Medical Applications in the Scientific Domain

Parallel Three-Dimensional Simulation of Ultrasound Imaging

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Outline

Ultrasound imaging

3D parallel ultrasound simulator

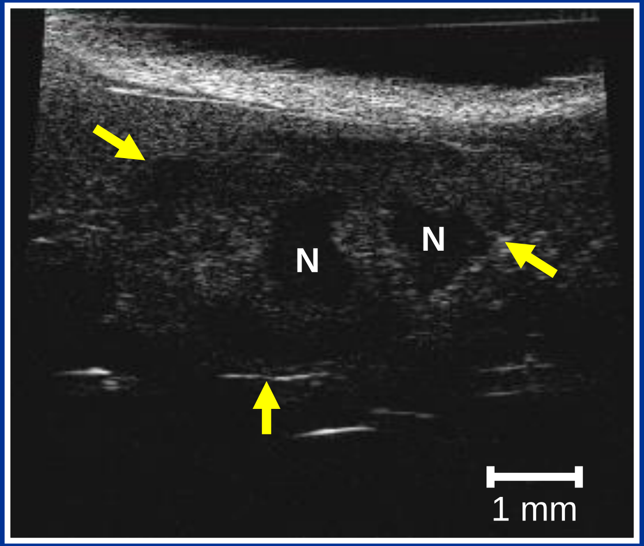
Numerical accuracy

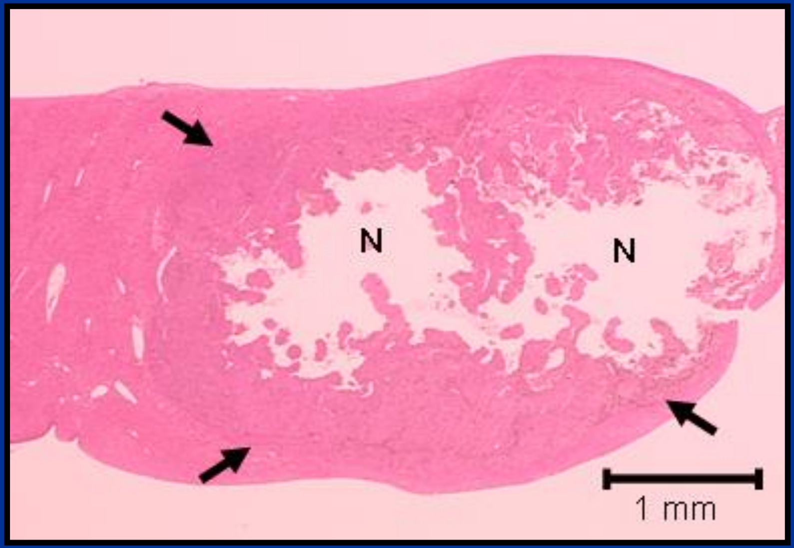
Parallel performance

Ultrasound imaging simulations

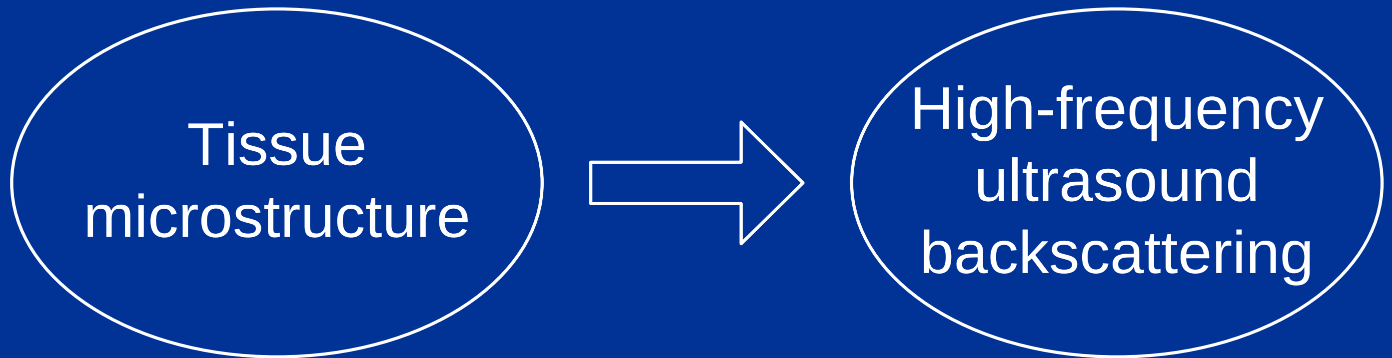
Motivation

High-frequency ultrasound imaging can be used to track tumor growth in cancer research



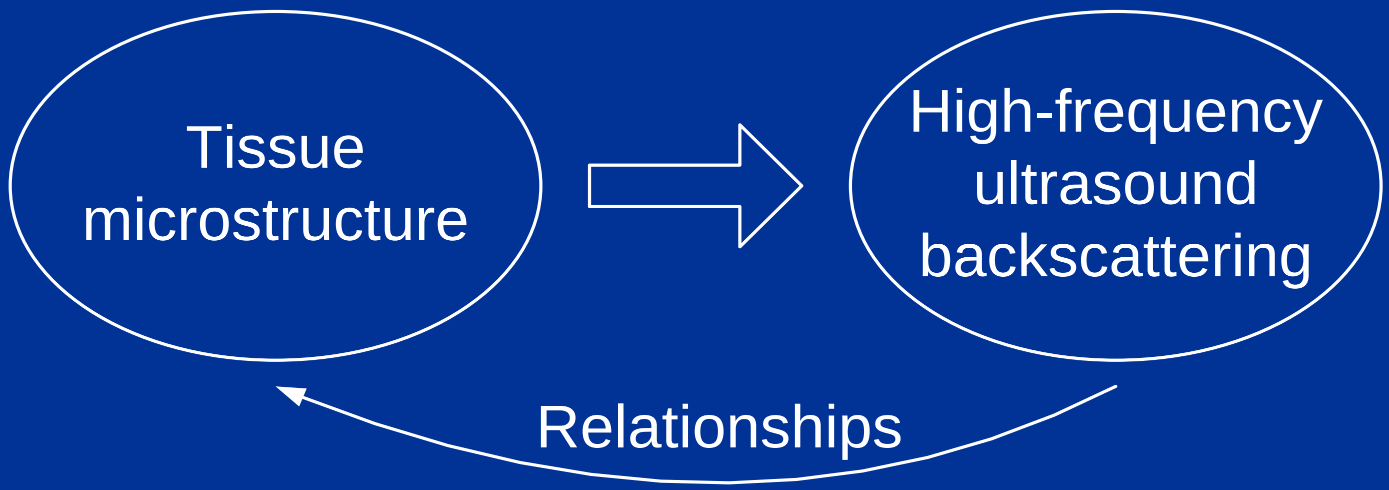


Motivation



Tumor size and shape

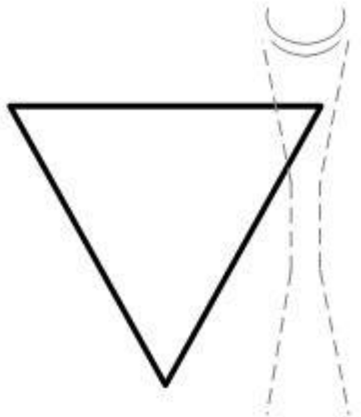
Motivation



Additional information about tumor microstructure

Ultrasound Imaging

Scan lines acquisition

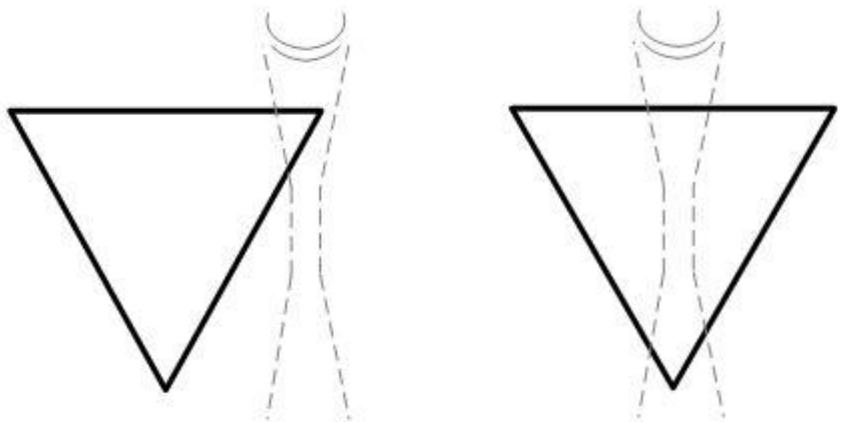


Time

B-mode image

Ultrasound Imaging

Scan lines acquisition

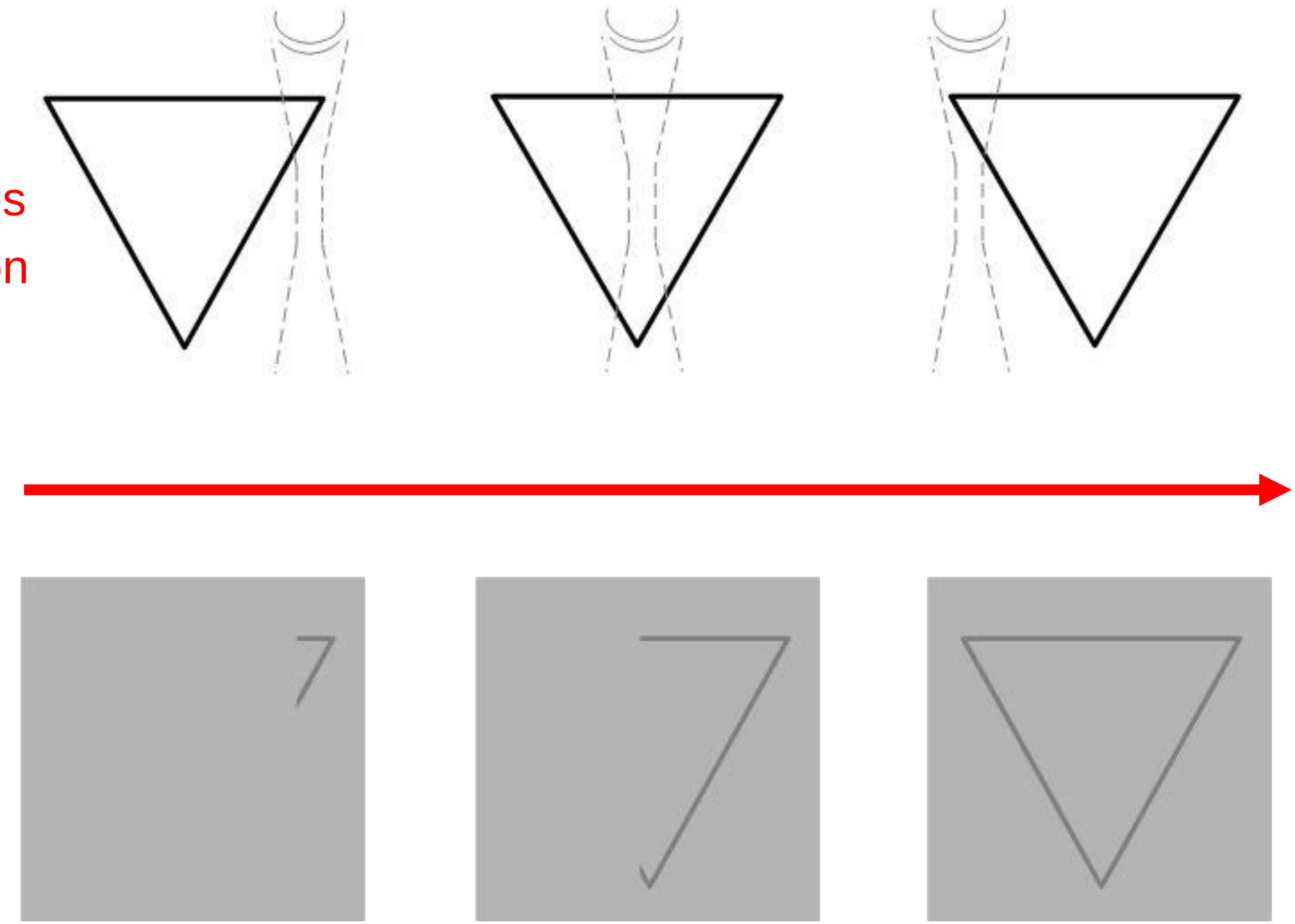


Time

B-mode image

Ultrasound Imaging

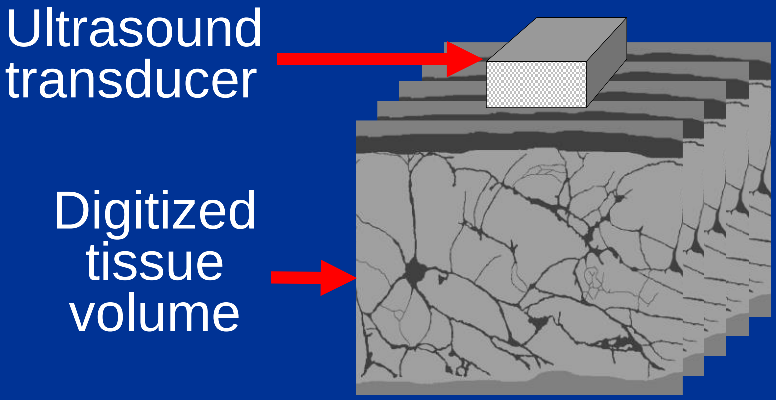
Scan lines acquisition

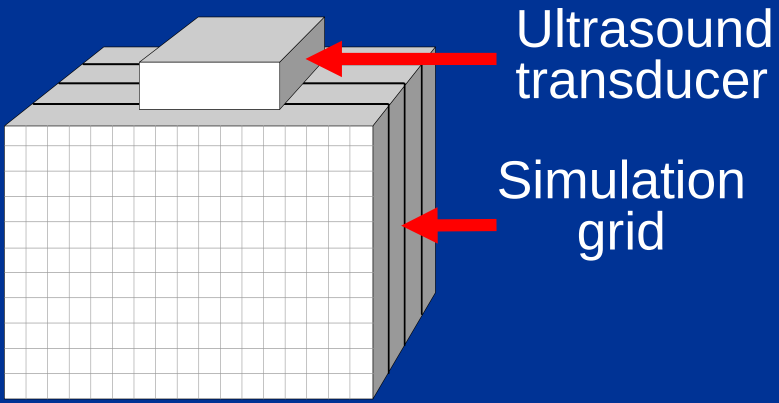


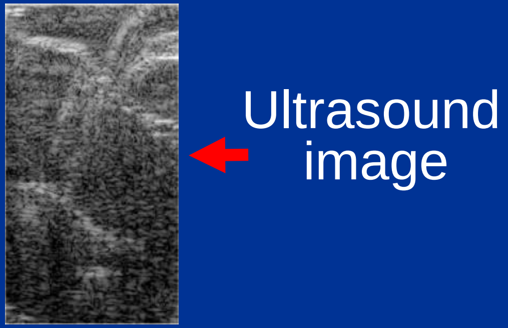
Time

B-mode image

Ultrasound Imaging Simulations







Computational Complexity

Ultrasound imaging simulations require extensive computational resources and long running times

Accurate and fast three-dimensional (3D) simulations can be achieved by combining

- Efficient numerical methods
- Parallel computing

The First-Order *k*-Space Method

An efficient 3D *k*-space method[1] was developed based on coupled first-order wave equations

$$\nabla \cdot \left(\frac{1}{\rho(r)} \nabla p(r,t) \right) - \frac{1}{\rho(r)c(r)^2} \frac{\partial^2 p(r,t)}{\partial t^2} = 0$$

$$\equiv$$

$$\nabla p(r,t) = -\rho(r) \frac{\partial u(r,t)}{\partial t}$$

$$\nabla \cdot u(r,t) = -\frac{1}{\rho(r)c(r)^2} \frac{\partial p(r,t)}{\partial t}$$

[1]**M. Daoud *et al.*, Phys. Med. Biol. 54:5173-5192 (2009).**

Ultrasound Simulator: The First-Order *k*-Space Method

Spatial derivative evaluation

$$\boldsymbol{F}\left\{\frac{\partial \emptyset(x,y,z,t)}{\partial x}\right\} = ik_x \boldsymbol{F}\big(\emptyset(x,y,z,t)\big)$$

$$\boldsymbol{F}\left\{\frac{\partial \emptyset(x,y,z,t)}{\partial y}\right\} = ik_y \boldsymbol{F}(\emptyset(x,y,z,t))$$

$$\boldsymbol{F}\left\{\frac{\partial \emptyset(x,y,z,t)}{\partial z}\right\} = ik_z \boldsymbol{F}(\emptyset(x,y,z,t))$$

Temporal derivative evaluation

$$\frac{\partial \emptyset(x,y,z,t)}{\partial t} \approx \frac{\emptyset(x,y,z,t) - \emptyset(x,y,z,t-\Delta t)}{\Delta t}$$

The First-Order *k*-Space Method

Spatial derivative evaluation + temporal correction term

→ *k*-space propagation operator

$$\frac{\partial \emptyset(x,y,z,t)}{\partial^{(c_o \Delta t)} x} = \boldsymbol{F}^{-1}\left\{ sinc\left(\frac{c_o \Delta t k}{2}\right) i k_x \boldsymbol{F}\{\emptyset(x,y,z,t)\}\right\}$$

$$\frac{\partial \emptyset(x,y,z,t)}{\partial^{(c_o \Delta t)} y} = \boldsymbol{F}^{-1}\left\{ sinc\left(\frac{c_o \Delta t k}{2}\right) i k_y \boldsymbol{F}\{\emptyset(x,y,z,t)\}\right\}$$

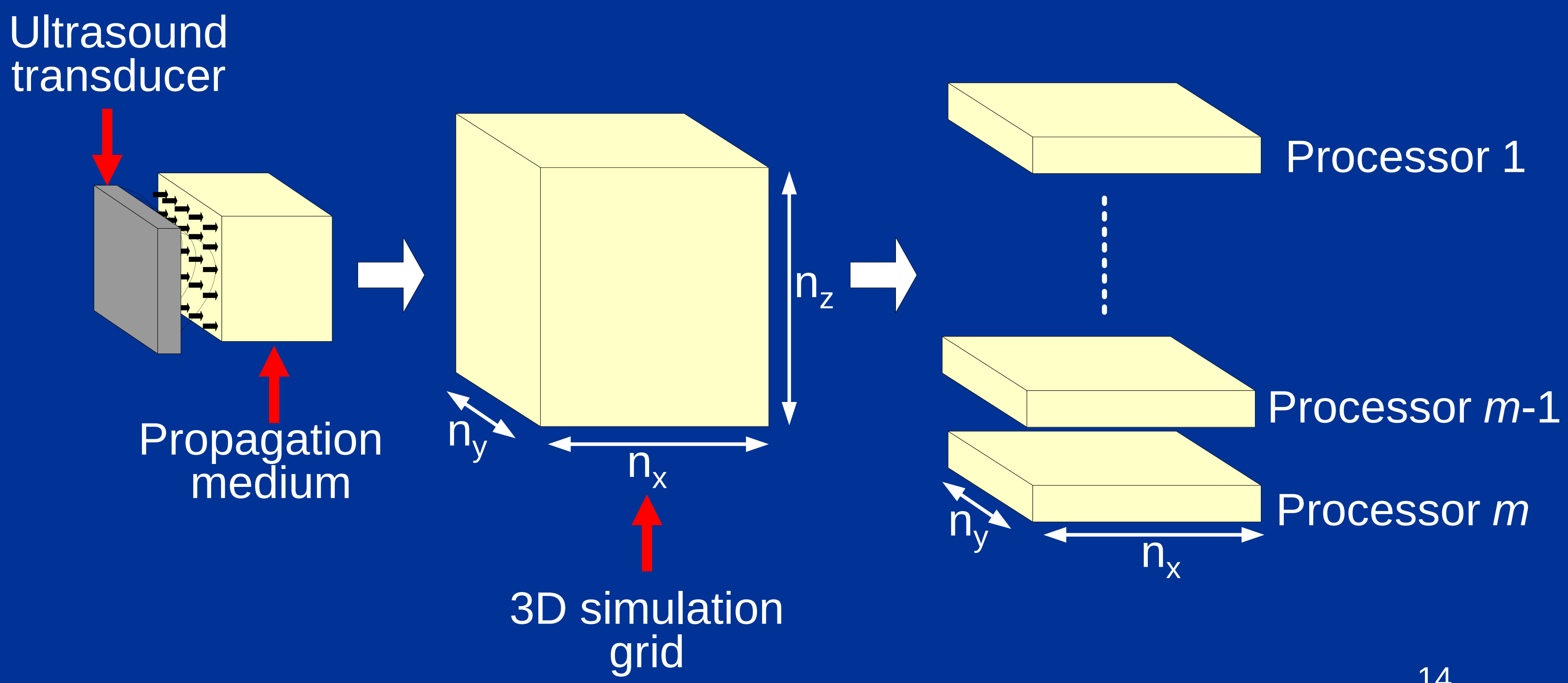
$$\frac{\partial \emptyset(x,y,z,t)}{\partial^{(c_o \Delta t)} z} = \boldsymbol{F}^{-1}\left\{ sinc\left(\frac{c_o \Delta t k}{2}\right) i k_z \boldsymbol{F}\{\emptyset(x,y,z,t)\}\right\}$$

Correction term

Fourier transform of spatial derivative

Enabling 3-D Imaging Simulations

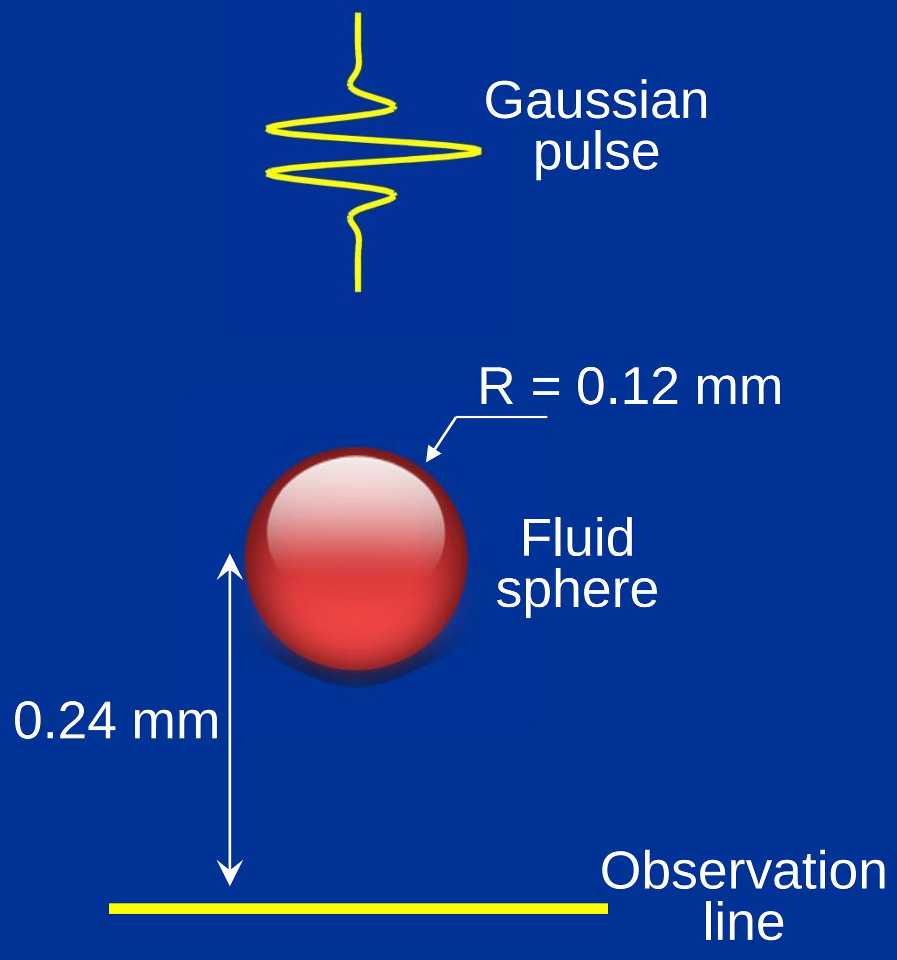
The 3D first-order *k*-space method is implemented to run on computer clusters



Numerical Accuracy

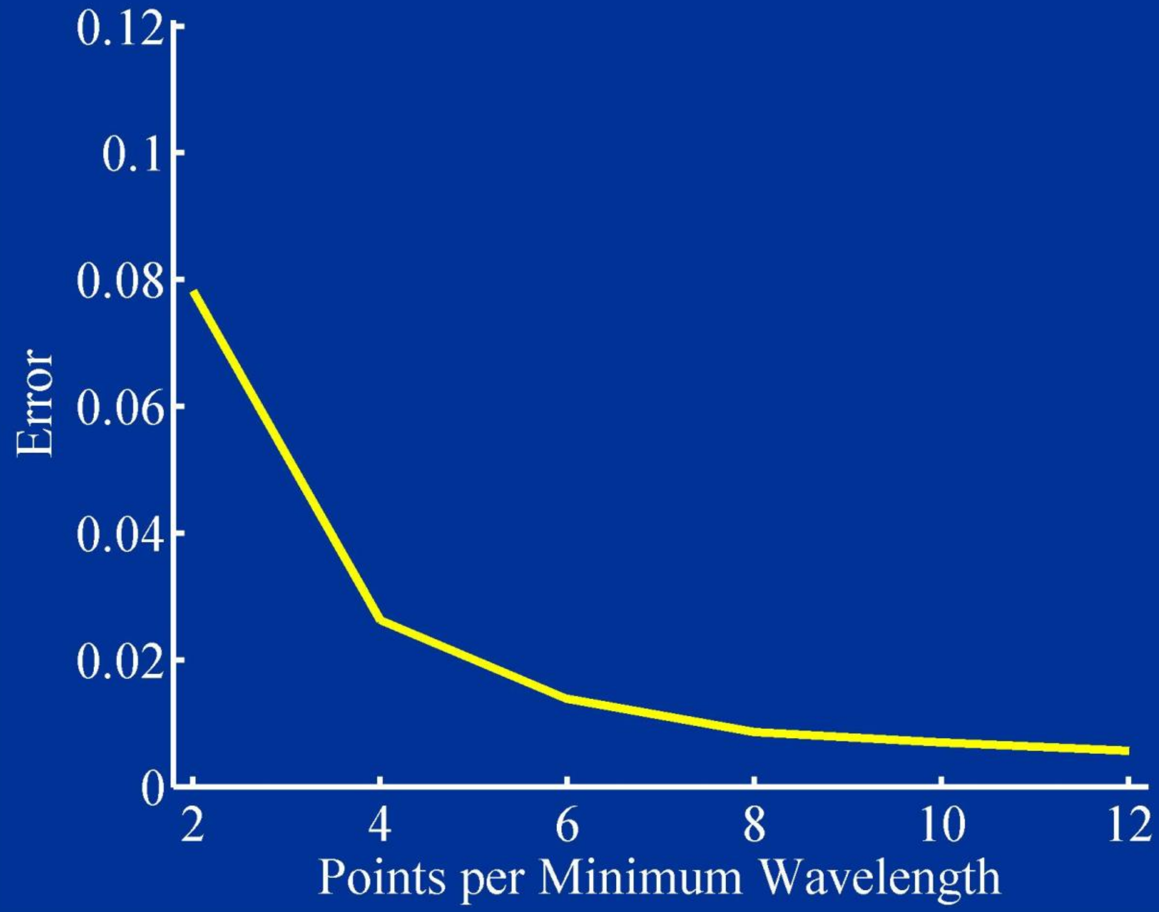
Compute the scattering of a 40-MHz Gaussian pulse by a fluid sphere

The *k*-space solution is compared with an exact analytical solution[1]



[1]P. M. Morse and K. U. Ingard, Theoretical Acoustics, McGraw-Hill, 1968, ch. 8.

Numerical Accuracy



Parallel Performance of a Single Scan Line

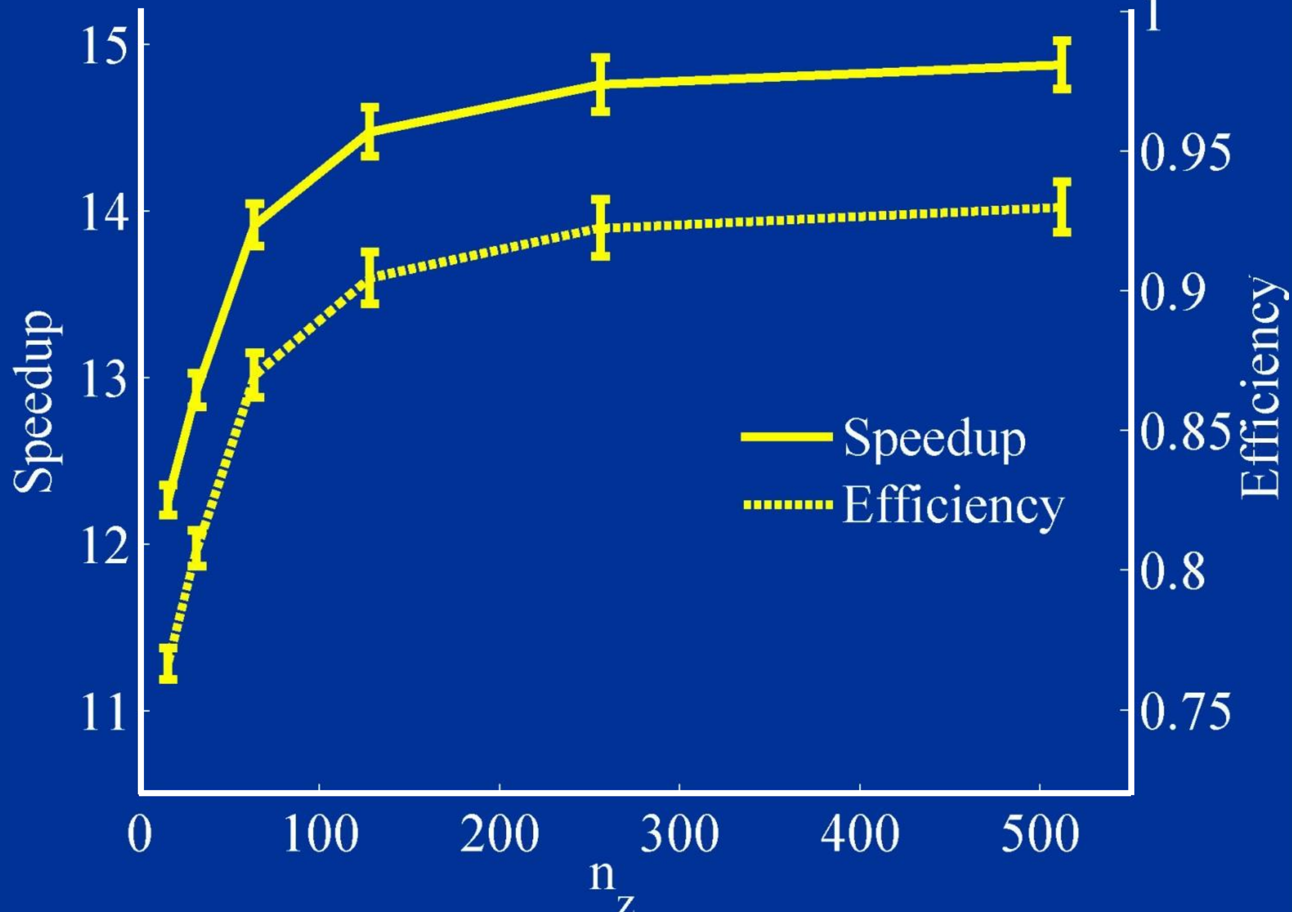
Two performance metrics are used

- Speedup: the ratio of the serial running time to the parallel running time
- Efficiency: the ratio of the speedup to the number of processors used

Parallel Performance of a Single Scan Line

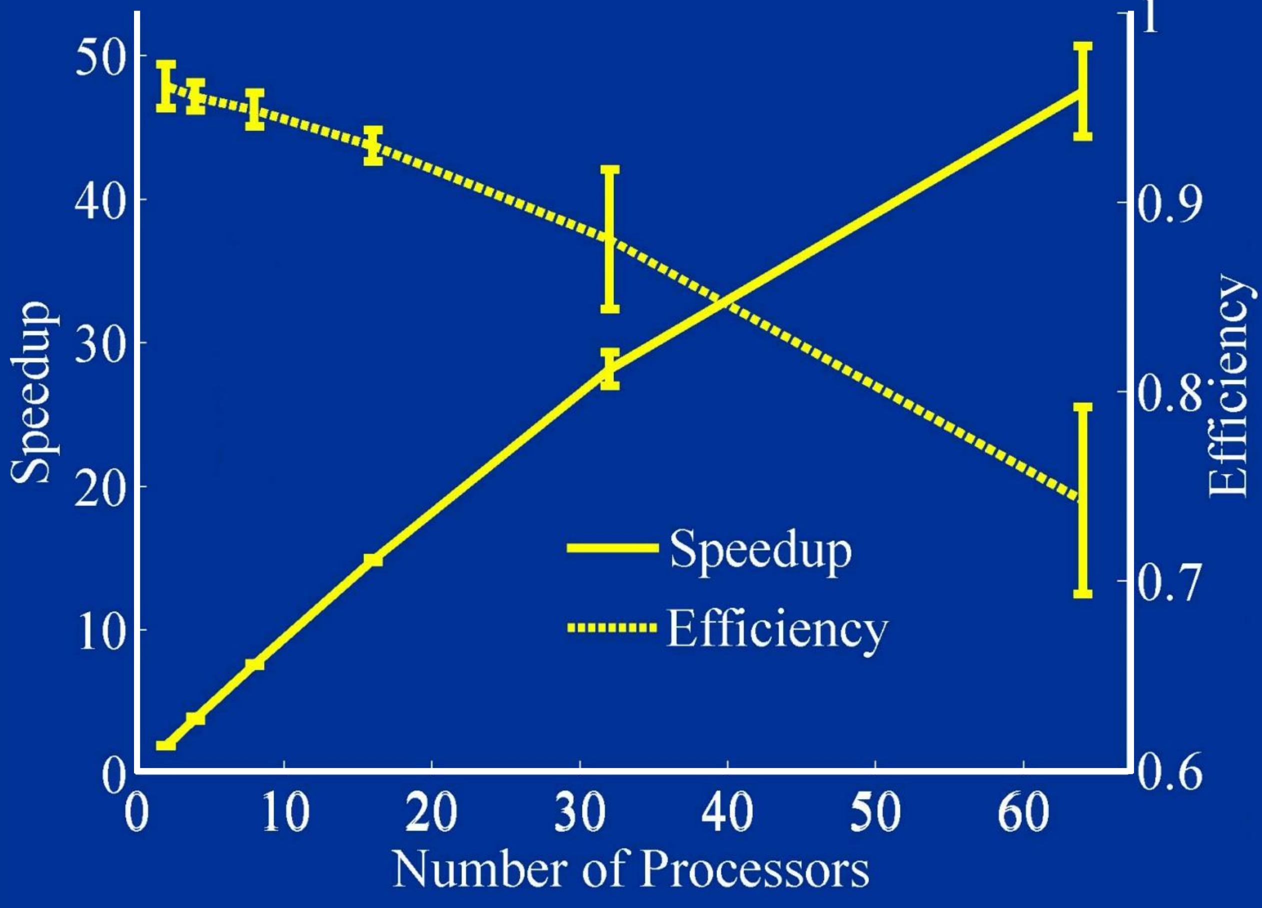
Number of processors= 16

Grid size= 512×512×nz

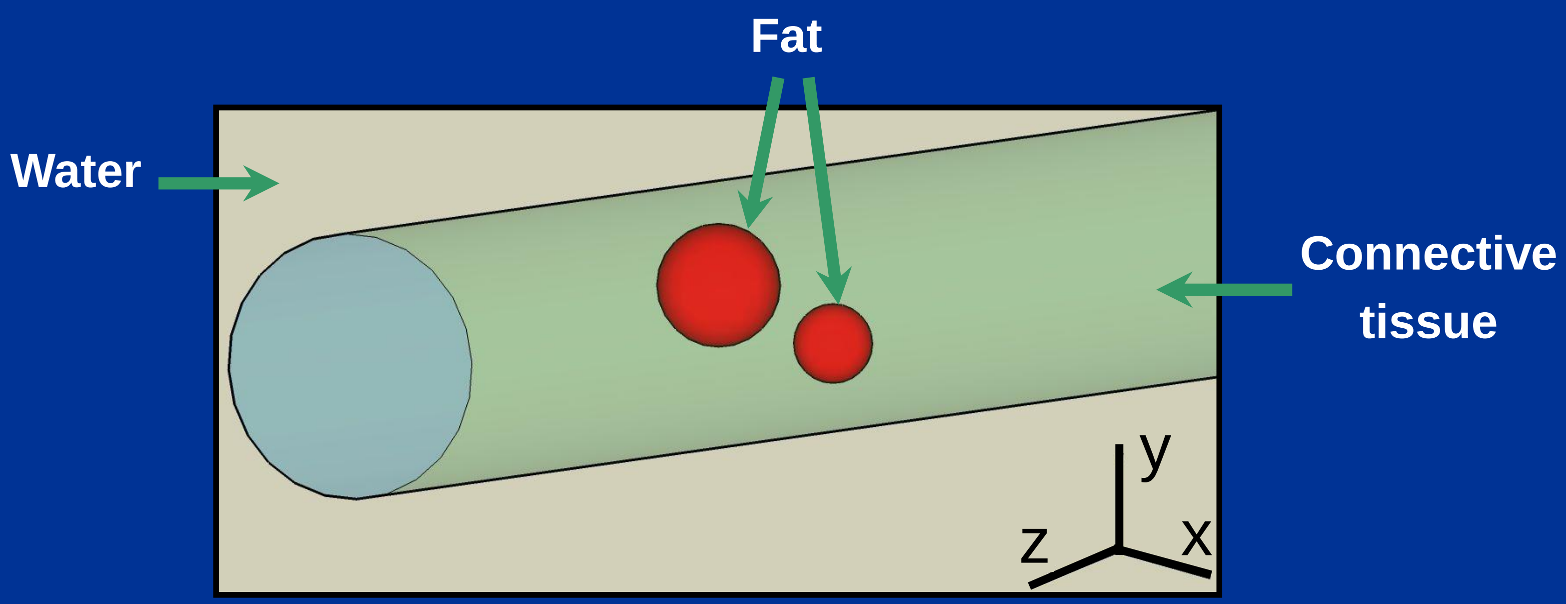


Parallel Performance of a Single Scan Line

Grid size= 512×512×512

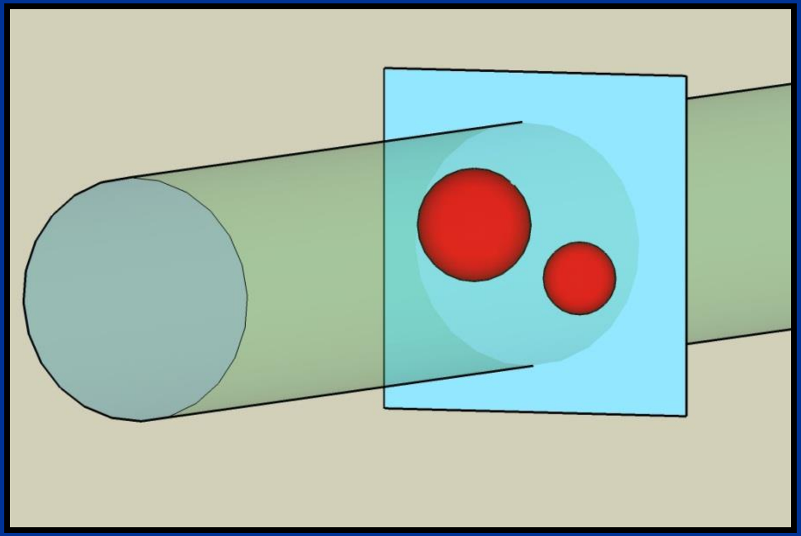


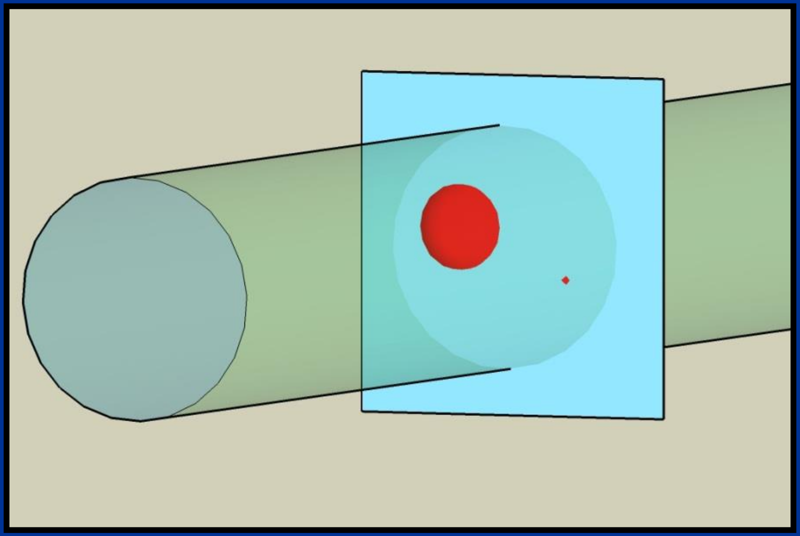
B-Mode Imaging Simulations



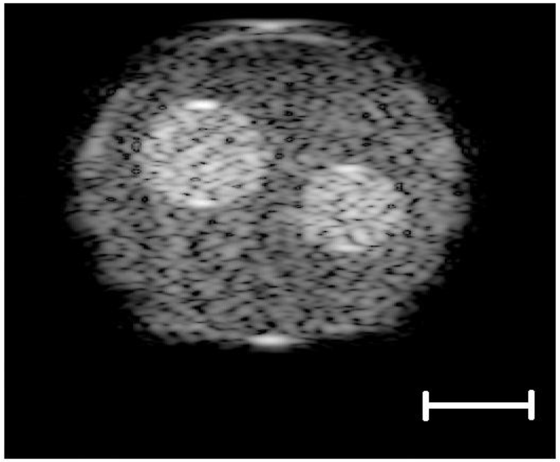
The incident pulse has a Gaussian envelope, a center frequency of 40 MHz, and −6-dB bandwidth of 24 MHz

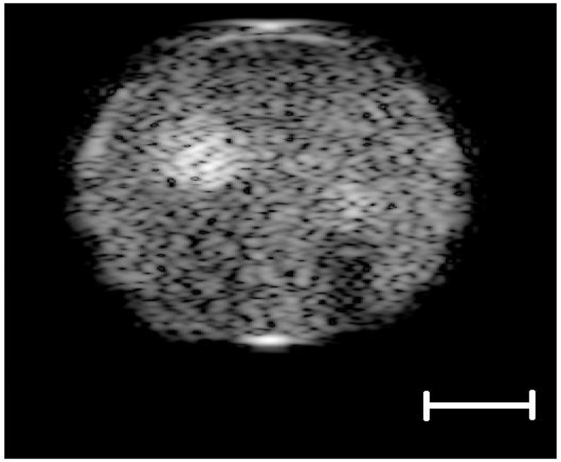
B-Mode Imaging Simulations





B-Mode Imaging Simulations





Scale bar = 0.5 mm

Serial simulation time: 357.5 hours

Parallel simulation time (20 processors): 18.6 hours

Summary and Conclusion

A 3D ultrasound simulator is developed based on a 3D formulation of a *k*-space method

The simulator is implemented to run on computer clusters

An error value of 2.6% is achieved using 4 points per minimum wavelength

Efficiency values greater than 93% can be achieved by assigning 16 processors or less

The results demonstrate the efficiency of the 3D parallel simulator for accurate and fast 3D imaging simulations