Multi-GPU Accelerated Refraction-Corrected Reflection Image Reconstruction for 3D Ultrasound Breast Imaging

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Presentation Overview

- Background
- Motivation & Problem Statement
- Technical Design
- GPU Implementation
- Results
- Contact Information

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Scanner Introduction

Figure 1 QTultrasound scanner

- For breast tissue evaluation;
- Quantitative transmission image;
- Qualitative reflection image;
- No radiation;
- Patient comfort improvement.

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Scanner Geometry

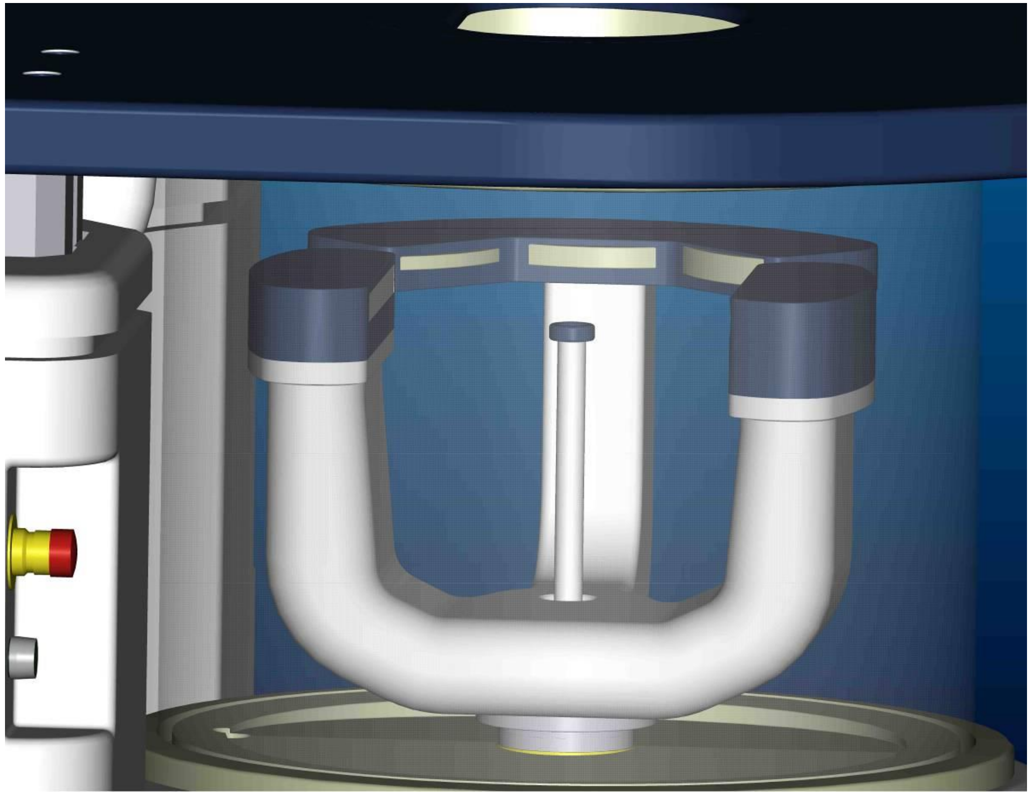


Figure 2 Five scanning arrays mounted on the tri-channel

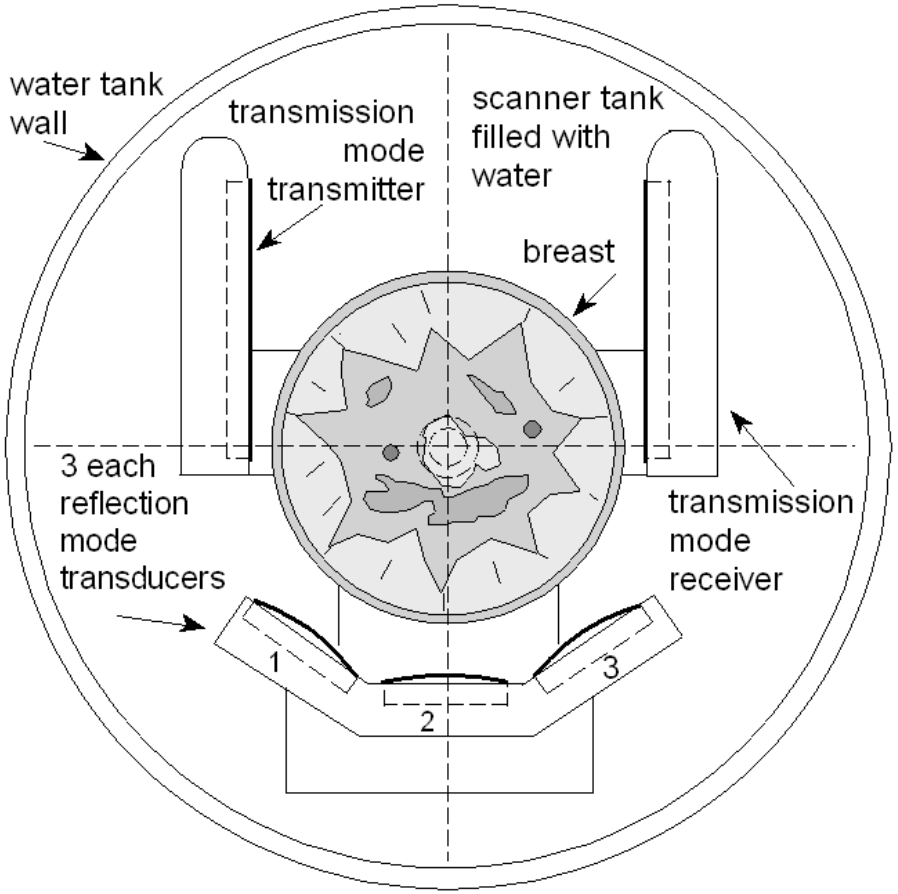
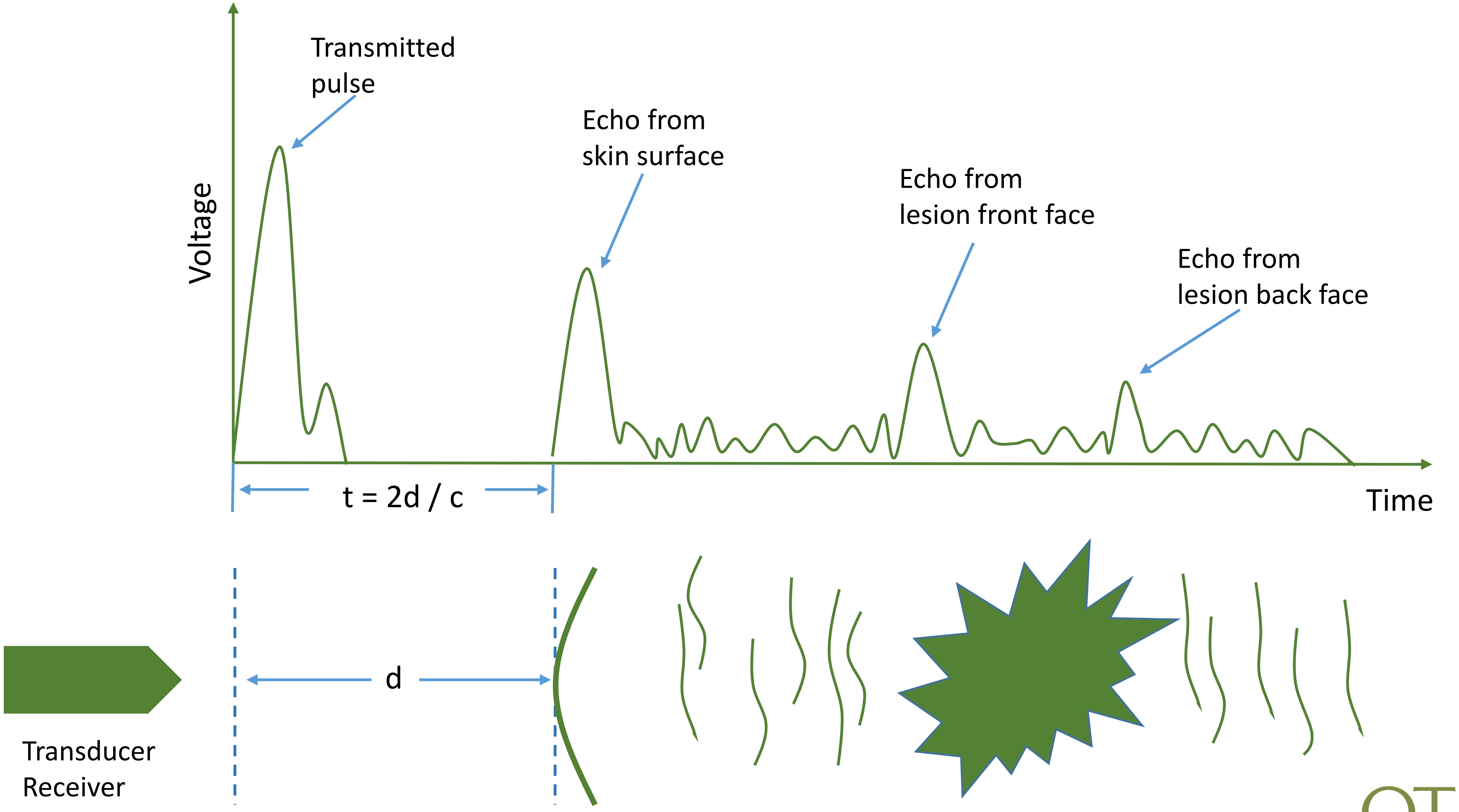


Figure 3 Geometry of three reflection arrays and a pair of transmission arrays

Data Acquisition



B-mode Scan and Acoustic Wave Behavior

Background

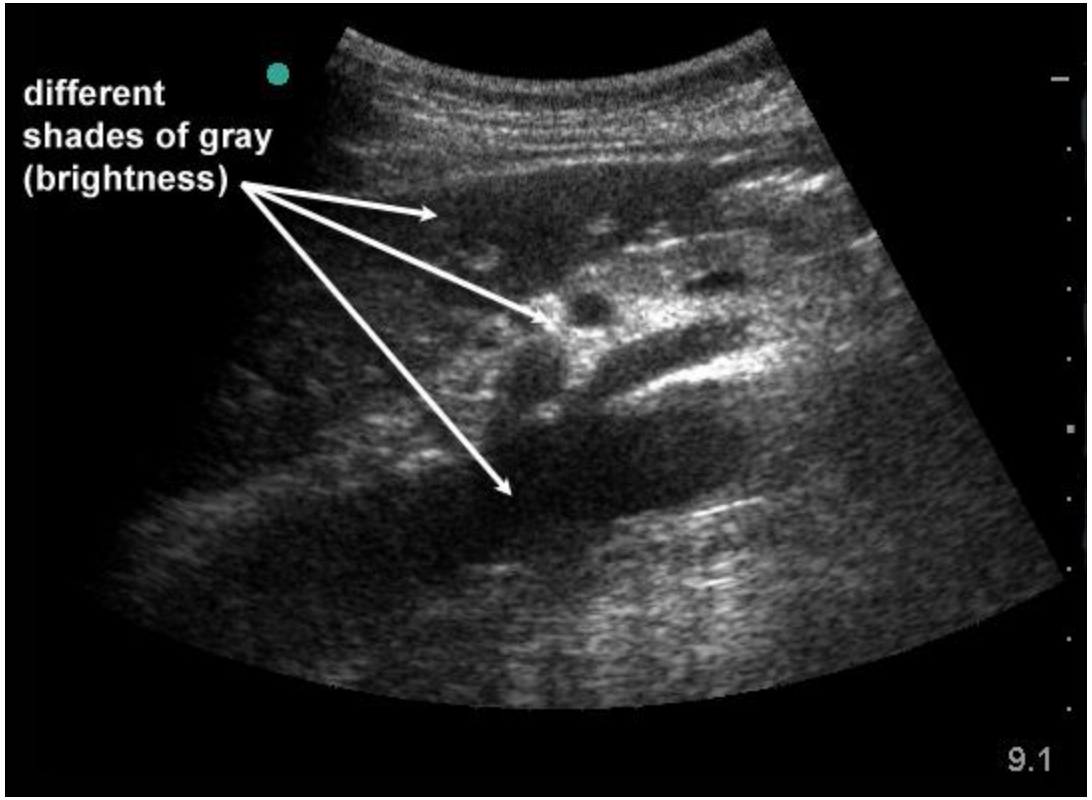


Figure 4 Sample of B-mode (brightness mode). Image driven.

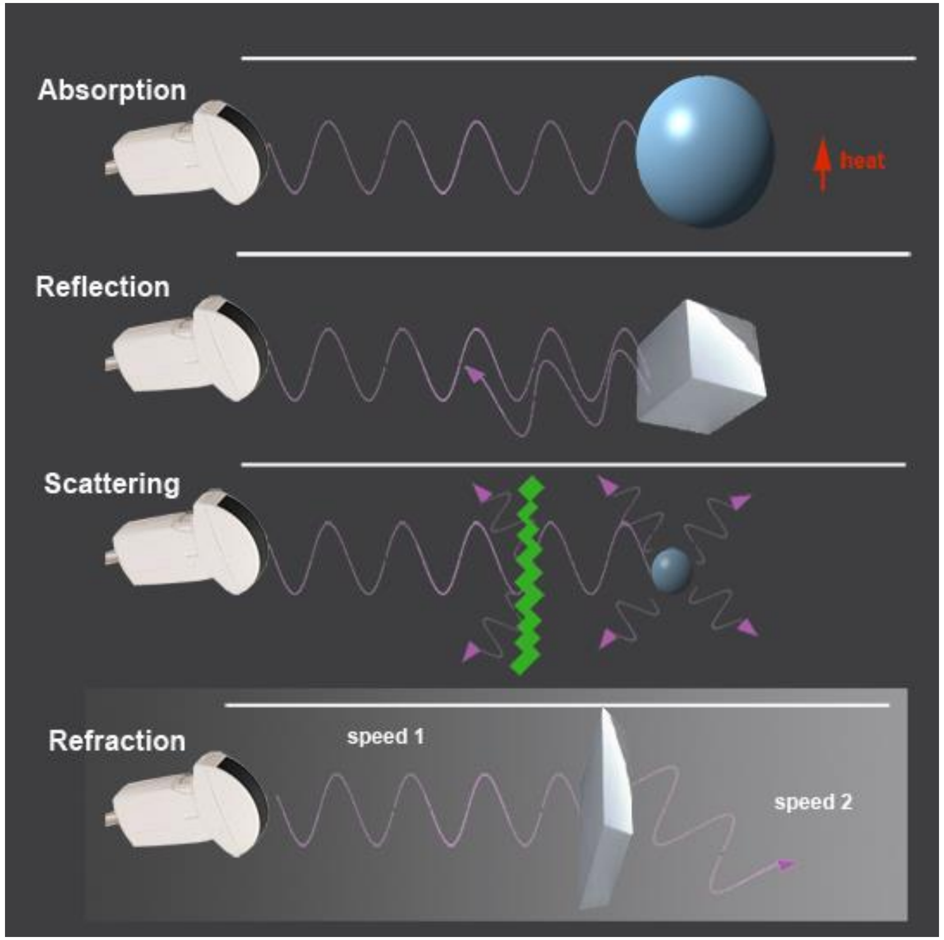


Figure 5 Acoustic wave behavior between the inhomogeneous border of two different mediums.

http://www.sonoguide.com/physics.html

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Image Reconstruction Algorithm

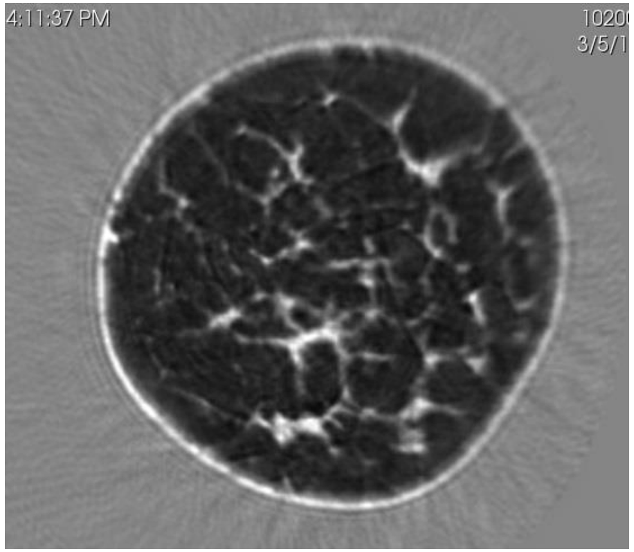
Transmission Image Preprocessing	Mapping transmission results into reflection image space.
Support Function Generation	Signal gain control for attenuation.
Refraction-corrected Ray Tracing	Ray (data) driven B-mode back-projection tomography
Image Postprocessing	Readability improvement

Refraction-Corrected Ray Tracing

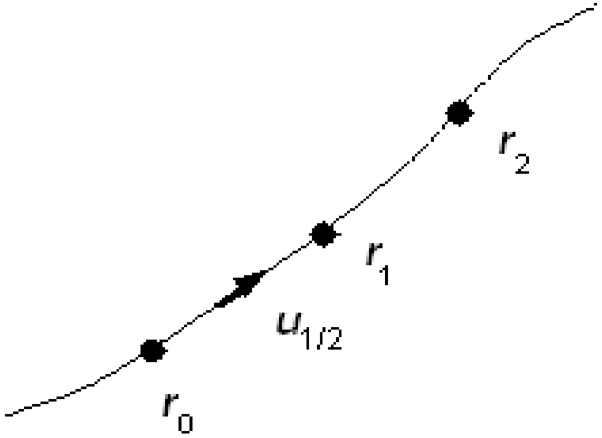
Eikonal equation: $$\frac{d}{ds}\left(n\frac{d\boldsymbol{r}}{ds}\right) = \nabla n$$

s: arc length along the ray;
r: ray position vector in 3D;
n: refractive index.

$$n(\boldsymbol{r}) = c_0/c(\boldsymbol{r})$$



Euler step method:

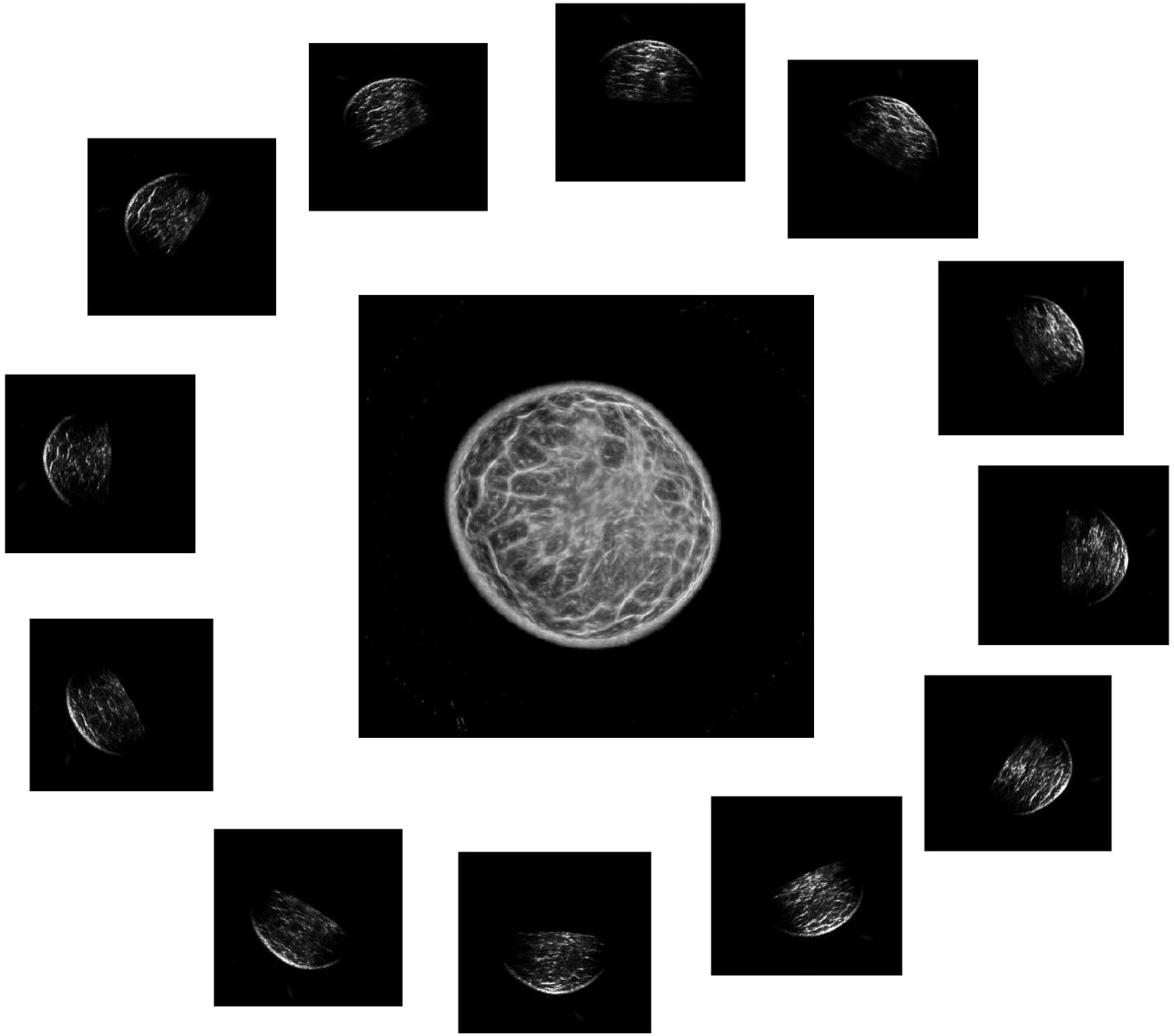


For i = 1,...

$$\boldsymbol{r}_{i+1} = \boldsymbol{r}_i + h \cdot (u_{\boldsymbol{r}})_{i+1/2}$$

h: step length;
u: unit tangent vector to the ray path.

Compounding to Tomography



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Challenges for Parallel Computation

Sequential operation of refraction-corrected ray tracing

Each step of each ray depends on the previous step's position and refractive index and the current step's refractive index;

Each pixel's signal weighting is contributed by multiple rays;

Each ray behavior is unpredictable in terms of position ranges.

File access speed limitation

Data writing and reading between pipeline stages allows for all the operations in each stage to be computed independently;

However, the data throughput on an SSD or a hard drive becomes a limiting factor.

Large amount of memory management

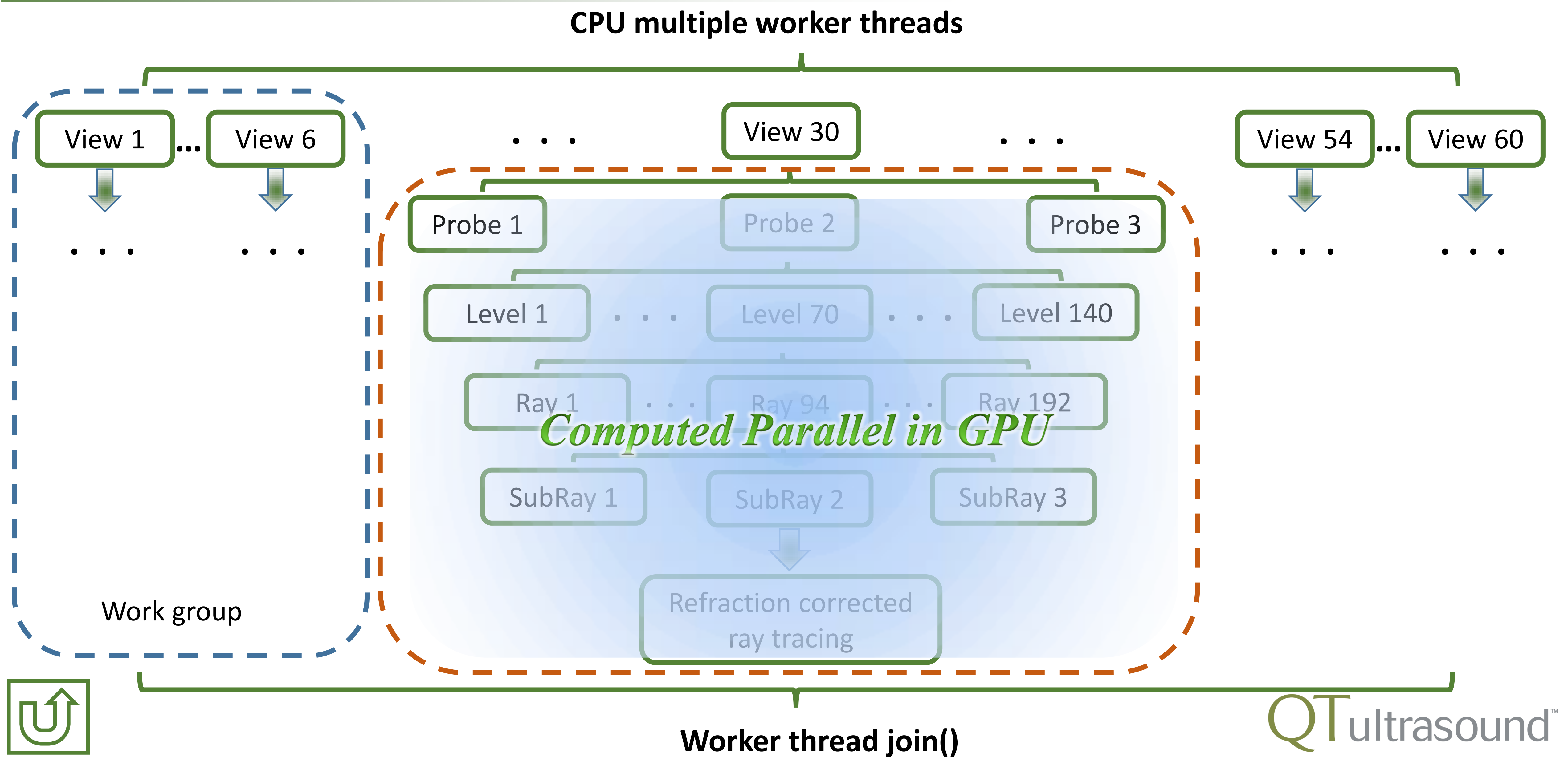
Unknowns: 32390540 pixels;

Acquired data: around 1.88 GB;

Computation data: around 9.4 GB.

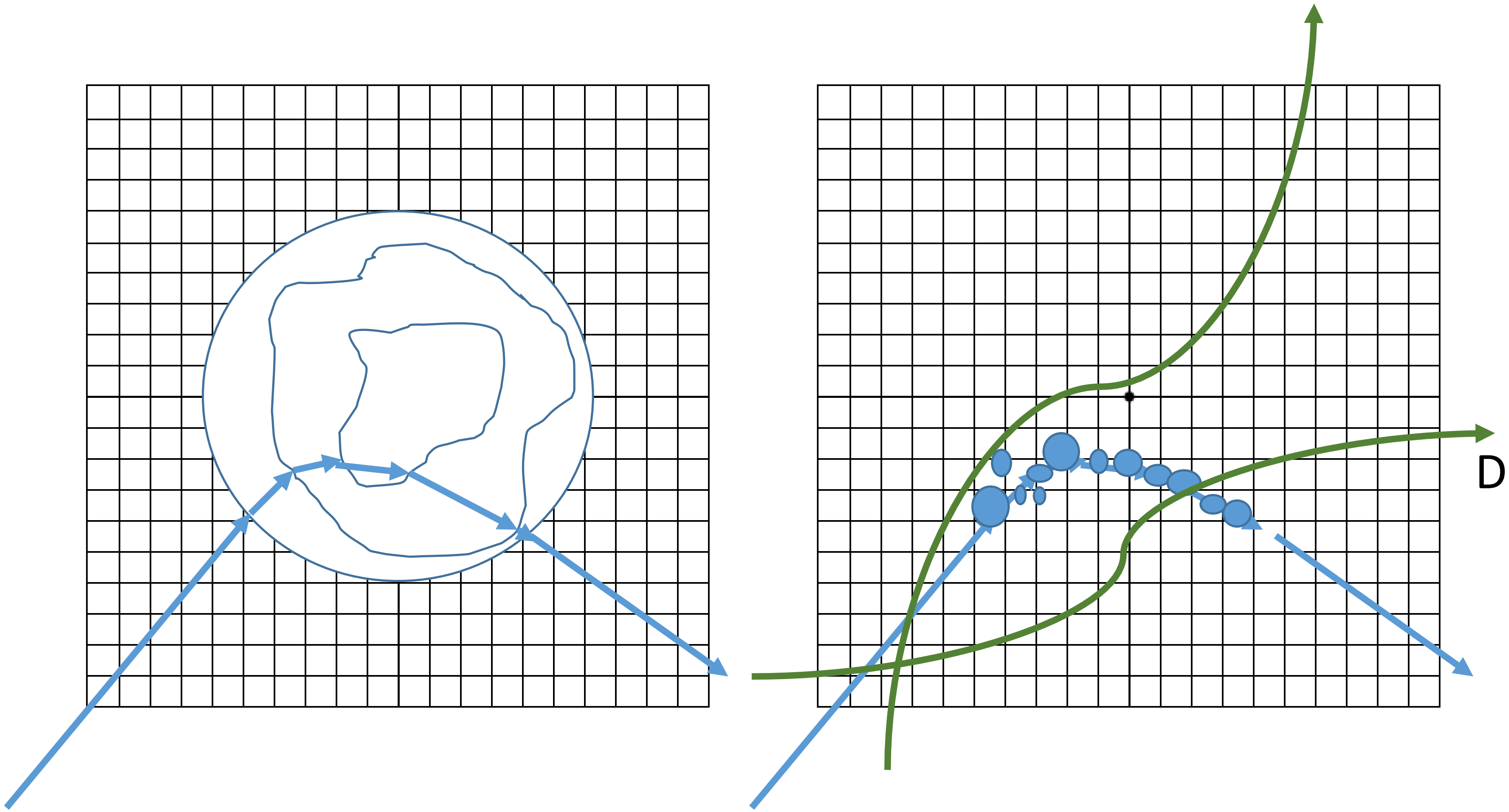
Parallelism with multi-core CPU and GPU streaming processors

Design



Ray Tracing in Parallel

Design



3D sparse matrix

Dictionary of Keys (DOK)
Pixel position-> key
Weight-> Value
Time sample-> Value

Design

Concurrent Operations of CPU and GPU

```
cudaMalloc (&dev, size);
…

cudaStream_t stream[nStreams];
For (int iStream = 1; iStream <= nStreams; ++iStream)
        cudaStreamCreate (&stream[iStream]);

cudaEvent_t event;
cudaEventCreate (&event);

For (int iView = 1; iView < nViews; ++iView)
{
        …read the data for iView

        cudaMemcpyAsync (dev, host, size, H2D, stream[iView]);
        kernel <<< grid, block, 0, stream[iView]>>> (…, dev, …);

        if (iView != nViews)
        {
                cudaEventRecord (event, stream[iView]);
                cudaStreamWaitEvent(stream[iView + 1], event, 0);
        }
}

cudaMemcpy (host, device, size, D2H);
…destroy stream and event
```

- Create streams for each view computation
- Only one event needed to be created
- Asynchronous with stream
- Wait for the previous event done

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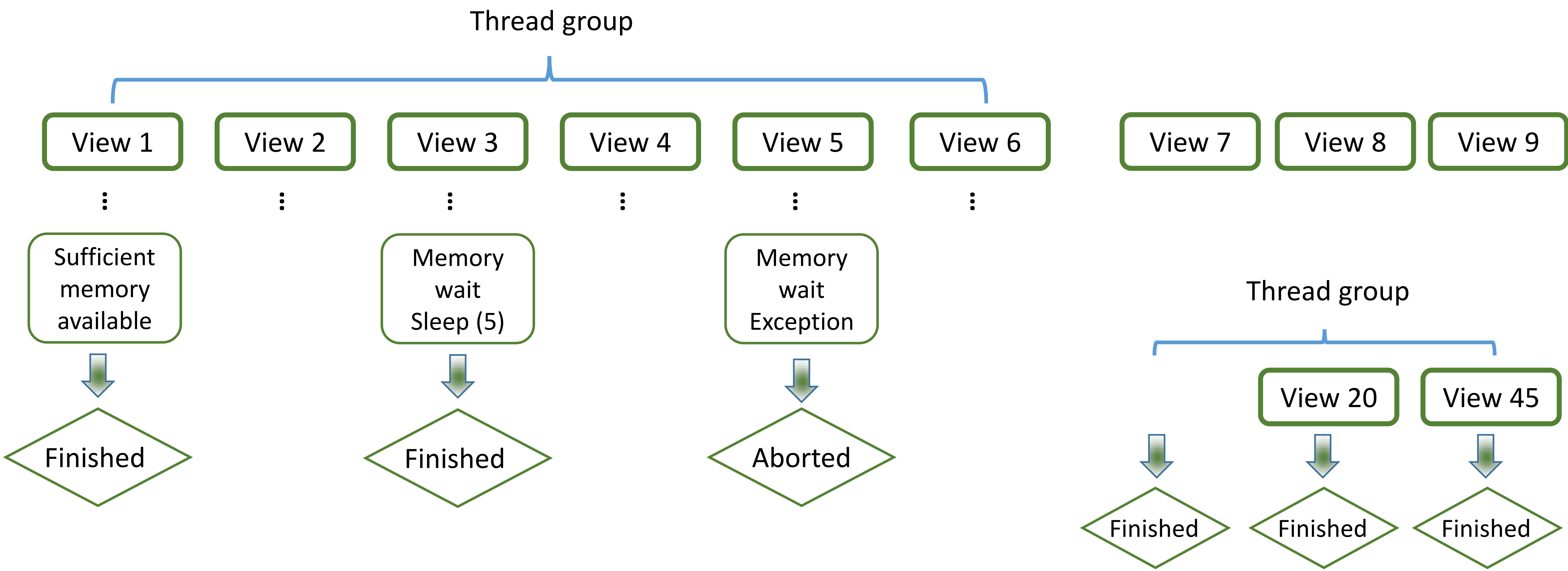
Memory Contention Solution



Hardware Selection

Tesla K40 GPU

- Stability and reliability:
  long-term product;
- High single precision floating-point performance:
  4.20 TFlops;
- Large memory to support multiple CPU worker threads operation:
  12 GB.

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Software Architecture Design

- Interface to rest of production software
- GUI
- Standalone

- **Pipeline Layer** — Read parameters, order of algorithm operations, etc, from a configuration file
- **Interface Layer** — Object-oriented API for each stage of reconstruction algorithm
- **Host Layer** — Manage GPU memory; CPU and GPU data transfer; Call GPU kernels and check kernel errors; schedule asynchronous operations; Support multi-GPUs
- **GPU Layer** — GPU kernels implementation

Performance Test (individual functions)

Functions	Single CPU time	Single GPU time	Speedup
Bilinear interpolation	1930.00	33.28	57.99X
Blurring filter (FFT included)	15660.00	129.17	121.24X
L1 norm fit third-order polynomial	100.00	7.24	13.81X
Nearest points mapping	6850.00	39.98	171.34X
Compounding images	366800.00	4403.09	83.31X
Dynamic gain for images	910.01	42.88	21.22X

Note: The calculation of GPU time includes data transfer from host to device and back from device to host.
All times are given in milliseconds.

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Performance Test (overall)

Result

Reconstruction Stage	Single CPU time	Single GPU time	Single GPU speedup	Two GPU time	Two GPU speedup
Preprocessing and Support Function	34.09	9.36	3.64X	7.72	4.42X
Refraction-Corrected Ray Tracing	1899.98	63.29	30.02X	45.53	41.73X
Compounding Views	39.33	0.84	46.71X	0.84	46.71X
Entire Reflection Reconstruction	2108.40	79.16	26.63X	54.57	38.64X

Note: All times are presented in seconds.

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Case Images 1: Multiple Cysts

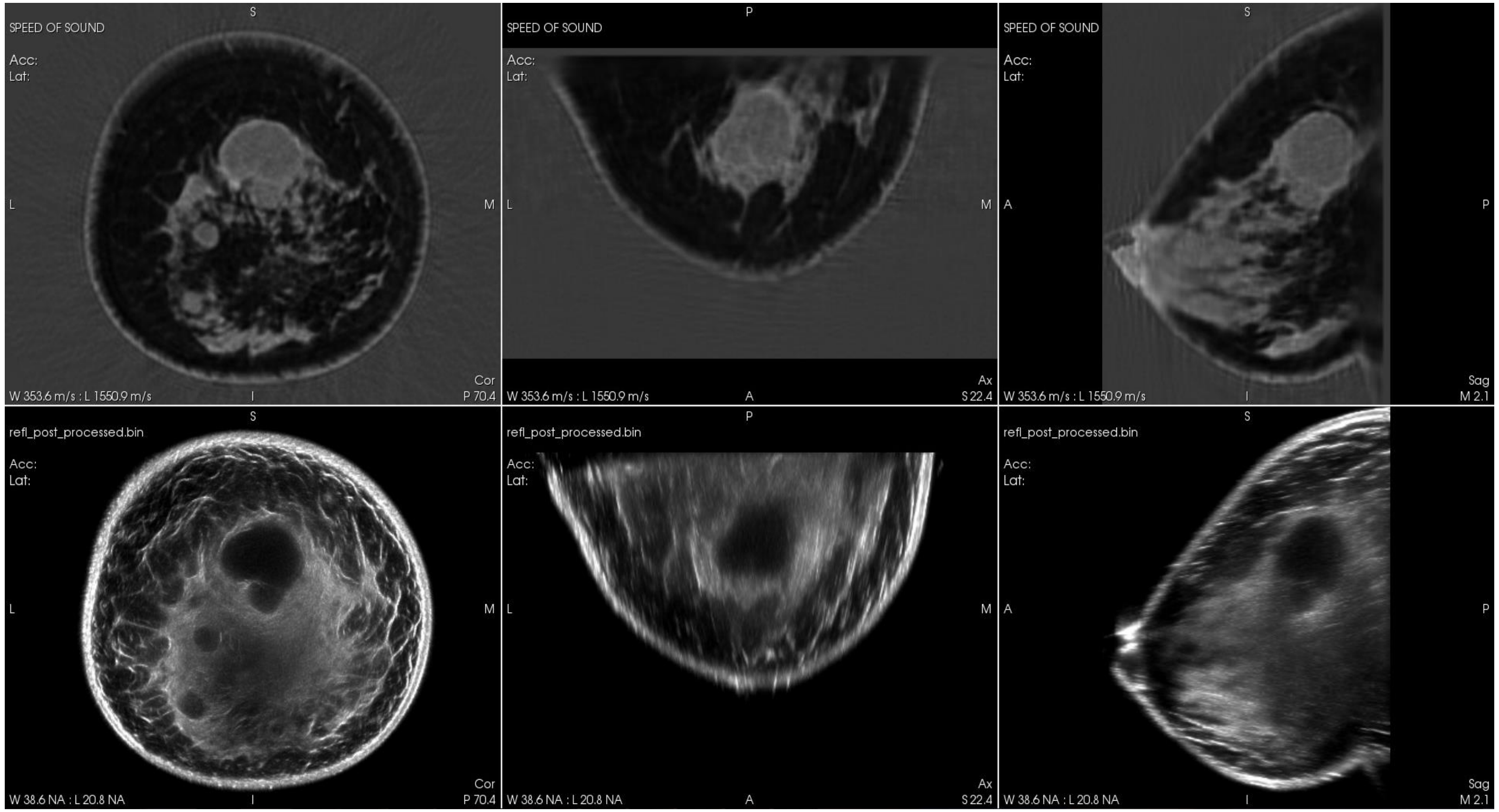

Figure 9 Coronal, Axial and Sagittal images present multiple cysts.

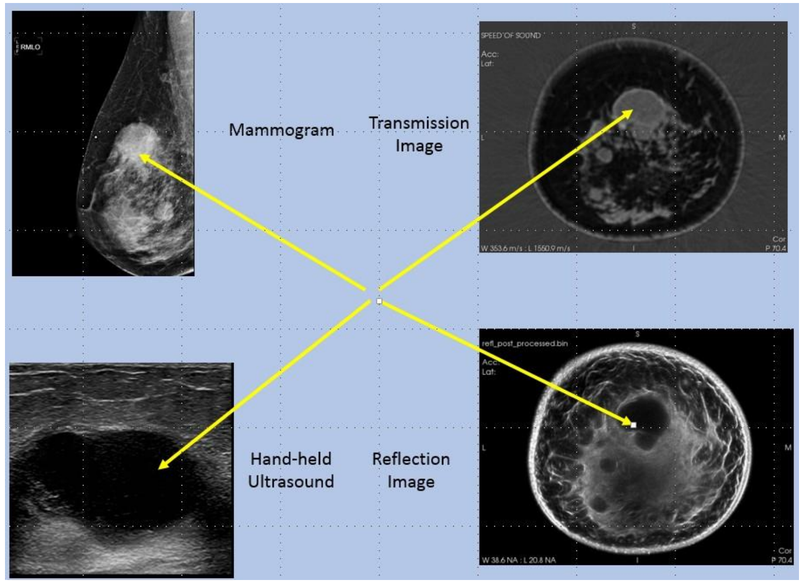

Figure 10 Comparison with mammography, hand-held ultrasound

Result

Case Images 2: Invasive Ductal Carcinoma

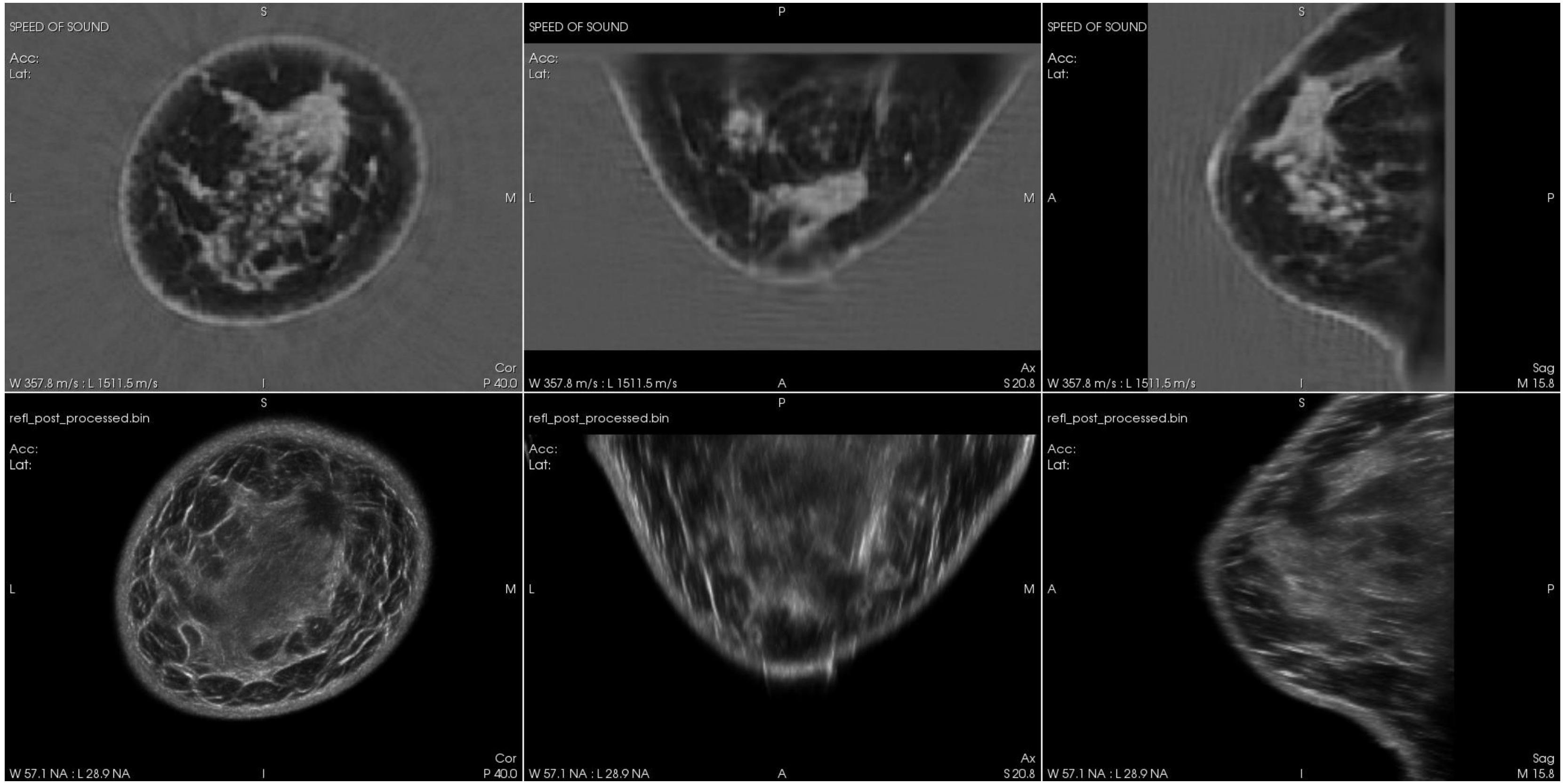

Figure 11 Coronal, Axial and Sagittal images present invasive ductal carcinoma

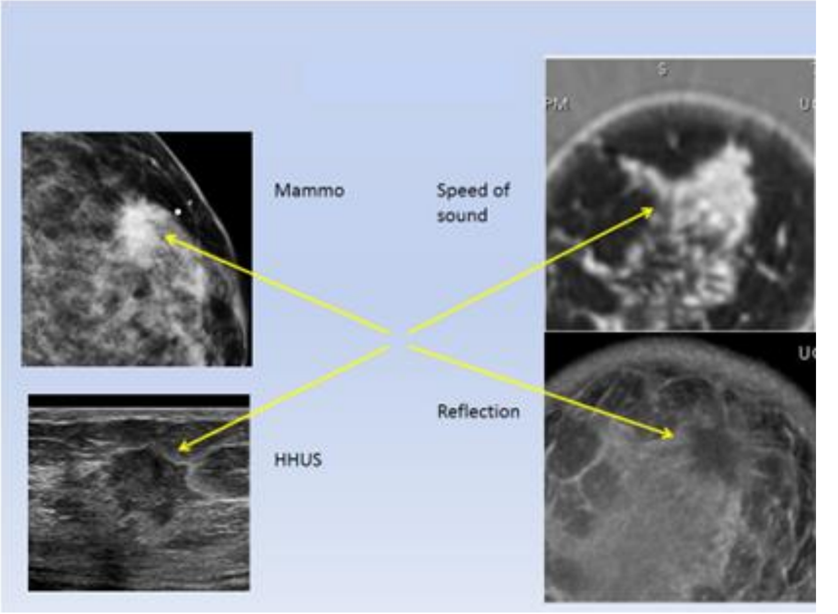

Figure 12 Comparison with mammography, hand-held ultrasound

Contact Information

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GPU TECHNOLOGY CONFERENCE

Thank you