GPU Ultrasound Simulation and Volume Reconstruction

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Outline

- (3D) Freehand ultrasound volume reconstruction / MPR generation
- Ray-based ultrasound simulation
- Wave-based ultrasound simulation

What is 3D freehand ultrasound?

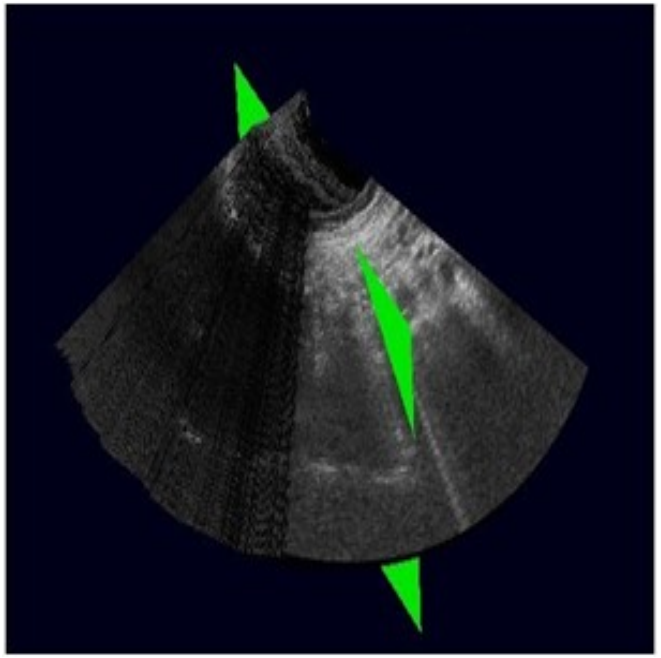
Multiple US Image Acquisitions

- 1D Transducer tracked (optic or electromagnetic)
- Transducer position and orientation is arbitrary
- Multiple 2D US images recorded together with spatial information

Motivation

- **MPR Generation**
  - Additional clinical value
  - Multi-modal registration
  - Image-based calibration
- **Volume Reconstruction**
  - Make sweep available to existing clinical tools, including: volume visualization, segmentation, registration, etc.
  - Multi-modal registration
  - Improved compatibility (e.g. PACS)

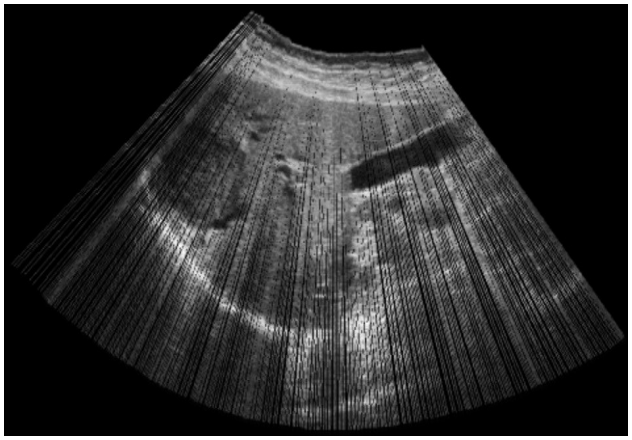
Volume Reconstruction



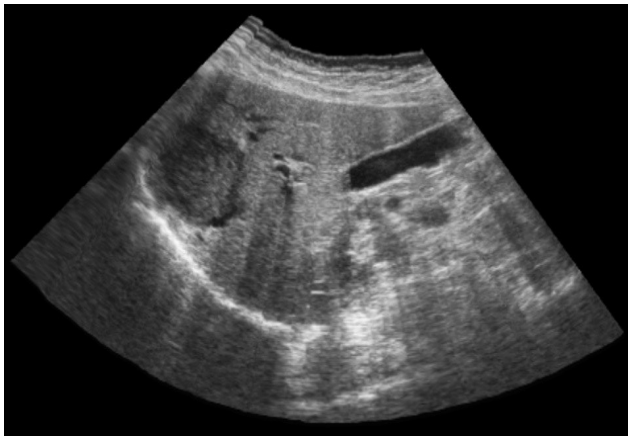
US Sweep, MPR (green)

- Reconstruct Scattered 2D images (slices) into regular 2D/3D grid
- Data interpolation (between slices)
  - Limited assumptions about the acquisition can be made

Available methods



MPR (without filing gaps)



MPR (interpolating between slices)

- Forward reconstruction (Pixel-based) – Fast, Low quality
- Backward reconstruction (Voxel-based) – Slow, High quality
  - Distance-weighted, Probe Trajectory weighted
- Advanced methods
  - Radial Basis Function Interpolation (RBF) – Very Slow, High quality

Goals

- Fast volume reconstruction, On-the-fly MPR
- Develop new approach suitable for GPU implementation
  - Hardware accelerated interpolation
- At least same visual quality as existing, slower methods
  - Focusing at Distant-Weighted Methods

Approach:
Fast MPR reconstruction on GPU to reconstruct entire Volume

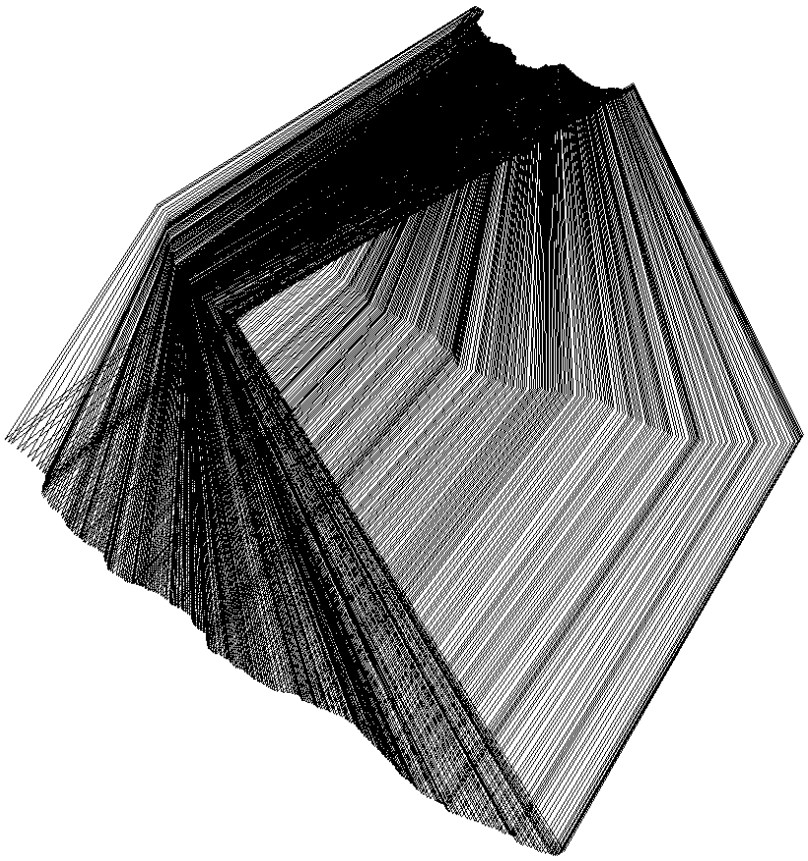
Method – 2D US Image representation

- Using point coordinates of each ultrasound image

$$p_0, p_1, p_2, p_3 \in \mathbb{R}^3$$

- Define line for each edge

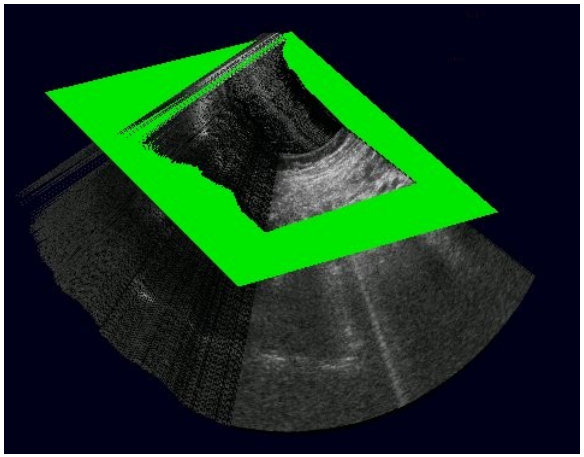
$$p = p_n + u \cdot \vec{v}$$



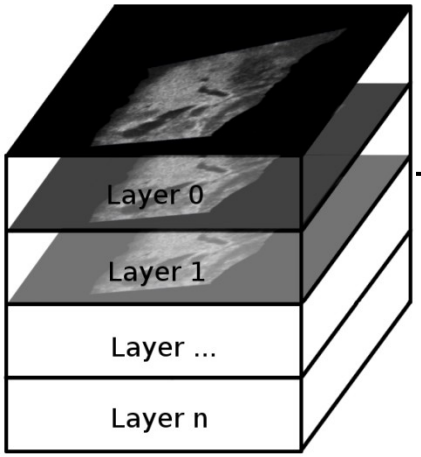
Sweep edge lines

Method – MPR Representation

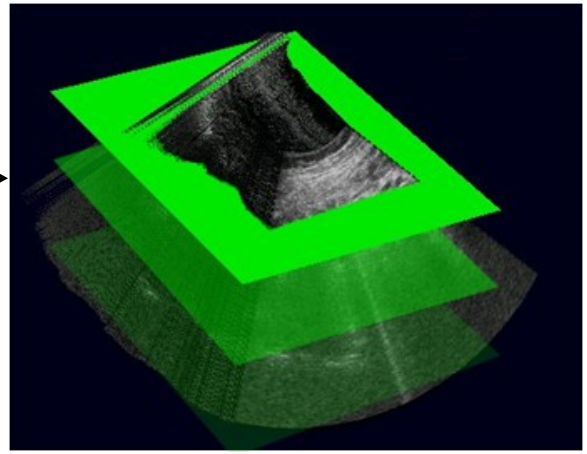
- Each MPRs is represented by a sampling plane $\vec{n} \cdot (x - x_0) = 0$
- Multiple MPRs/Planes for volume reconstruction
  - One MPR for each volume layer



Single MPR/Plane



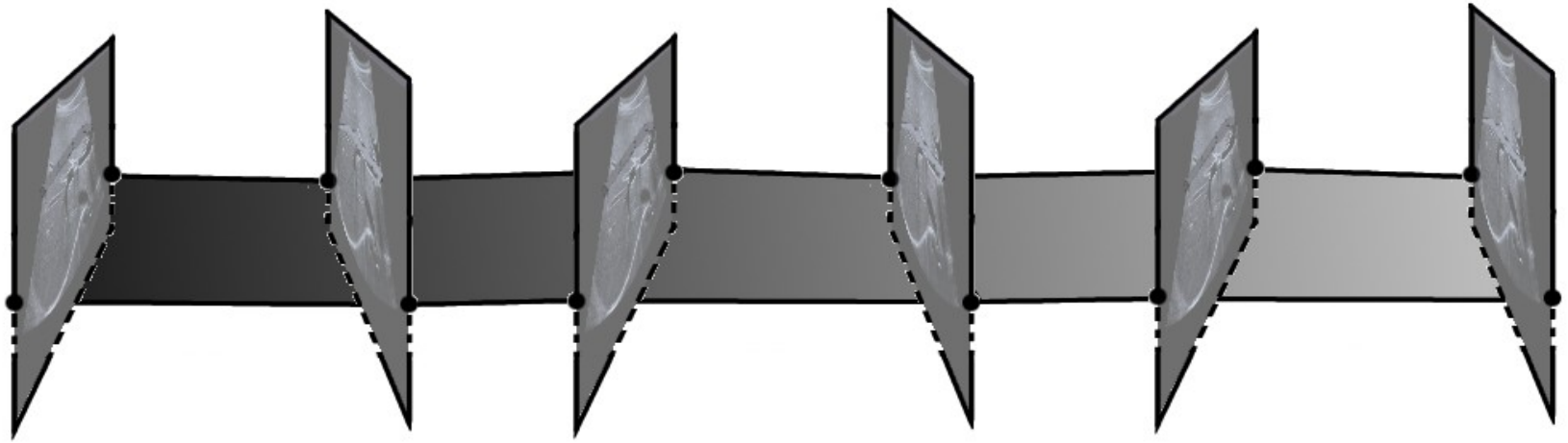
3D Volume



Multiple MPRs/Planes

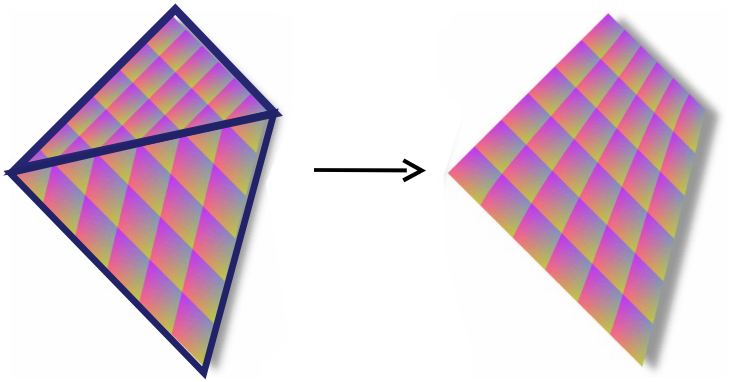
Method – MPR Reconstruction

- Find all intersections between image edge lines and sampling plane(s)
- For each image pair
  - Use four points to form a connecting quadrilateral
  - Bilinear interpolate at quadrilateral edges along the images
  - Linear interpolate the values at the edges along the quadrilateral
- MPR from multiple quadrilaterals



Method – Interpolation Problem

- GPU hardware does not support continuous interpolation of irregular quadrilaterals
- Solution
  - Split quadrilateral
  - Or generalized barycentric coordinates



[Horman and Tarini]

Default *Quadrilateral Split* *Barycentric*

Results - Performance

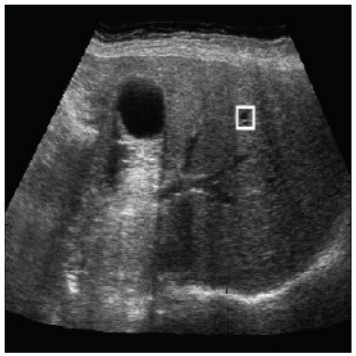
- System: 8800 GTX 768 MB - Xeon 3.2GHz – 2 GB RAM
- Reconstructing 293 slices in a 256^3 volume

GPU Reconstruction	Backward Trajectory	Backward Maximum	Backward Gaussian	Forward (non optimized)
0.35s	72.72s	60.80s	69.78s	471.88s
Gain	208x	174x	199x	1348x

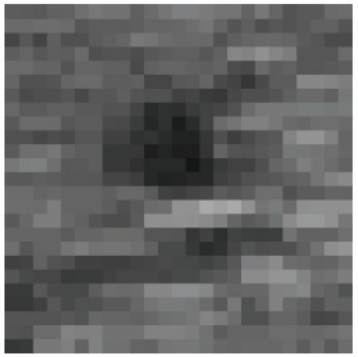
**Barycentric 0.82s*

- MPR of 293 slices
  - GPU: 124 FPS
  - CPU: <= 1FPS

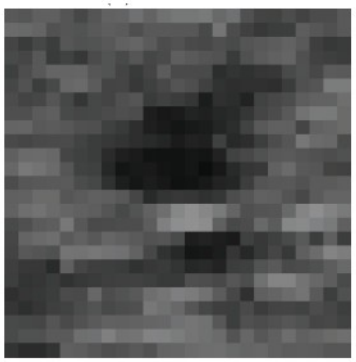
Results - Quality



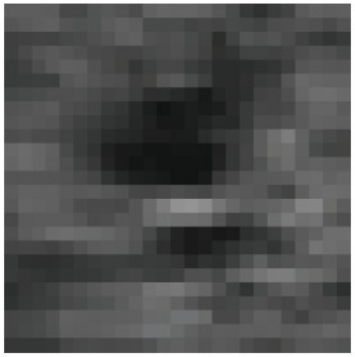
MPR



Maximum



Trajectory



Quad Split

	Nearest	Maximum	Trajectory	Inverse	Gaussian	Weighted
Quad Split	8.16	12.68	7.66	7.43	7.68	8.07
Bary-centric	10.38	13.83	9.87	9.72	9.61	10.11

Mean of Absolute Differences, Pixel Intensities [0..255]

Future Work

- Make approch available for discontinuous sweeps
  (continuous sweeps most common case in our clinical scenario)

- Averaging of coicident images
  - Does not always yield better reconstruction results

- MPR planes parallel to US images are sampled insufficiently
  - Detect case and use alternative method. For example, projecting adjacent slices onto MPR

Outline

- (3D) Freehand ultrasound volume reconstruction / MPR generation
- Ray-based ultrasound simulation
- Wave-based ultrasound simulation

What is it about?

- Simulation of medical ultrasound images from CT datasets
- GPU accelerated, Real-time simulation
- Model sound physics with rays
  - Rays: Faster simulation, decreased realism
  - Waves: Considerably slower simulation, increased realism

Motivation

- 2D/3D medical ultrasound training
  - Experience through training
  - CT datasets commonly available in clinical setups
    - Variety of pathological cases available
  - **Requires:** Real-time simulation and visualization
- Accelerating multi-modal image registration
  - Registration of 2D US with CT
  - Fast ultrasound simulation beneficial (might improve accuracy)
- Future: Fast 3D-3D deformable multi-modal CT-US registration
  - **Requires:** Fast simulation

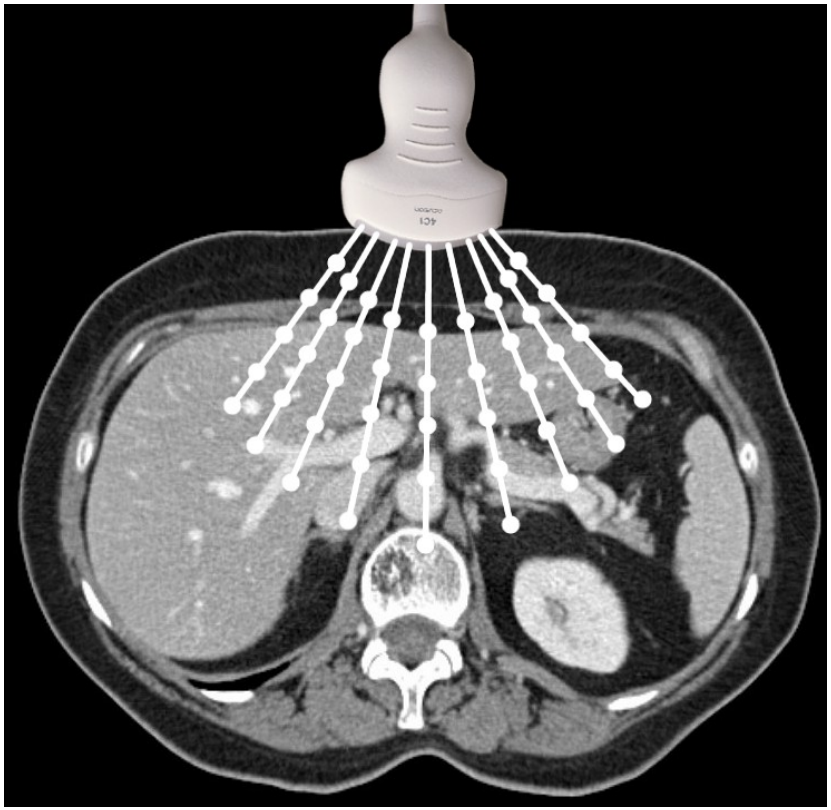
Method-Basics

- One ray for each transducer element
- The CT volume is sampled at equidistant points on the rays
- Samples used to calculate
  - reflection coefficient

$$I_r^k = I_i^k \frac{(Z_2 - Z_1)^2}{(Z_1 + Z_2)^2}$$

  - transmission coefficient

$$I_t^k = I_i^k \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2}$$



Ray sampling

Method – Scanline Computation

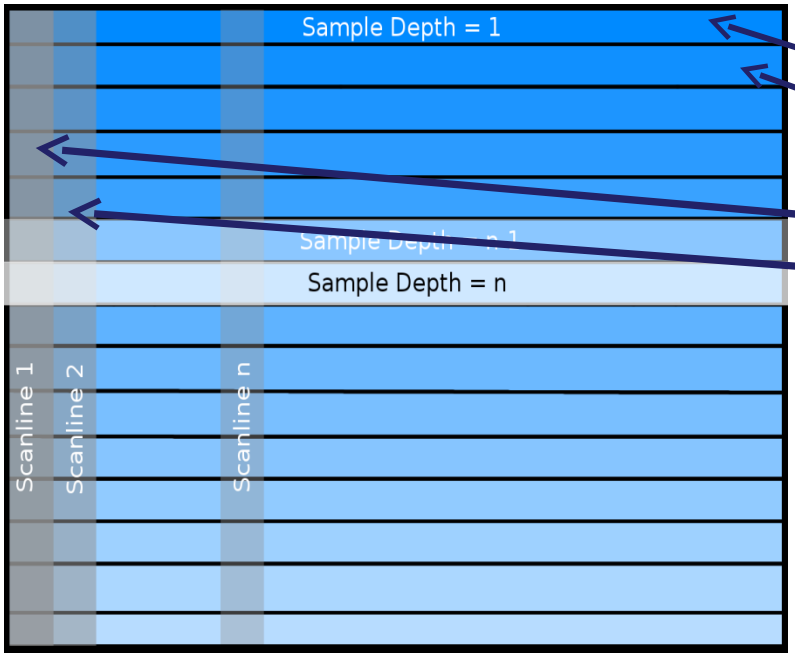
- Initially, method seems similar to ray-casting, however:
  - Ray-casting returns only a single value and
  - Performs only a single render pass

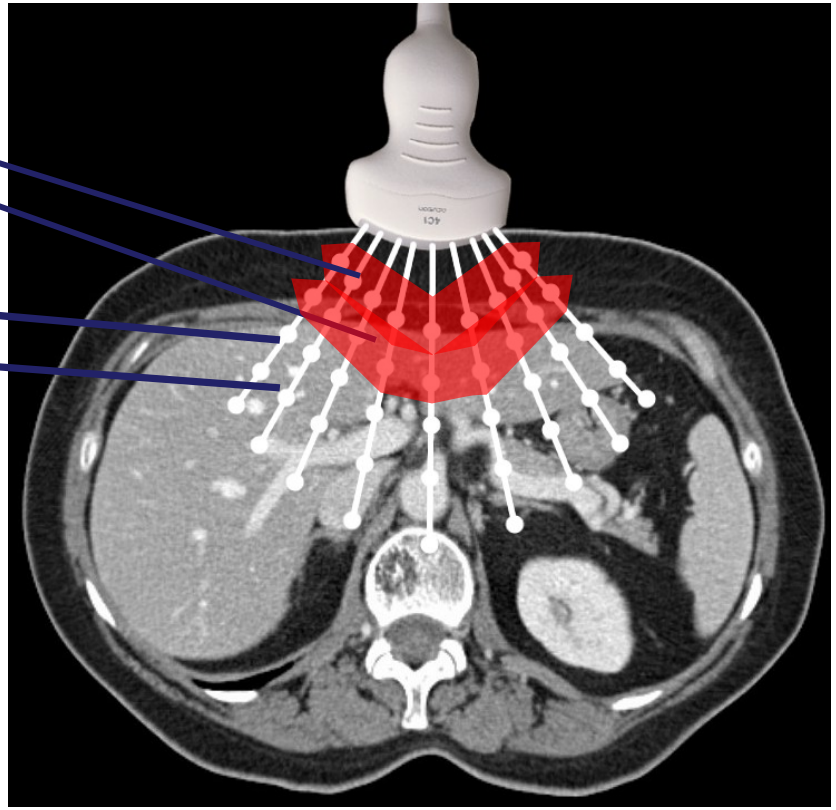
- Scanline computation :
  - Returns multiple values along the rays
  - Performs recursive calculation of reflection and transmission

$$I_i^k = \begin{cases} I_t^{k-1} & : k > 0 \\ 1 & : k = 0 \end{cases}$$

- **Solution:** Adjust initial ray-casting algorithm, introduce multiple render passes

Method - Scanline computation

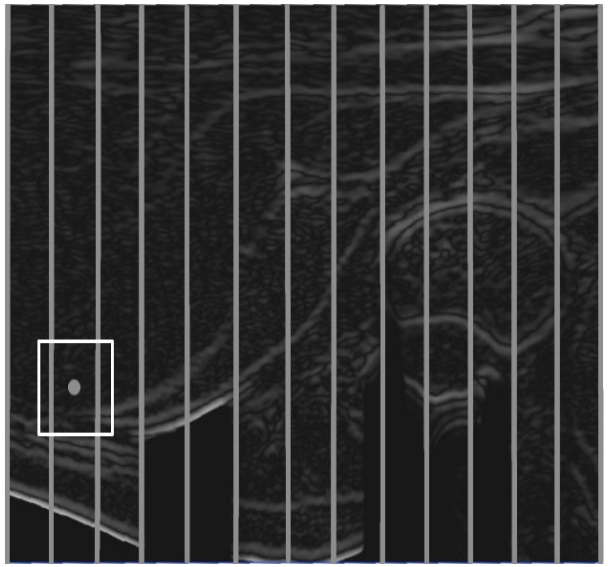




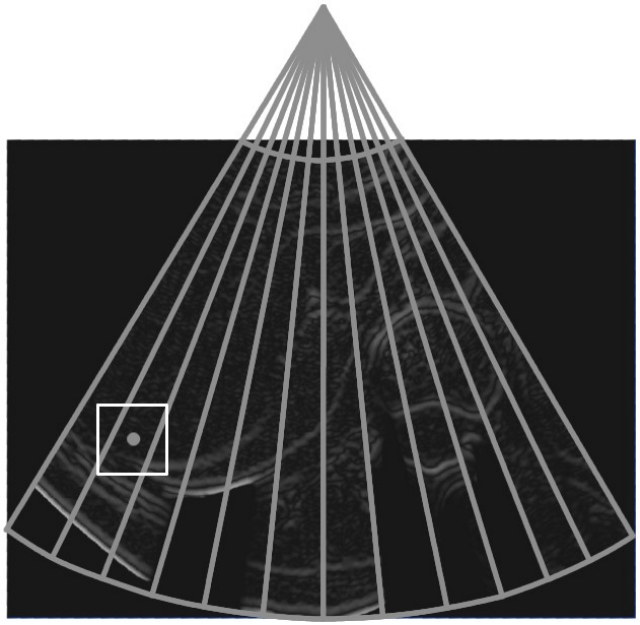
Scanline Texture Layout and computation

Method – Scan Conversion

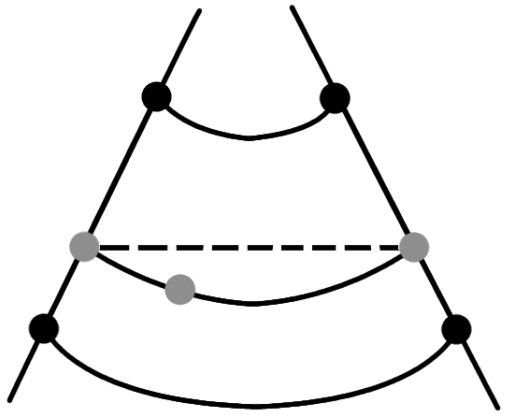
- From polar to Cartesian coordinate system
- Based on transducer geometry
- Interpolate between samples and scanlines



Scanline Image



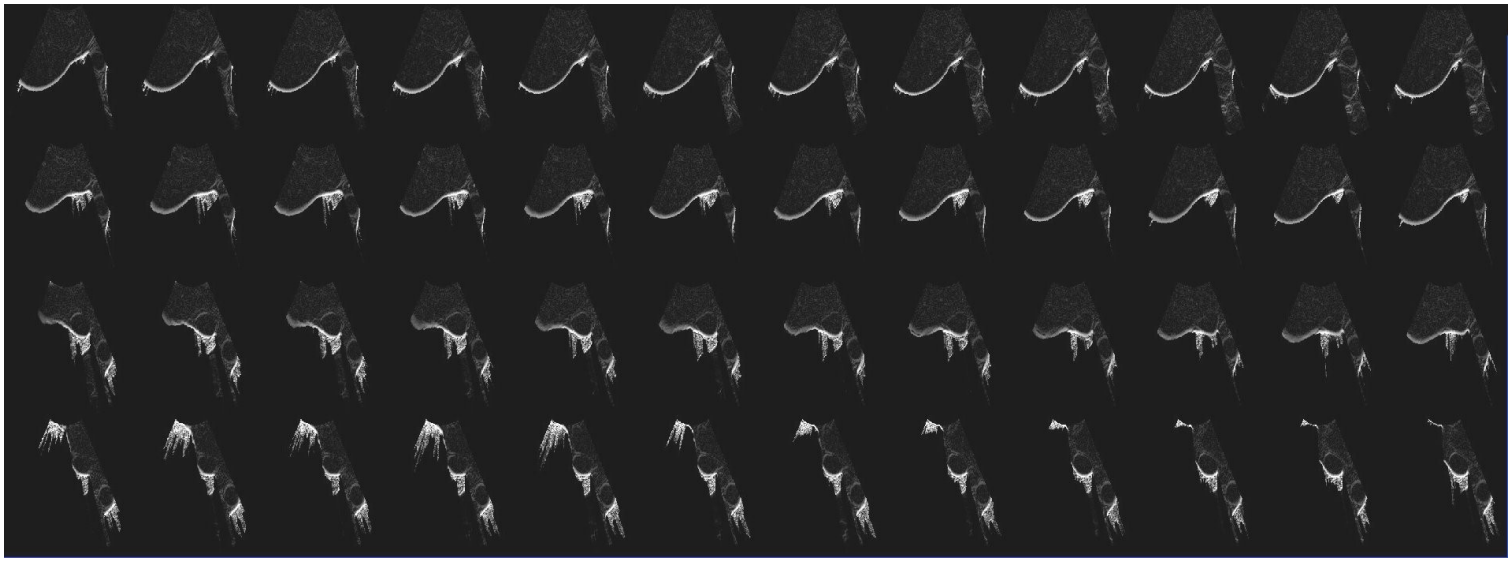
Scan Converted



Scanline Interpolation

Method – Multiple Image Simulation

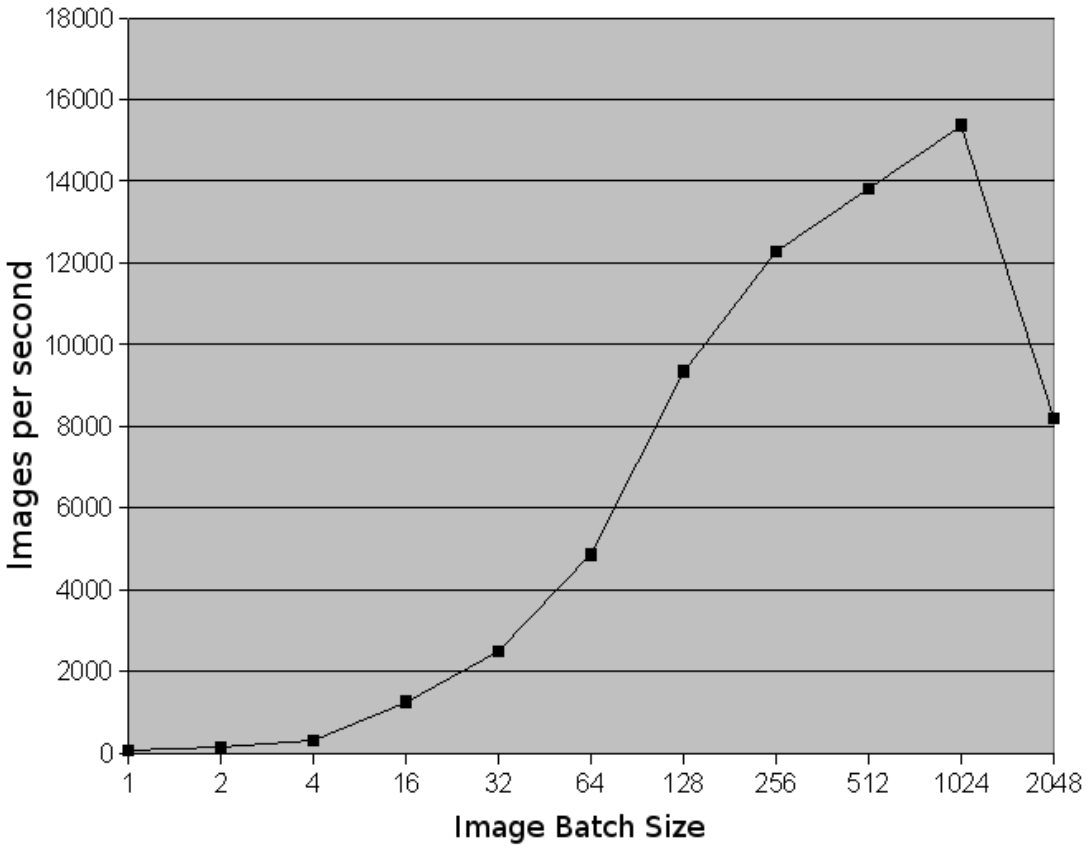
- Method extentable for simulating multiple images
- Number of multiple images limited by maximal texture size (currently 8192x8192)



Multiple Reflection Images

Results - Performance

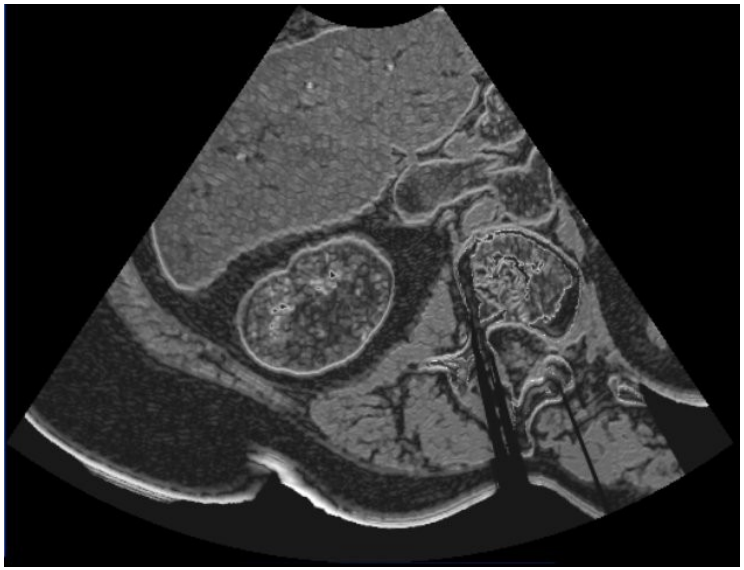
- Higher batch size → Higher throughput
- Less GPU hardware overhead
- Real-time 3D ultrasound simulation (128 images x 30 FPS = 3840 Images/sec)



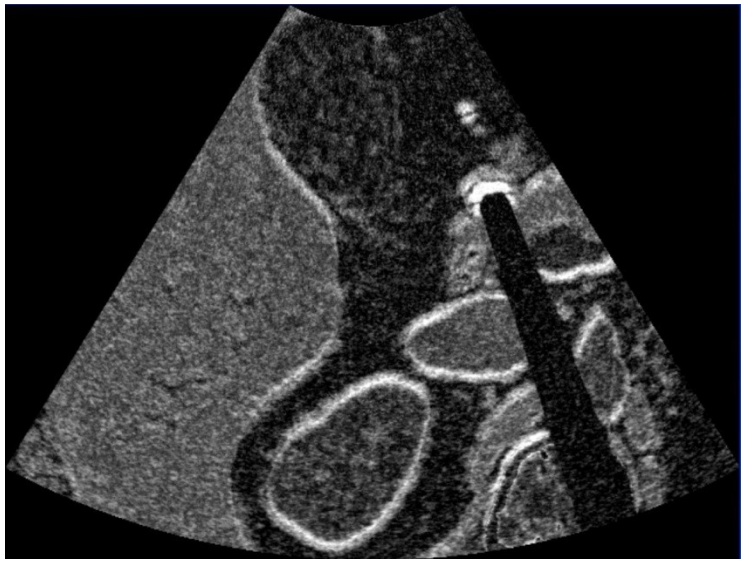
128 scanlines, 128 samples

Results - Images

- Additional real-time effects (single 2D image simulation)
  - Gaussian blurring
  - Horizontal Hanning Window
  - On-the-fly 3D Perlin Noise



Wein et al. model



Additional Effects

Future Work

- Additional effects, like
  - Multiple echoes (ray-tracing)
  - Tissue absorption (Look-Up-Tables)
  - Refraction
- Integrate framework into multi-modal registration pipeline
- Improve speckle simulation to add more realism

Outline

- (3D) Freehand ultrasound volume reconstruction / MPR generation
- Ray-based ultrasound simulation
- Wave-based ultrasound simulation

Motivation

- Ray-based models are rough approximations
- Wave-based models are more realistic, modeling:
  - Diffraction, Refraction, Interference and Scattering effects
- Current wave-based implementations show good results
  - Signal response simulation and ultrasound image simulation
  - Transducer and ultrasound system design
- But, simulations can take up to hours even on PC clusters, for example Field II simulation program

Goals

- Investigate GPU „friendly“ approaches
  - Lack of literature on GPU accelerated wave-based ultrasound simulation
  - Digital waveguide meshes
  - Finite-difference time-domain method
- Demonstrate feasibility of near real-time wave-based ultrasound simulation

Digital Waveguide Mesh Unsuitable for Ultrasound Simulation

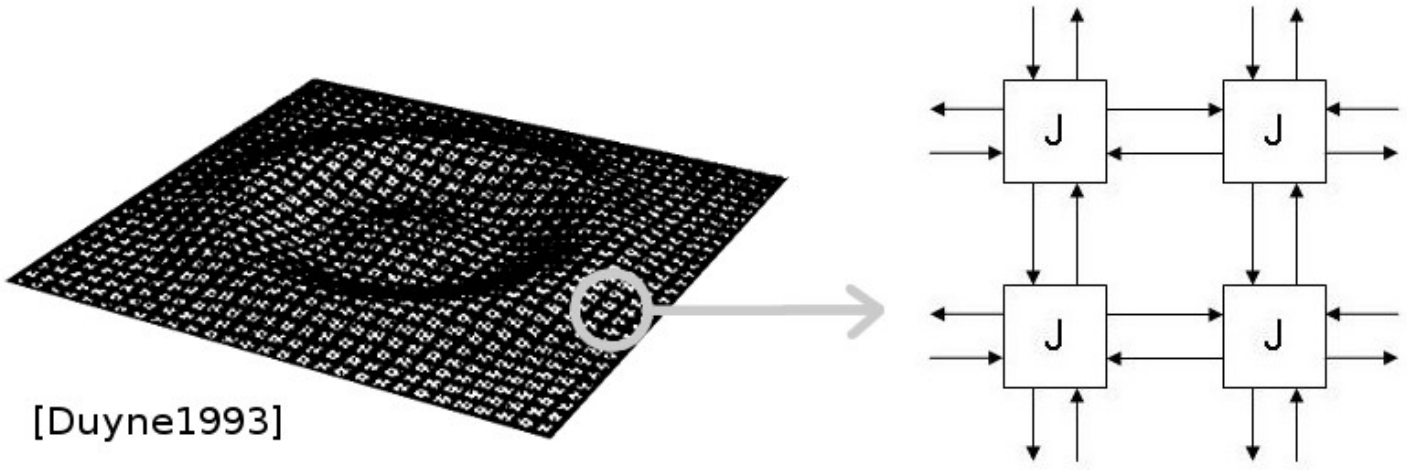
Outline

- (3D) Freehand ultrasound volume reconstruction / MPR generation
- Ray-based ultrasound simulation
- Wave-based ultrasound simulation
  - Digital Waveguide Mesh
  - Finite-Difference Time-Domain Method

Digital Waveguide Mesh

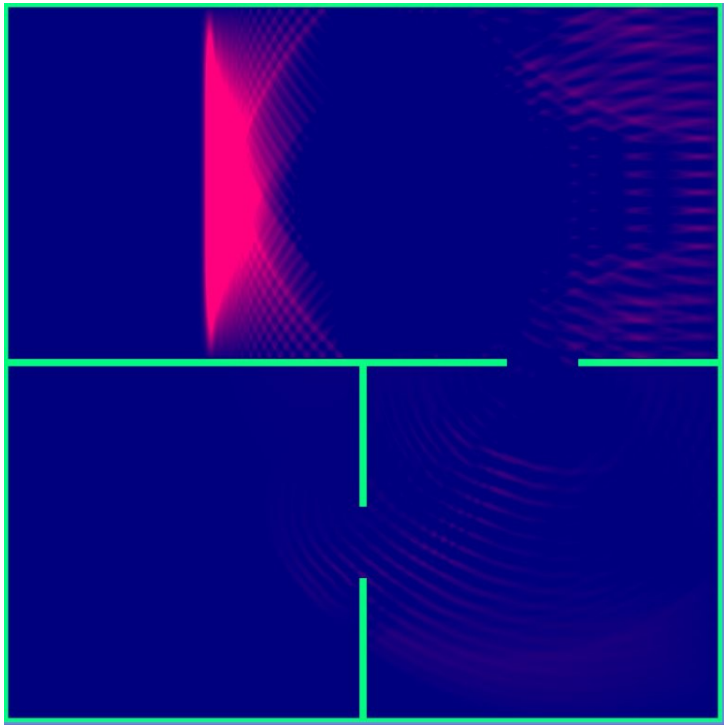
- Introduced for room acoustics and music instrument simulation
- Low computational demands and memory requirements

$$p_c(t) = \frac{1}{N} \sum_{2N}^{l=1} p_l(t-1) - p_c(t-2)$$



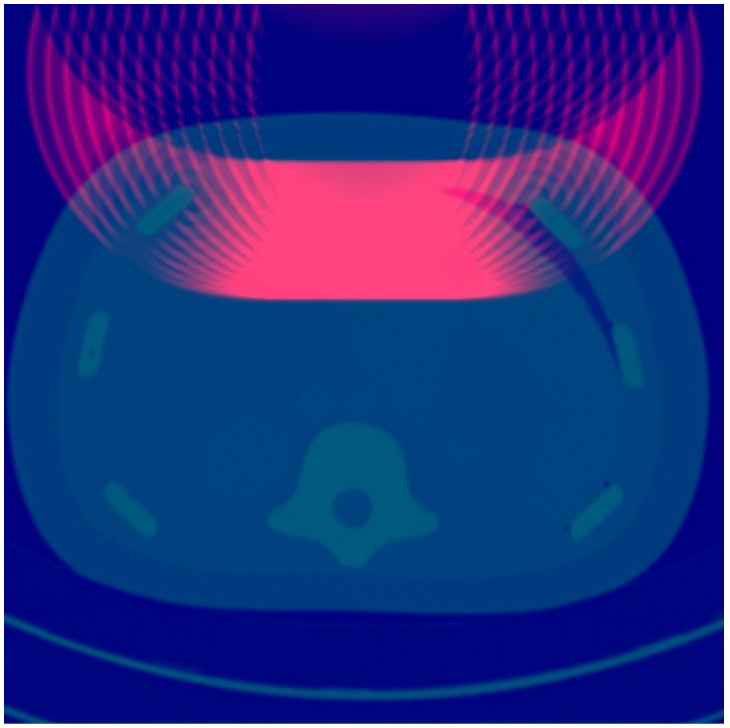
Waveguide *Scattering Junctions*

Results



Room acoustics

Avg. 1130
Time-steps/sec
512x512 grid



Segmented Phantom Dataset

Issues and Problems

- Dispersion error in the grid
- Boundaries are defined explicitly
- For each boundary additional errors are introduced
- Reflections at computational grid edges
  - Lack of sufficient absorbing boundary conditions (ABC)
- Considerable improvements have been suggested

However: Errors are still high! Especially for low reflection coefficients.

Approach unsuitable for Ultrasound Simulation

- For CT or MRI dataset
  - Numerous tissue interfaces
  - All tissue interfaces must be defined
  - Each interface must be defined as a boundary junction
- Therefore, numerous error sources are introduced
- Accumulation of errors during simulation
- Lack of sufficient ABCs further restricts approach

Outline

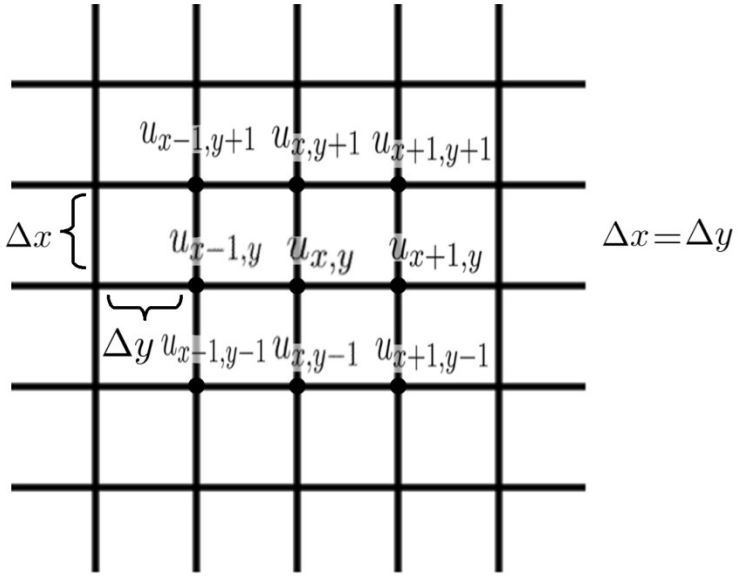
- (3D) Freehand ultrasound volume reconstruction / MPR generation
- Ray-based ultrasound simulation
- Wave-based ultrasound simulation
  - Digital Waveguide Mesh
  - Finite-Difference Time-Domain Method

Finite-Difference Time-Domain (FDTD) Ultrasound Simulation

- FDTD method introduced in computational electrodynamics, decades ago
- Rich literature, including ABC modeling
  - Perfectly Matched Layers (PML)
- Suitable for GPU acceleration
- Proven suitable for ultrasound simulation

FDTD Basics

- Solve Partial Differential Equation (PDE) by:
  - Discretizing simulation domain
  - Numerically approximating partial derivatives with finite differences
  - Solving for term of interest
- Example 1D wave equation



2D rectangular FDTD grid

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 u(x,t)}{\partial t^2}$$

$$\frac{\partial^2 u(x,t)}{\partial x^2} \cong \frac{u(x+\Delta x,t) - 2u(x,t) + u(x-\Delta x,t)}{\Delta x^2}$$

$$\frac{\partial^2 u(x,t)}{\partial t^2} \cong \frac{u(x,t+\Delta t) - 2u(x,t) + u(x,t-\Delta t)}{\Delta t^2}$$

GPU FDTD Solver

- Each grid point corresponds to one texel of a 2D/3D texture
- Textures are used for the current computations and to store the previous results
- For our example, the wave amplitude for the next time-step is :

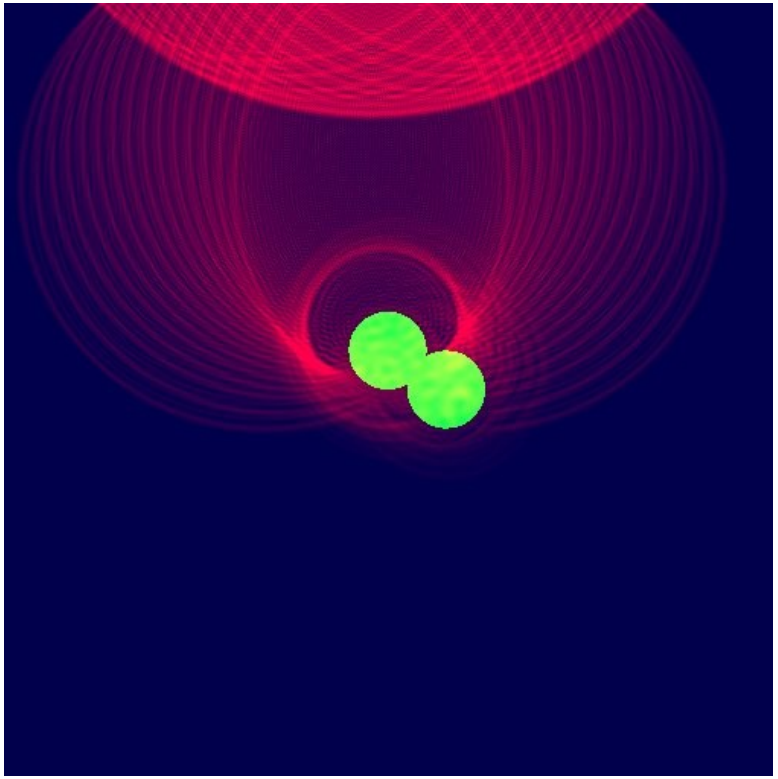
$$u(x, t + \Delta t) = c^2 \frac{\Delta t^2}{\Delta x^2} (u(x + \Delta x, t) - 2u(x, t) +$$

$$u(x - \Delta x, t)) + 2u(x, t) - u(x, t - \Delta t)$$

- Only the two previous timesteps are needed
- Calculations are performed in a GPU fragment shader

Initial Results

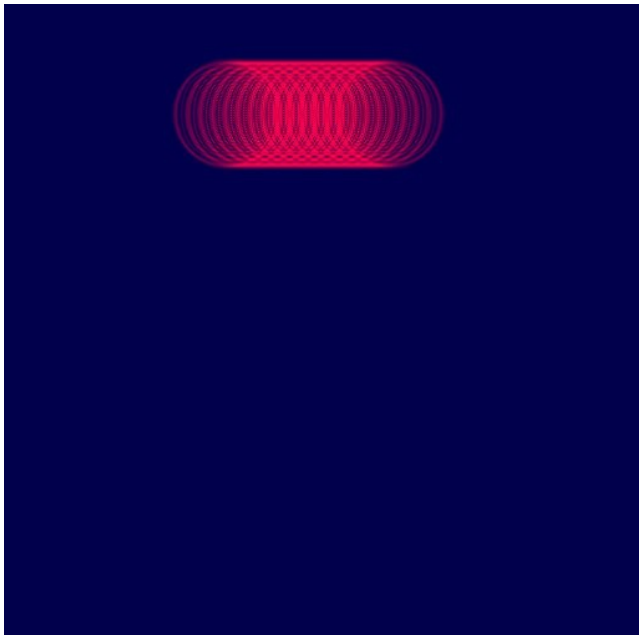
- Single Point source
- Two mediums with propagation speeds of 1200 and 1600 [m/s]
- Difference in propagation speed causes reflection
- Grid size 512x512



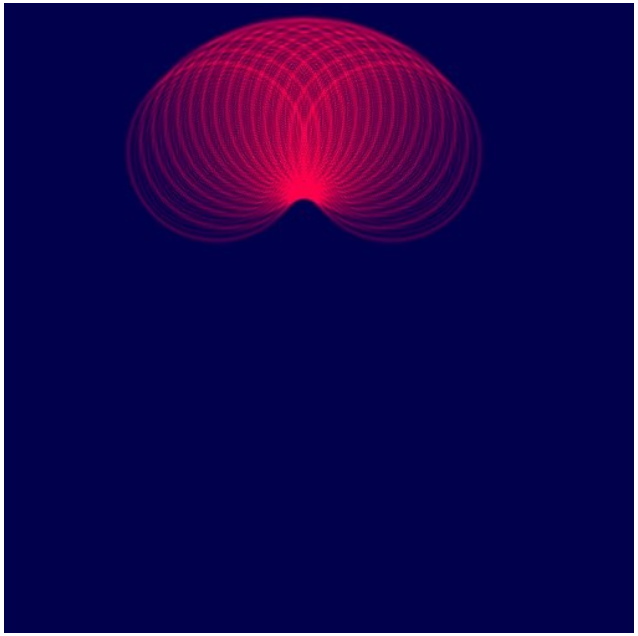
GPU FDTD Solver
2D Lossless Wave Equation

Initial Results

- Multiple sources possible
- Performance independent of number of sources
- Different wavefront / focusing schemes can be simulated



Linear Wavefront



Focused Wavefront

Westervelt Equation

- Full nonlinear wave equation for acoustic simulation
- Applications in Ultrasound Simulation
  - Signal response simulation
  - Harmonic Frequency simulation
  - Temperature field simulation
- First results indicate that simulated predictions
  - Coincidence with real measurements from water tanks
  - Are equivalent, and sometimes, superior to other methods

The equation itself

$$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \frac{\delta}{c_0^4}\frac{\partial^3 p}{\partial t^3} + \frac{\beta}{\rho_0 c_0^4}\frac{\partial^2 p^2}{\partial t^2} = 0$$

- First two terms identical to lossless wave equation
- Third term, attenuation
- Forth term, nonlinearity
- Terms:

p : Pressure

c_0 : Propagation speed

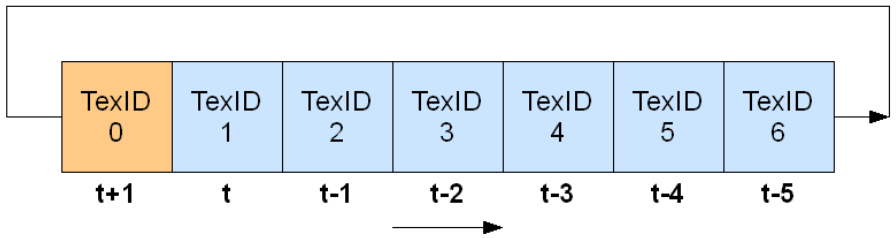
ρ_0 : Ambient density

δ : Diffusivity of sound

β : Coefficient of nonlinearity

GPU Implementation of FDTD-Westervelt Method

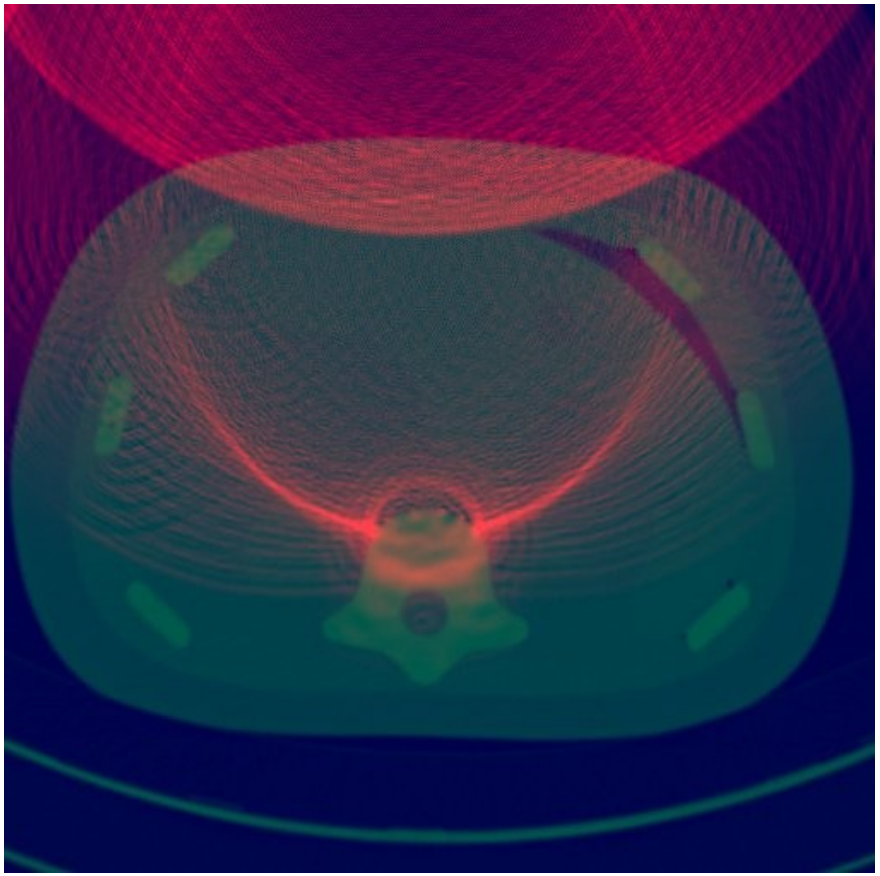
- Substitute partial derivatives with finite difference
- Solve for next time-step and use formulation in GPU fragment shader
- The previous 6 time-steps are required, thus, 6 textures are required
- Utilizing textures for time-steps and coefficient spefication
  - All coefficients are set constant, except propagation speed
- Texture queue used to reduce GPU overhead

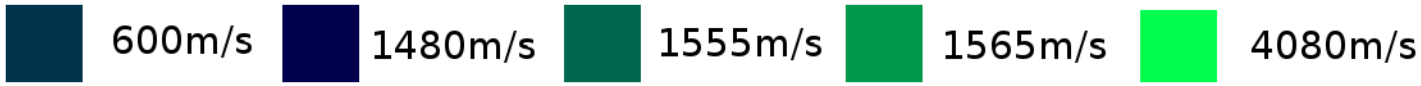


Texture Queue for GPU FDTD-Westervelt

Results

- Manually segmented CT phantom dataset
- Propagation speed varying for different pixels
- Nonlinear term omitted
- 512x512 grid
- Avg. 1078 Time-Steps/sec



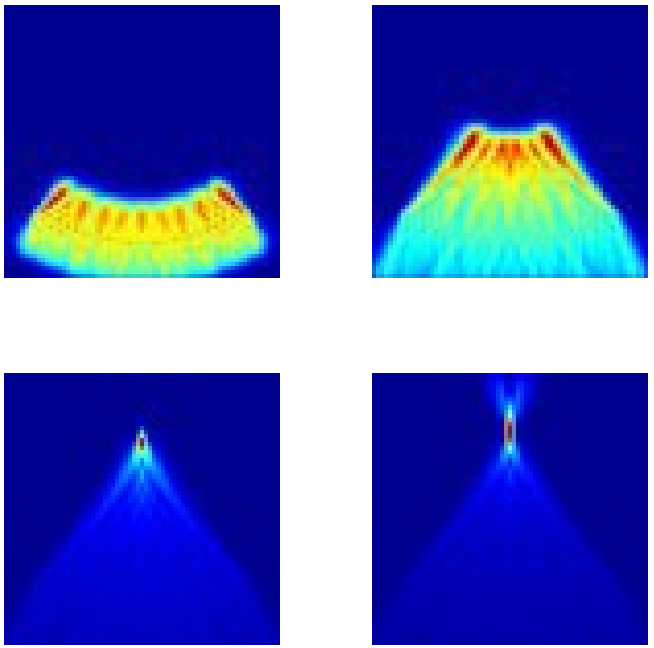


Future Work

- FDTD-Westervelt method promising for:
  - Real-time simulation
  - Accurate predictions
- Absorbing Boundary Conditions required (CPML)
- Segmentation/labeling of CT or MRI datasets
- Test different ecxitation pulses (currently Dirac)
- Different focusing strategies
- Post processing pipeline to transform pressure signal into B-scan ultrasound image

Distant Future

- Therapeutic applications using High Intensity Focused Ultrasound (HIFU)
- MRI guided ultrasound surgery already demonstrated potential
- First temperature field simulations for thermoviscous fluids showed potential
- Simulating focusing regions and defining safety regions would be extremely valuable



Focused US Temperature field [Hallaj and Cleveland]

THANK YOU FOR YOUR ATTENTION!

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