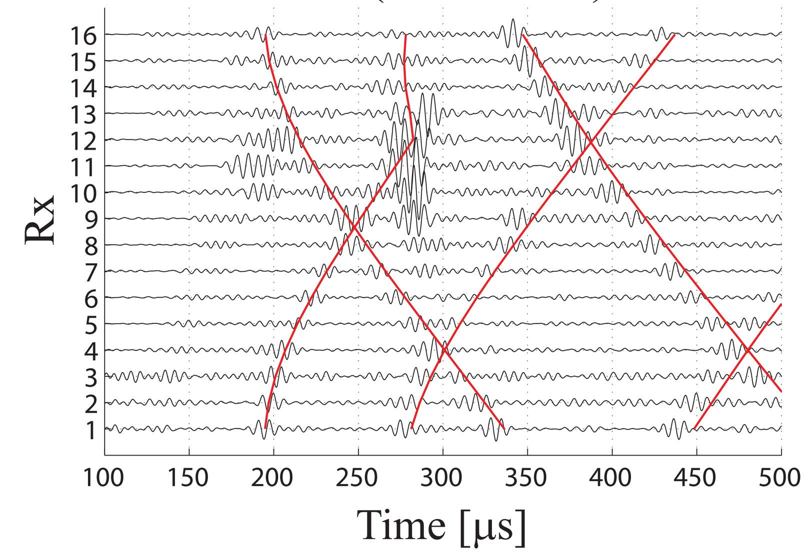
Measured signals vs. SPR traveltime predictions — **Predicted ray paths of first arrivals**

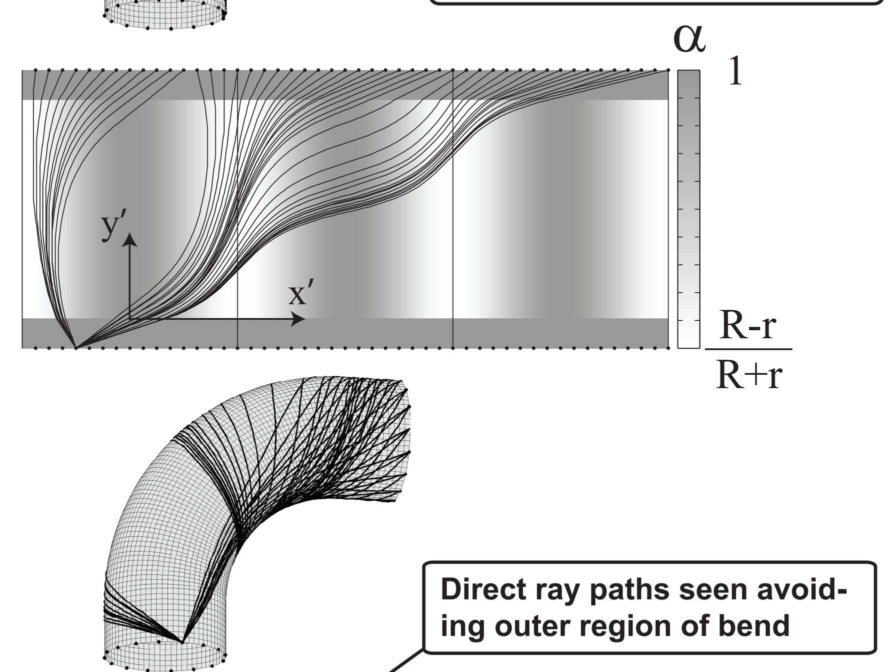
Tx 16 (3 o'clock)



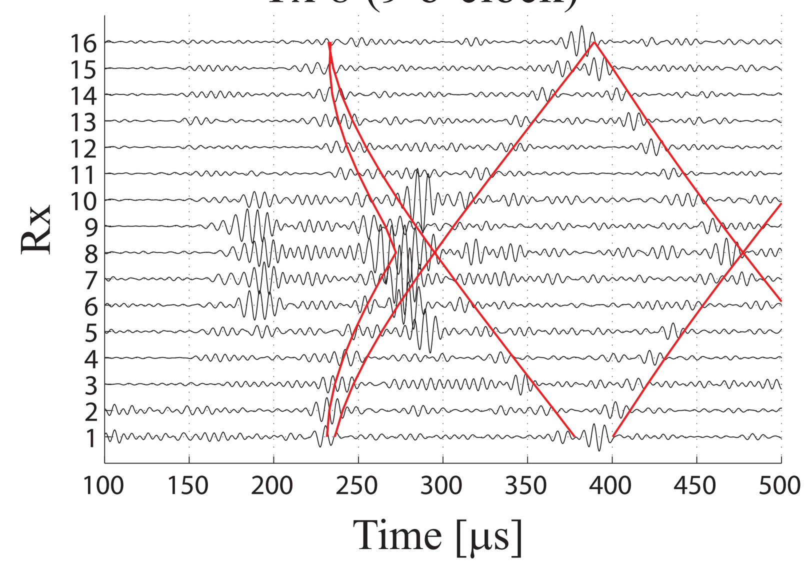


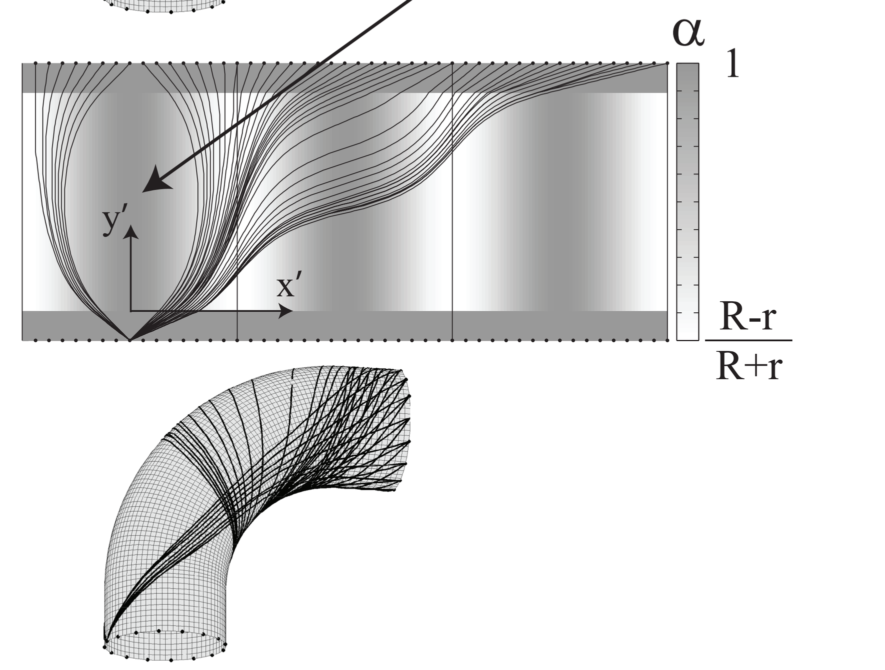
Tx 4 (12 o'clock)





Tx 8 (9 o'clock)



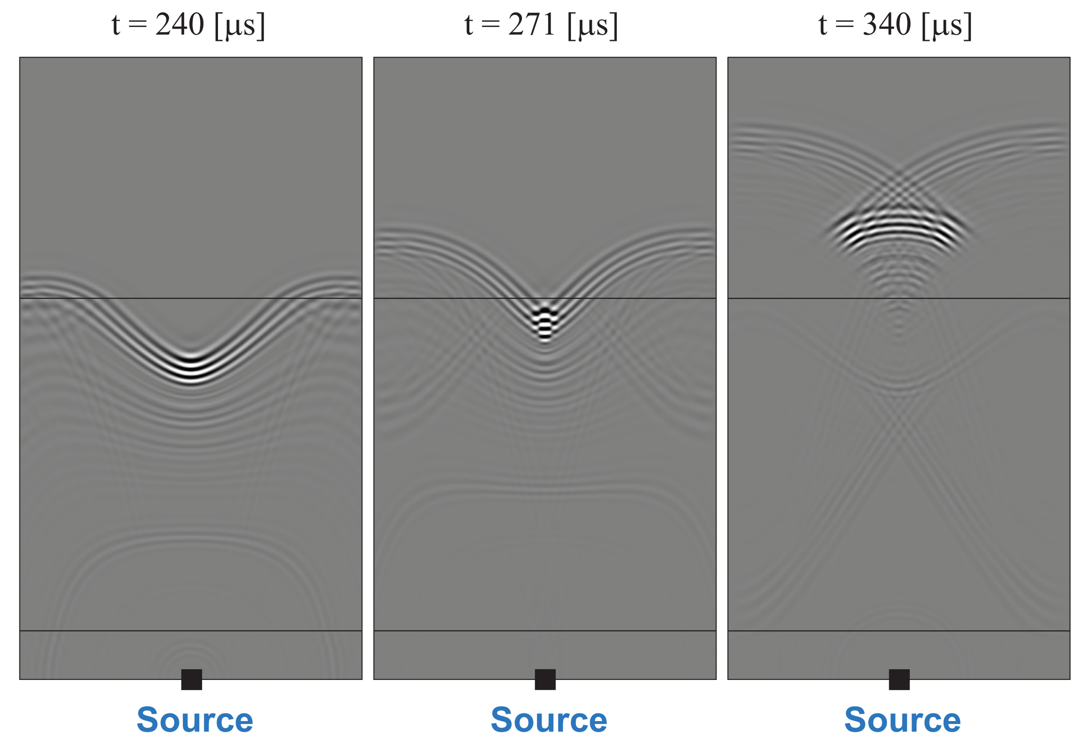


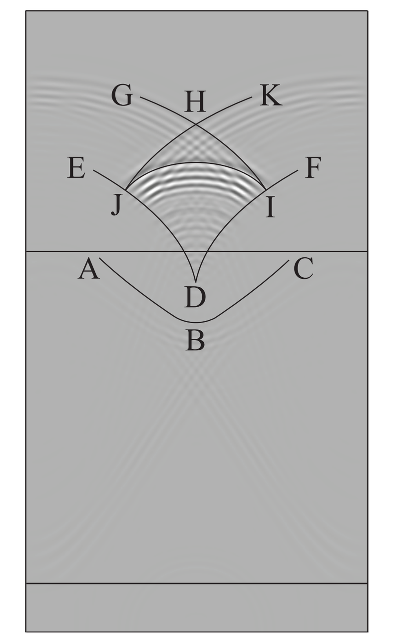
FOCUSING EFFECT

Finite element models simulating the full wave equation predict a focusing effect that occurs when the source is near the outside of the bend. The low sound speed valley in this region causes distortion of the wavefront radiating from the source, leadining to the concave front ABC. The wavefront continues to distort with propagation distance and eventually folds in on itself, causing an energized branch JI to trail behind the first arrivals JK and GI.

Anisotropic Acoustic Wave Equation

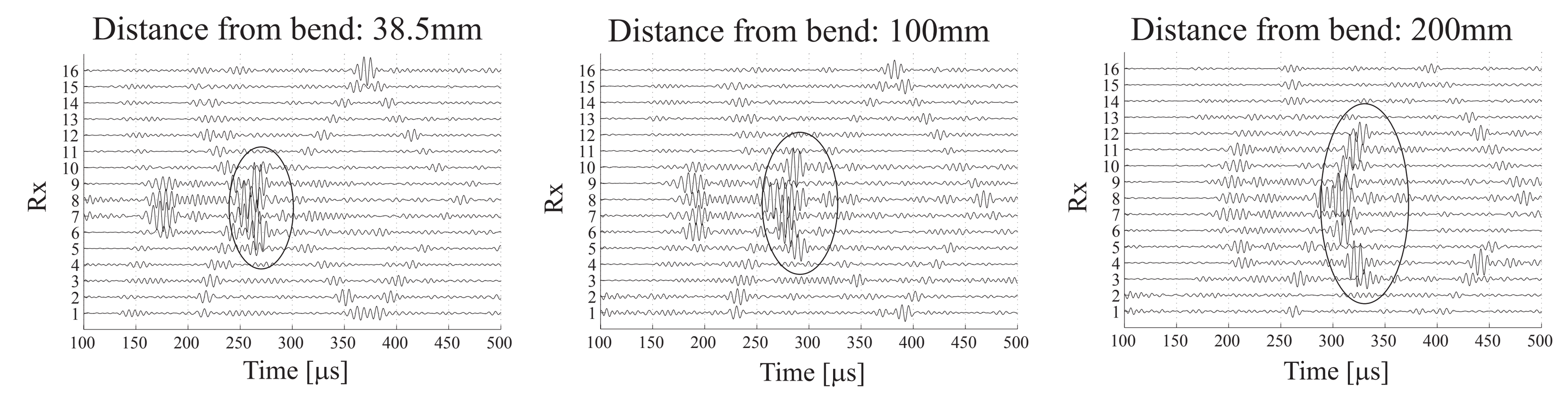
$$\frac{\partial^2 p}{\partial t^2} = c^2\frac{\partial^2 p}{\partial x^2} + \frac{c^2}{\alpha^2}\frac{\partial^2 p}{\partial y^2}$$





Experimental Observation of Focusing Effect

Measurements taken with source Tx 8 on the outside of the bend, and the receiver ring array in different positions show the growth of the energized branch, consistent with FEM predictions.



CONCLUSIONS

- The propagation of elastic guided waves through 3-D bends can be approximated with a 2-D anisotropic acoustic model
- A self-focusing effect is discovered when guided waves radiate from a source near the outer region of the bend
- SPR provides accurate and robust traveltime estimations for first arrivals through the bend
- SPR offers greater computational efficiency than numeric solutions of the full wave equation, making it ideal for use in traveltime tomography
- First arrivals which take a direct path avoid the outside of the bend and are not sensitive to defects in this area
- Modes that wrap around the pipe multiple times cross the outside of the bend and provide sensitivity to defects that would otherwise be elusive to direct paths