Recent Trends in Beamformation in Medical Ultrasound

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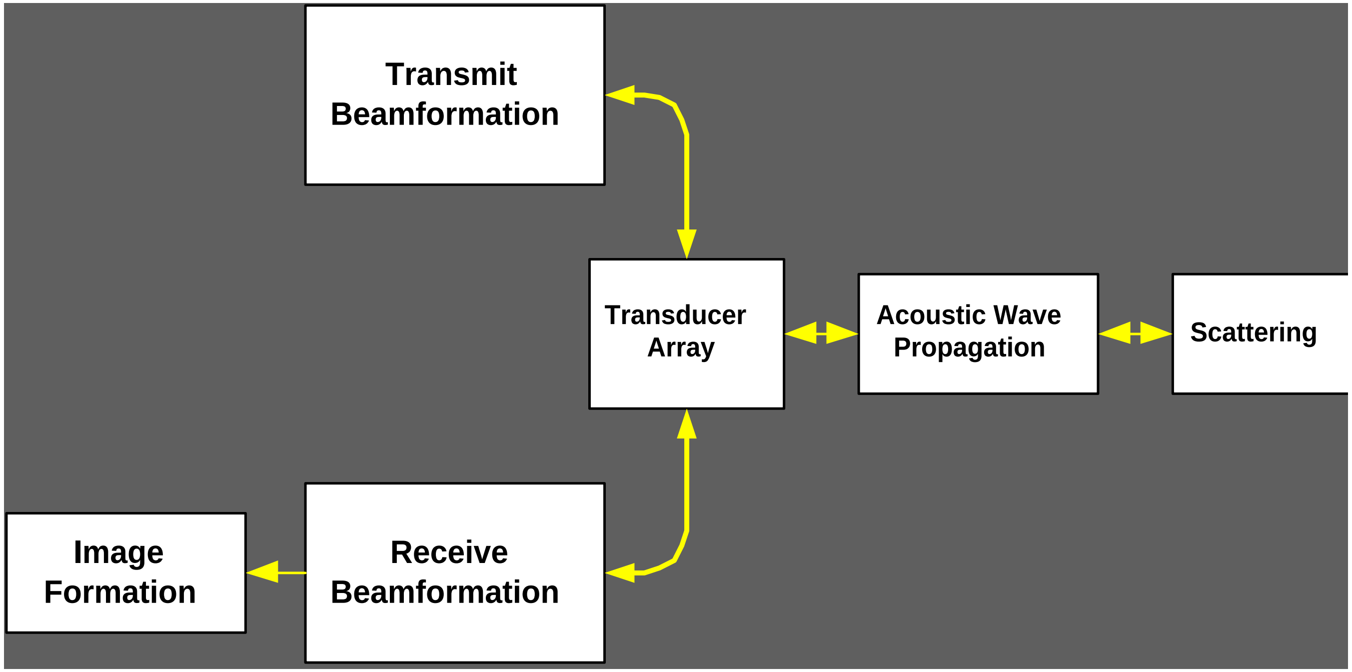
Broad Outline of Course

- Beamformation - basics, implementation
- Analysis of beamformation - simulation
- Application of analytical methods
- Recent trends

Four 50 minute talks, three 10 min breaks

Beamformation - role in an imager



Perhaps the most important building block.

- Soul of the machine?

Probably the most expensive building block.

- 30 - 50% of parts & labor of a scanner

Creates the transmit & receive beams

Some Beamformer History

Before the mid-70s

- Single element scanners, no beamformer necessary

1975 - 1980

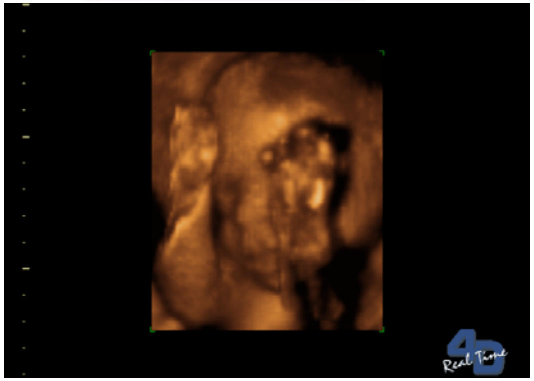
- Array based systems
  - Linear/curvilinear arrays
  - Linear phased arrays
- Analog beamformation
  - Tapped lumped constant delay lines
- Typically 32 channels

Mid 1980s

- High channel count systems
- High = 128

Early 90s

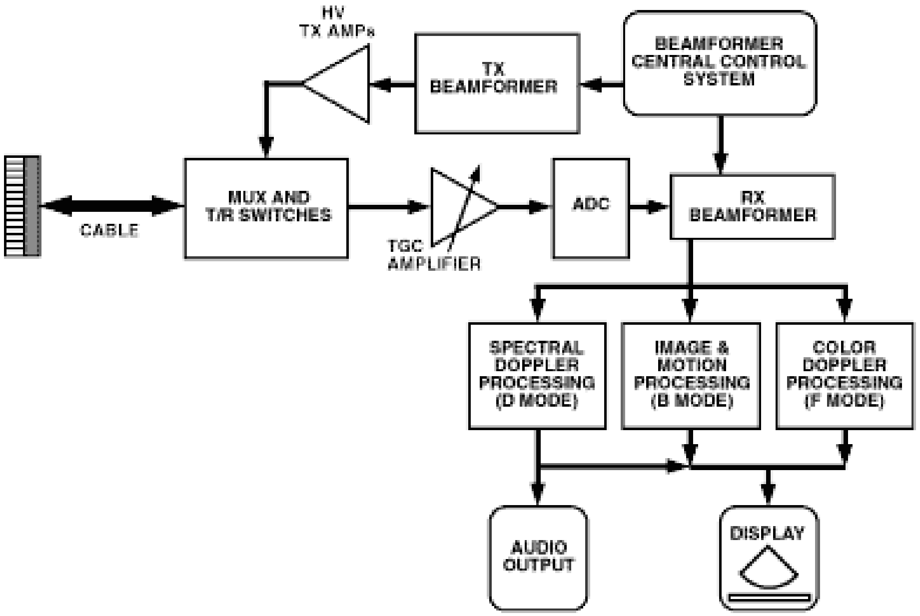
- Digital beamformation



http://www.ob-ultrasound.net/articulated-arm.html

Overall Imager Block Diagram

- Transmit beamformation
  - relatively simple delay generation
  - ASIC's, downcounters
  - generation of transmit codes

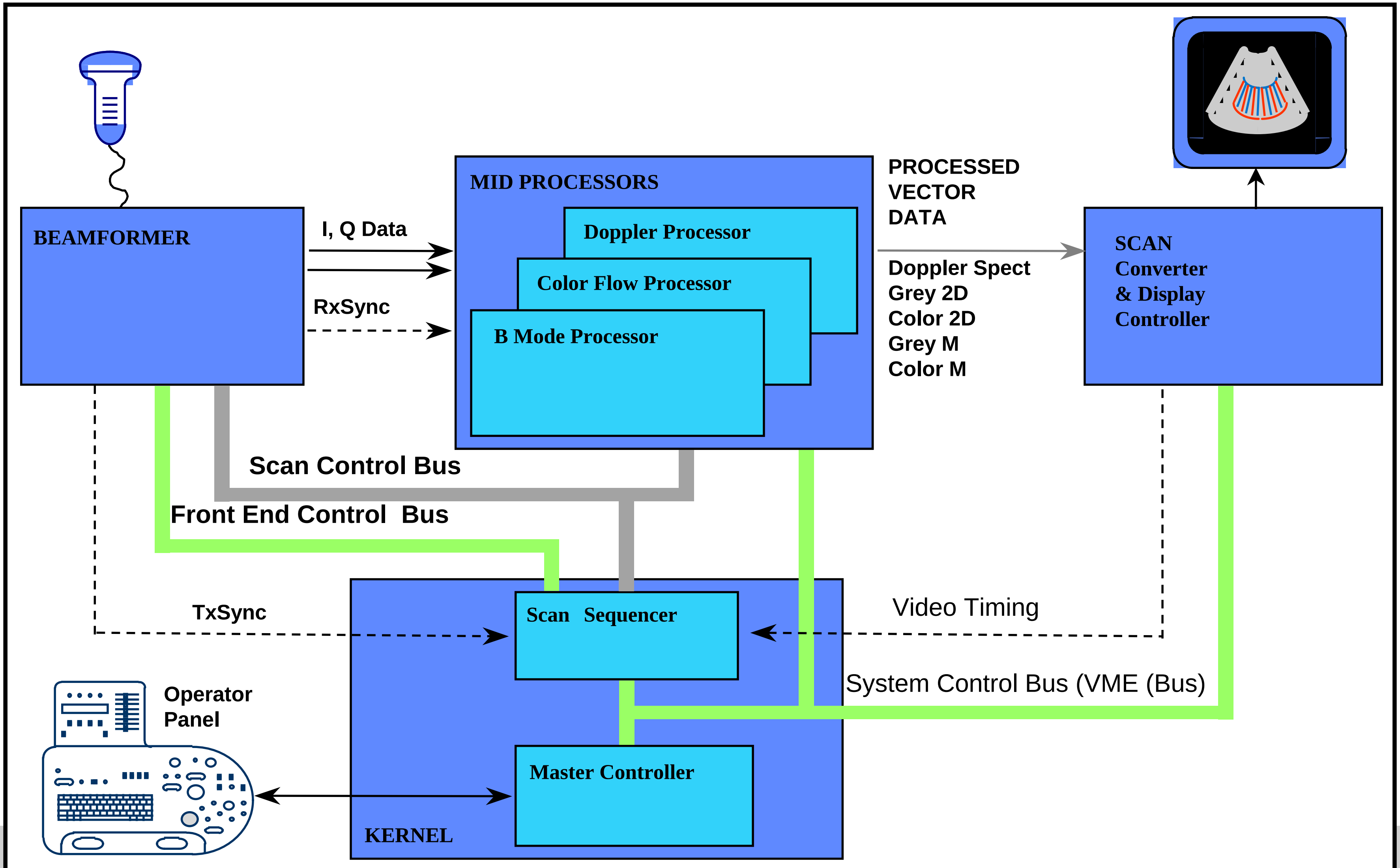


- Receive Beamformation
  - Data input:
    - sampled at 20 - 60 MHz
    - 8 - 14 bits
- Most important roles:
  - Delay generation for:
    - Beam steering
    - Dynamic focusing
  - Dynamic apodization
- Channel Count Definition
  - Many definitions, often marketing driven
  - I like definitions based on no. of ADCs

Acoustic Wave Propagation

- Transmit voltages are typically in order of 100 V.
- These create pressures of appr. several 100 KPa.
- Typical tissue attenuation: 0.5 dB/(cm MHz)
  - Example: 10 cm penetration @ 5 MHz – 25 dB one-way
- Backscatter from tissues - < 10% of incident pressure
- Transducer conversion efficiency – 50 – 75%
- If we wish to display 40 dB of info, we have to be able to handle > 100 dB of dynamic range.

Typical System Organiztion

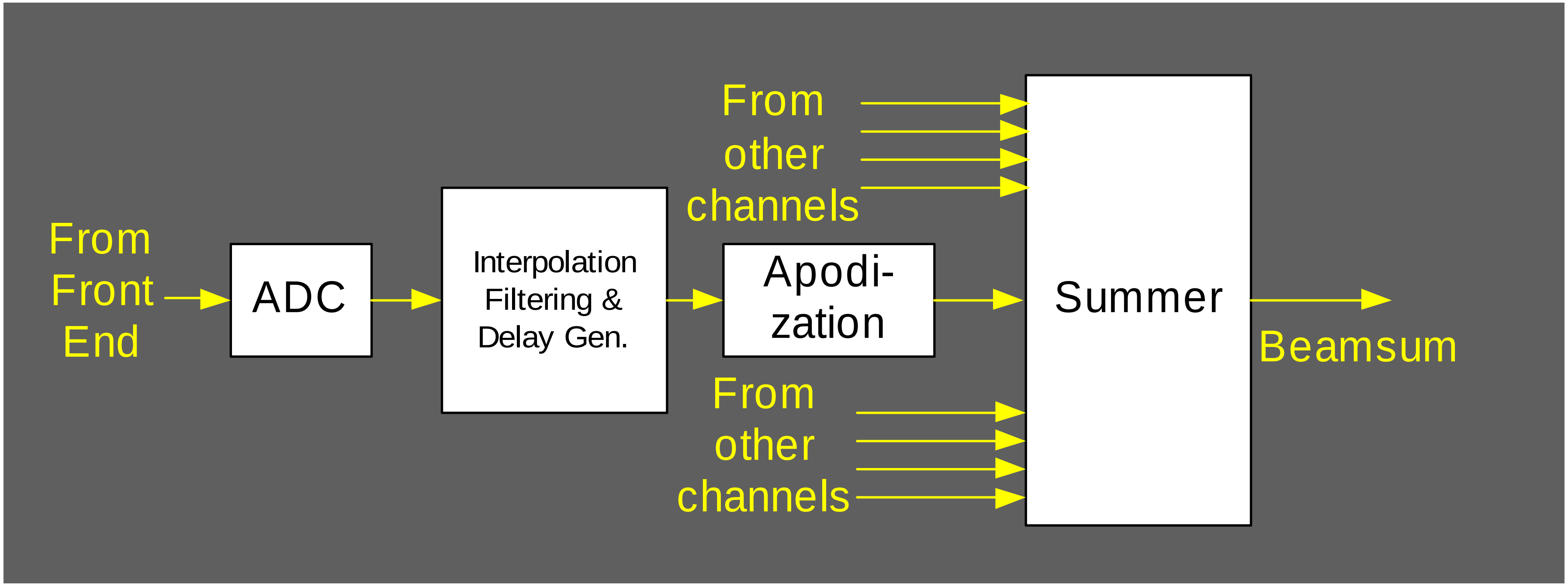


Beamformer Functions

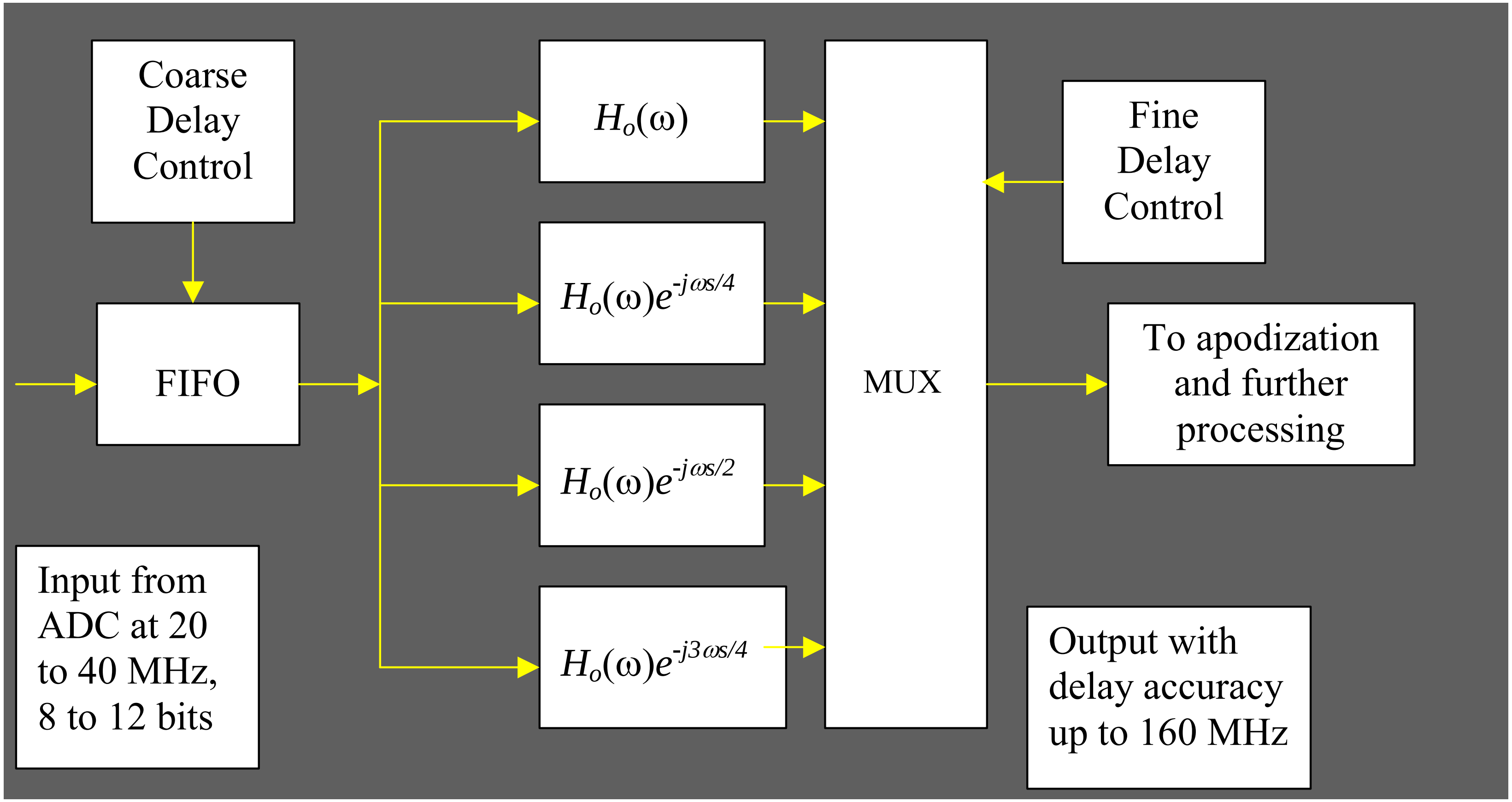
Receive beamformation block diagram

Three basic functions:

- Delay generation, dynamic and steering delays
- Apodization
- Summing of all delay signals

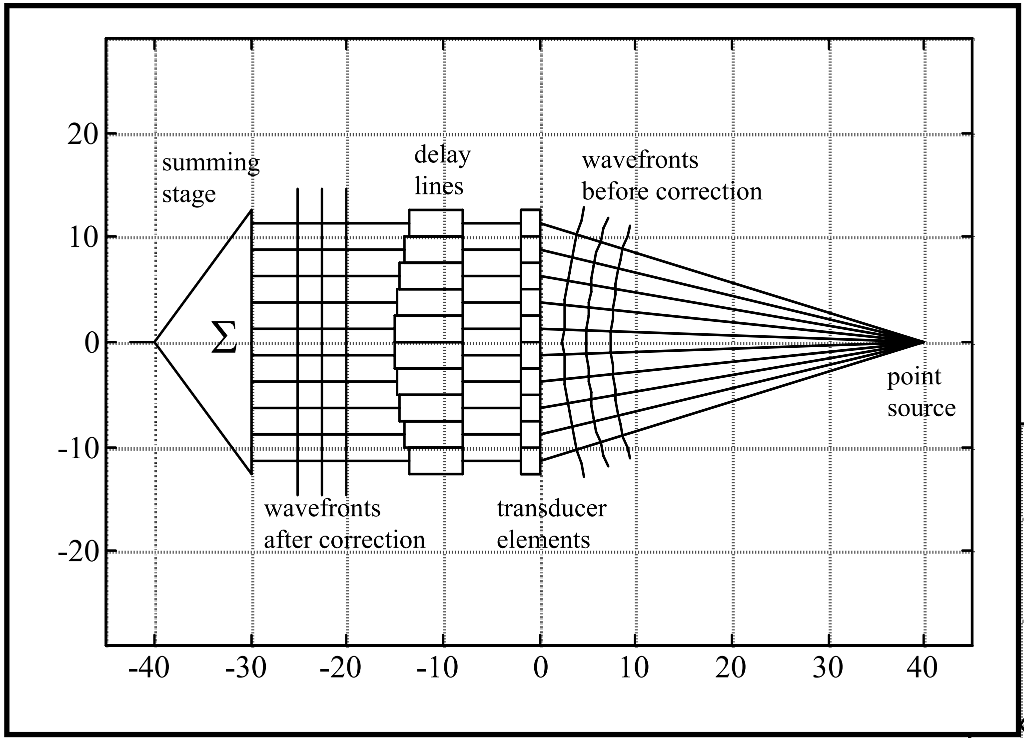


Interpolator Block Diagram

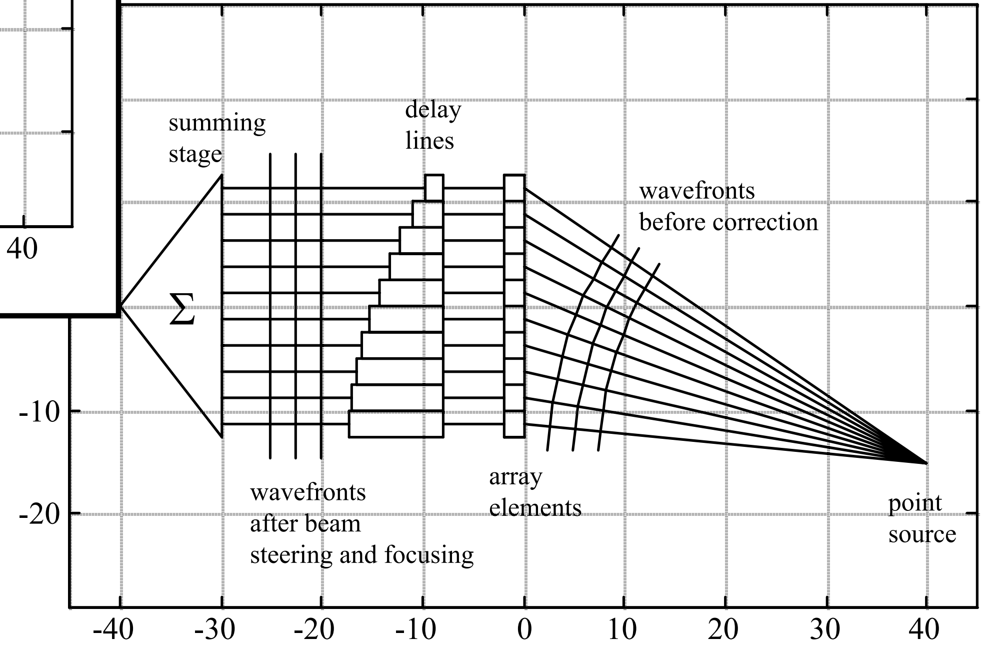


Beam Manipulations by the Beamformer

Focusing & Steering Delays

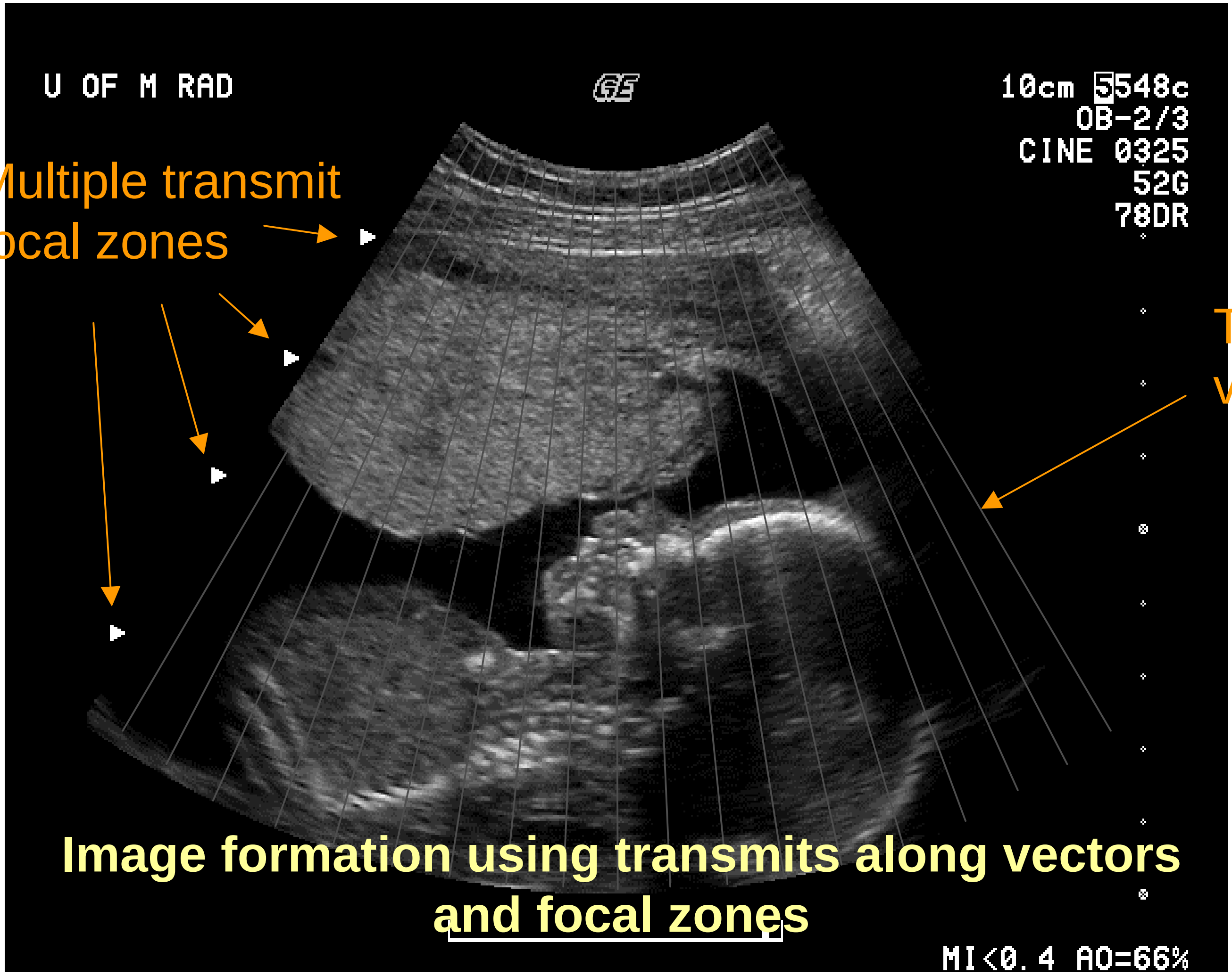


- Basic focusing type beamformation
- Symmetrical delays about phase center.



- Beam steering w. linear phased arrays.
- Asymmetrical delays, long delay lines

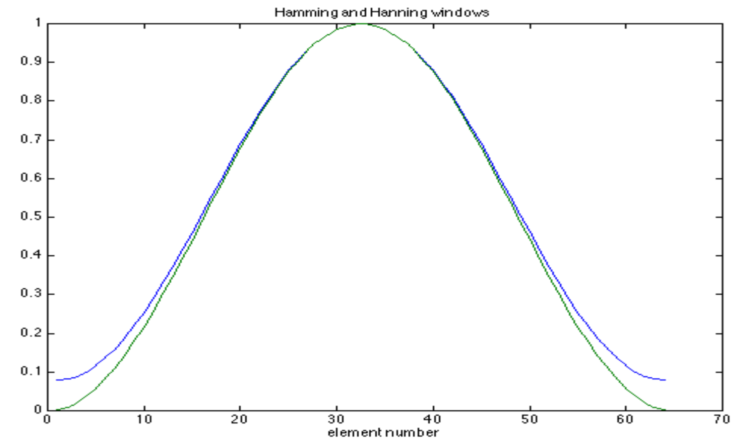
Transmit Vectors and Focal Zones



Beamformation: Apodization

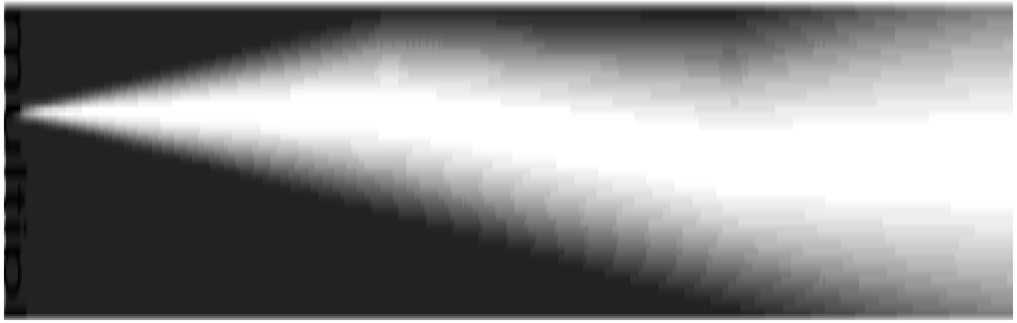
Main role

- apply a weighting function to aperture
- expand aperture w. receding wavefront
- maintain image uniformity
- supply walking aperture



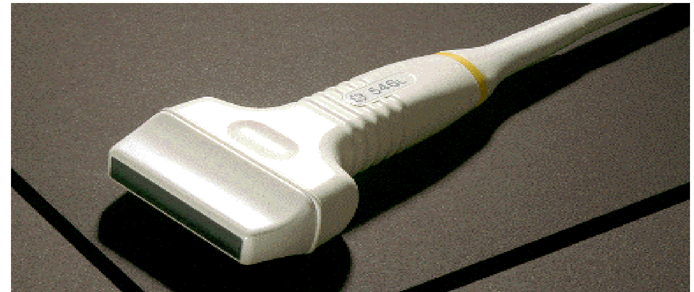
Implementation

- multipliers
- truly complex control



Highly beneficial impact on beam.

Types of Arrays & Beamformation



Linear array beamformation:

- Generation of focusing delays
- Beam steering by element selection

Curvilinear array beamformation:

- Generation of focusing delays
- Beam steering by element selection

Linear phased array beamformation:

- Generation of focusing delays
- Beam steering by phasing

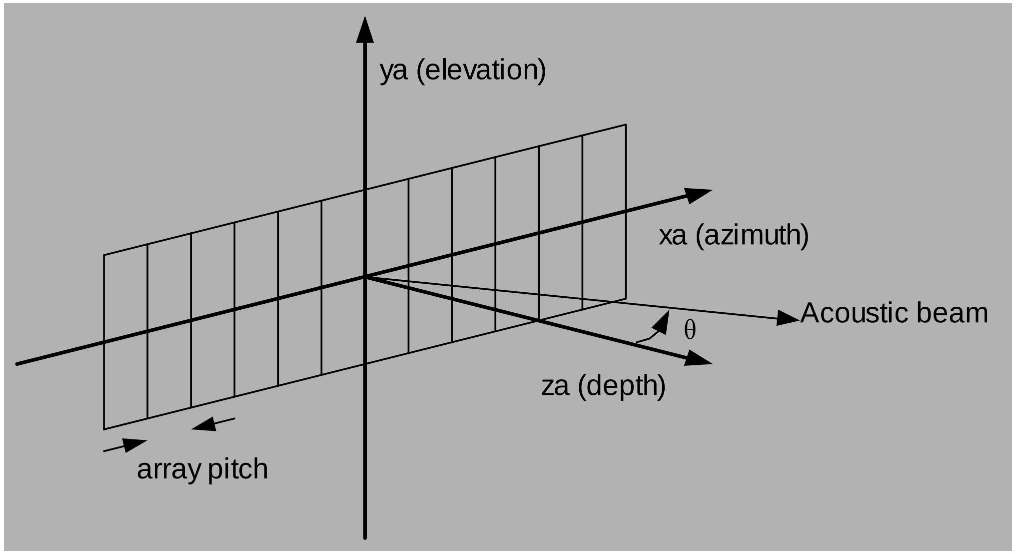
Array Geometries

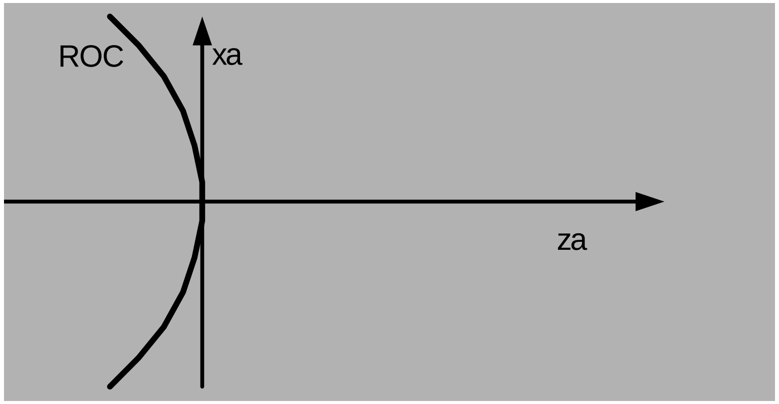
Schematic of a linear phased array

Definition of azimuth, elevation

Scanning angle shown, θ, in negative scan direction.

Similar definitions for a curved array





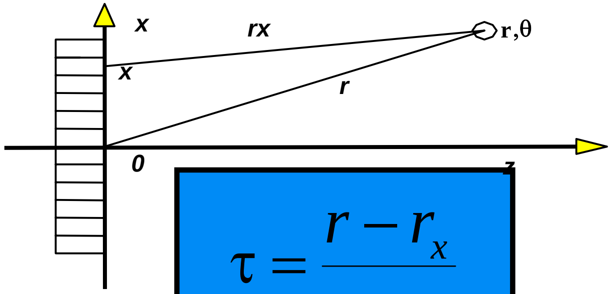
Some Basic Geometry

Delay determination:

- simple path length difference
- reference point: phase center
- apply Law of Cosines
- approximate for ASIC implementation

In some cases, split delay into 2 parts:

- beam steering
- dynamic focusing



$$\tau = \frac{r - r_x}{c}$$

$$\tau = \frac{1}{c}\left[\sqrt{x^2 - 2rx\sin(\theta) + r^2} - r\right]$$

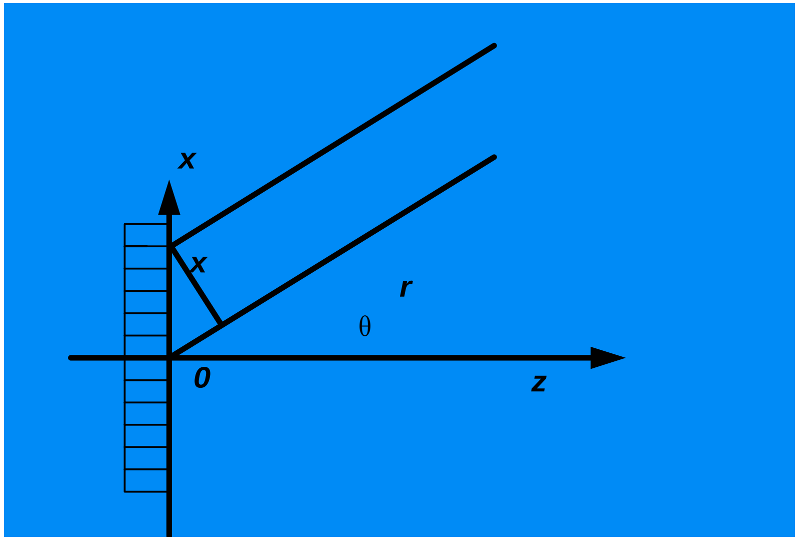
$$\tau = \tau_s + \tau_f$$

Far field beam steering

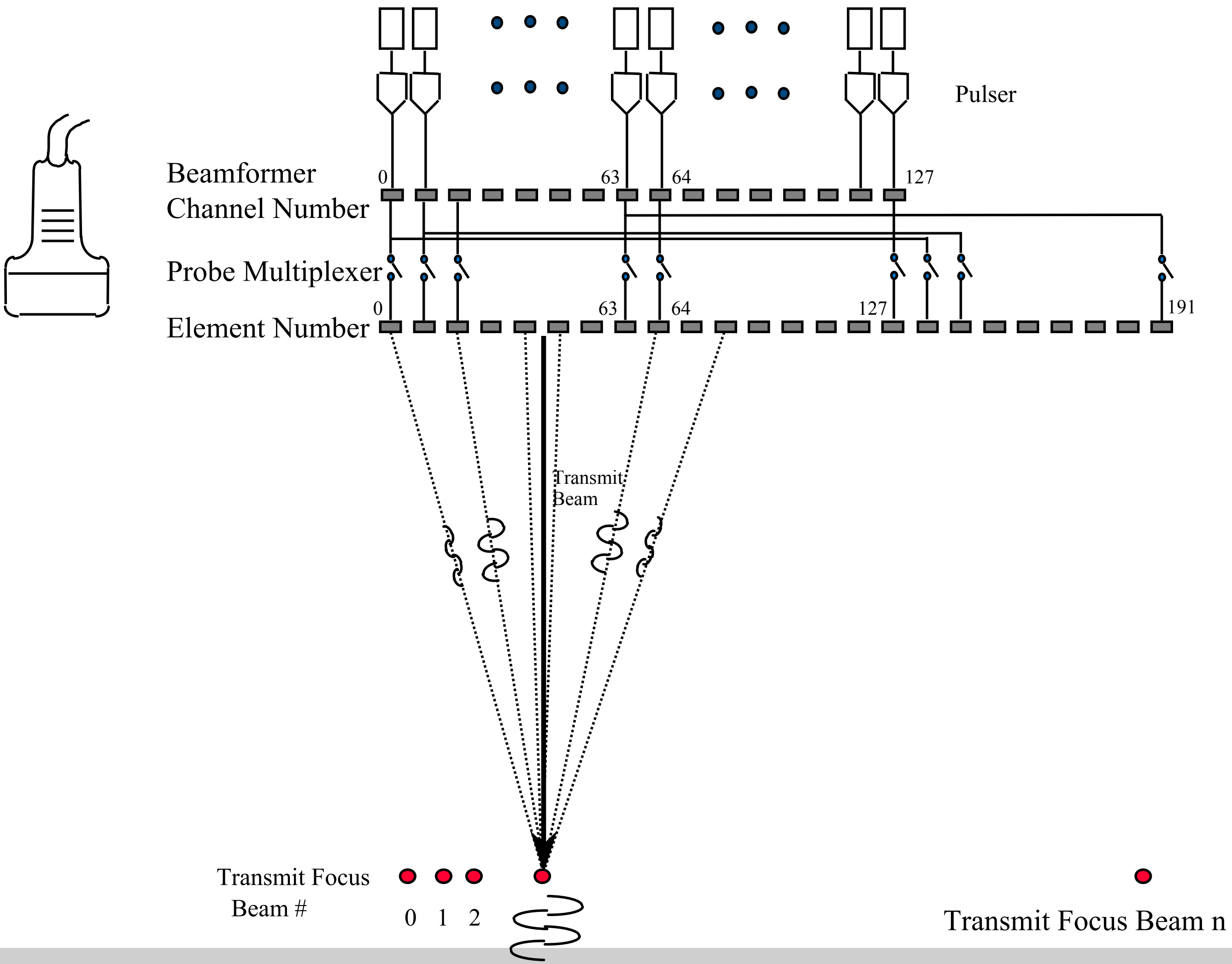
$$\tau_s = \frac{x\sin(\theta)}{c}$$

For beam steering:

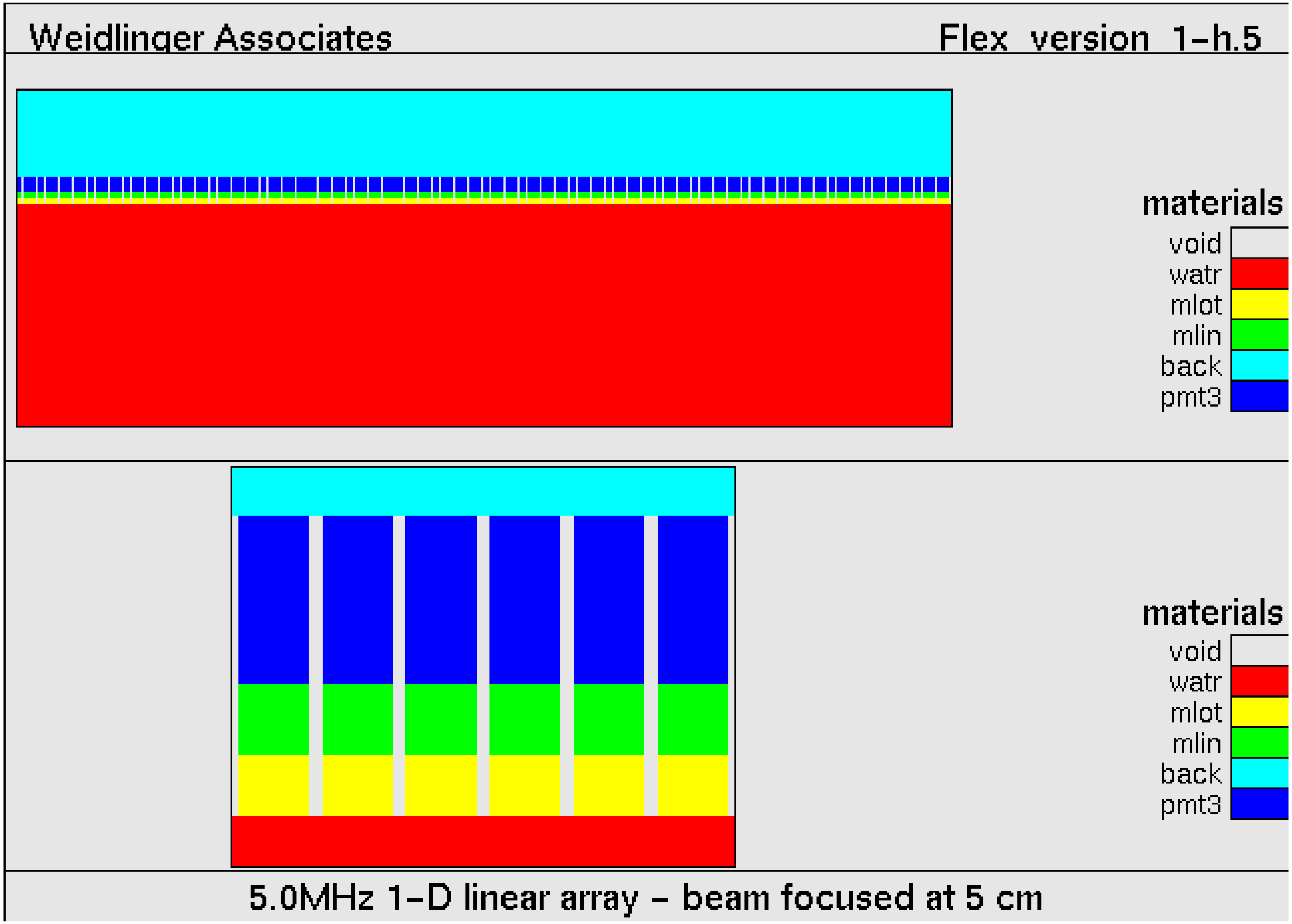
- easier to split the delays
- far field calculation particularly easy
- often implemented as a fixed delay



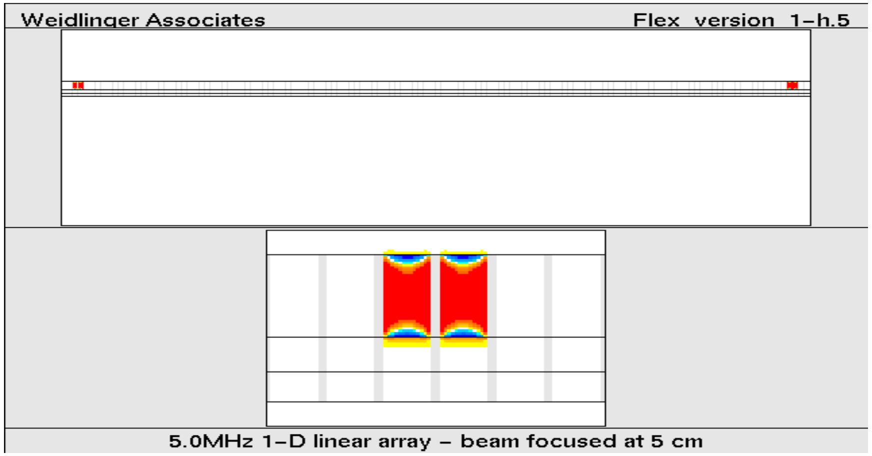
Linear Scan - Transmit Beamforming

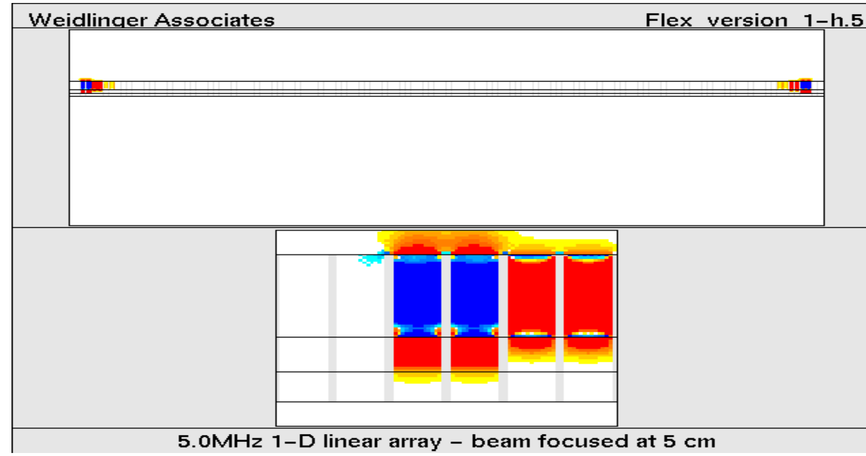


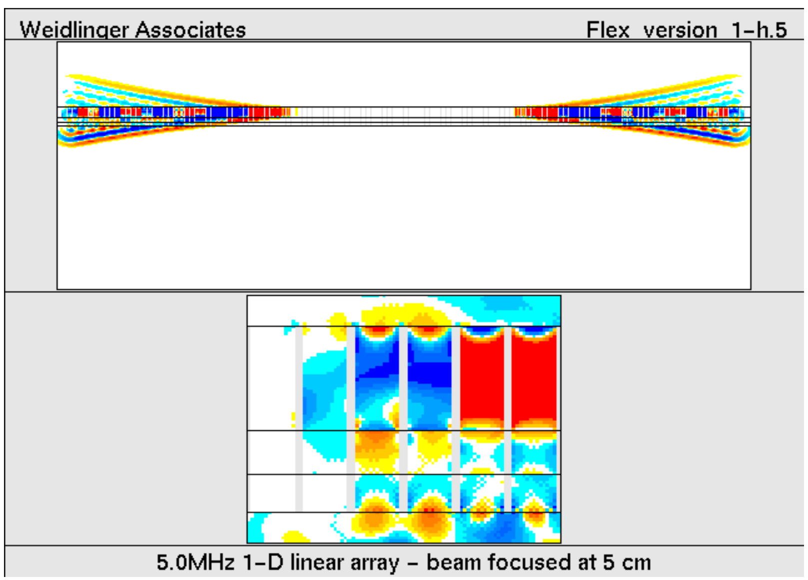
Beamformation: the movie

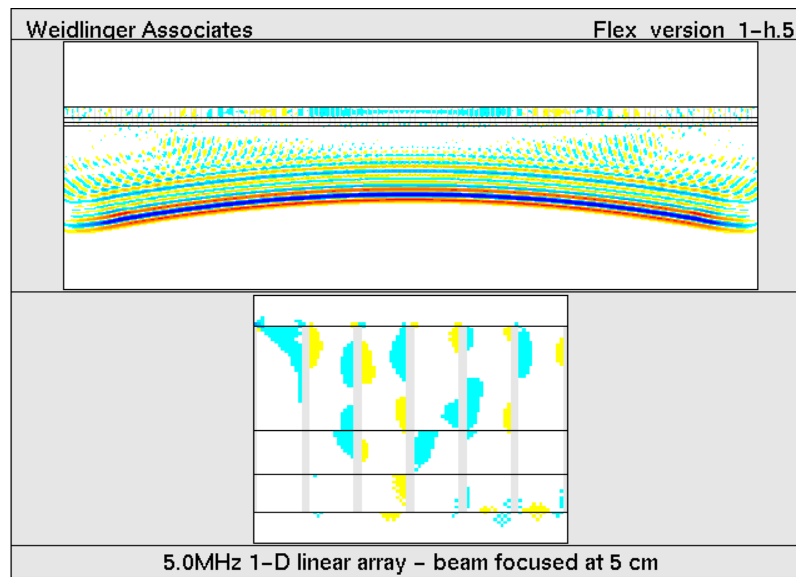


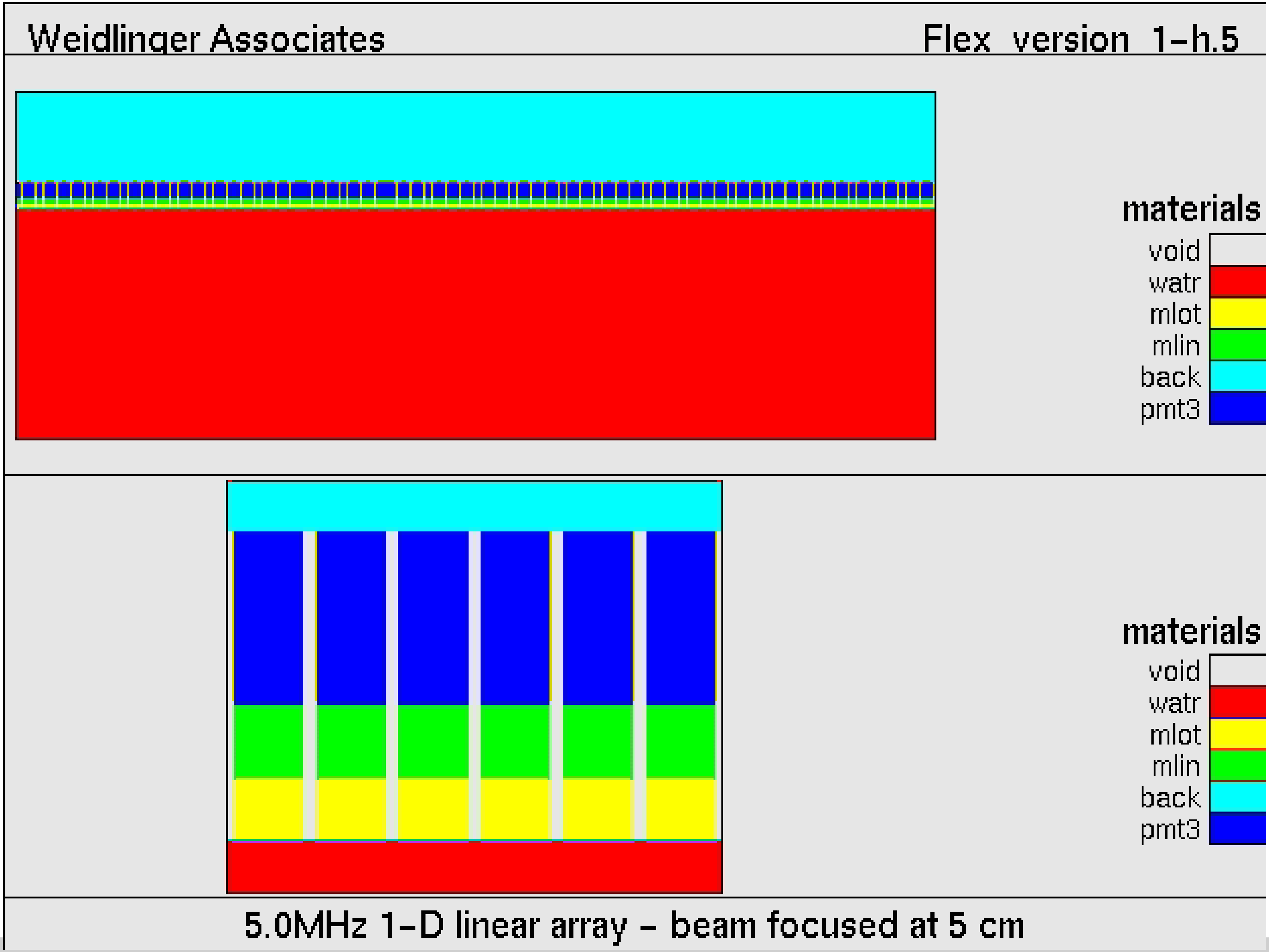
Still images from pulsing sequence







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materials
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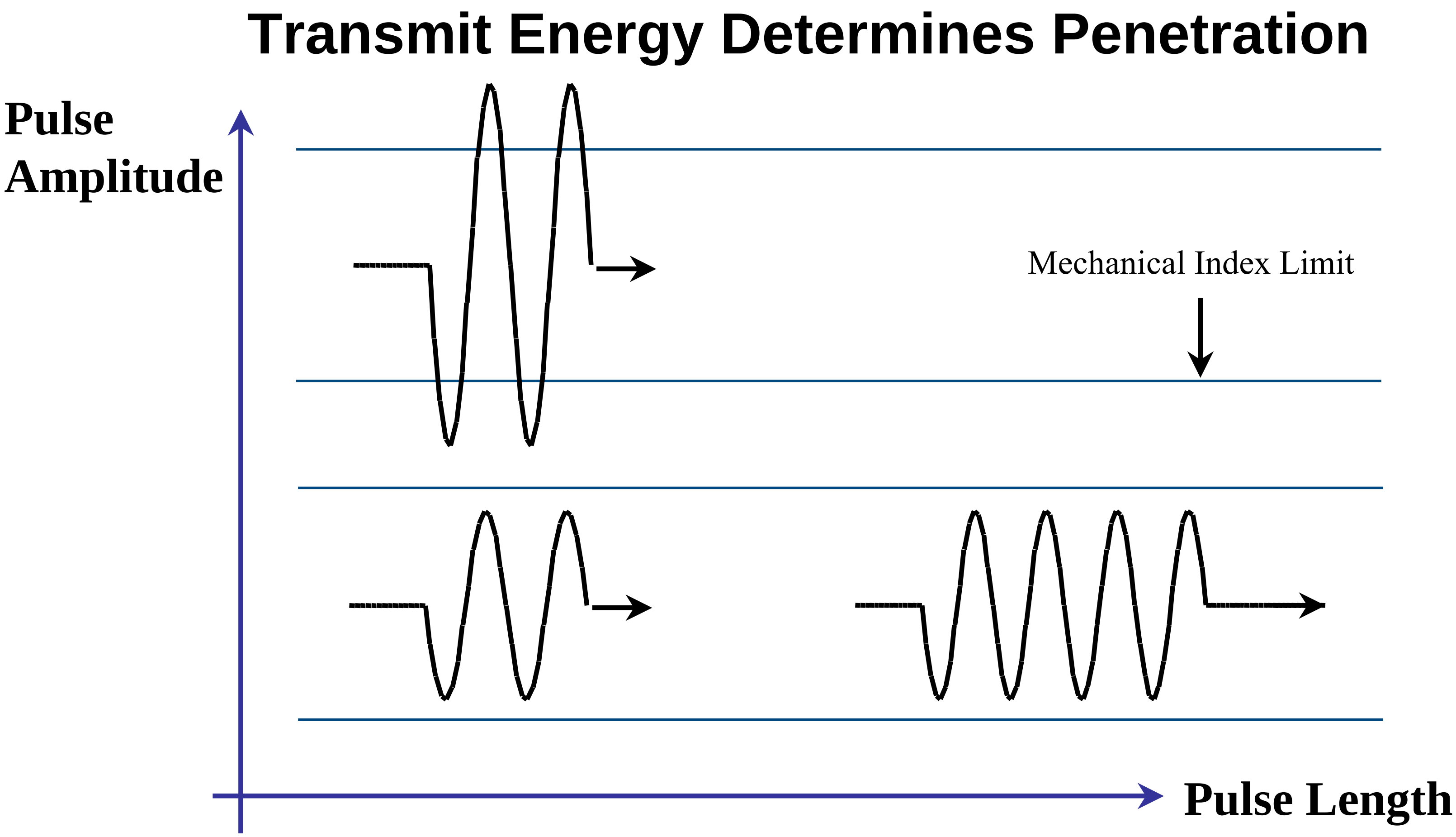
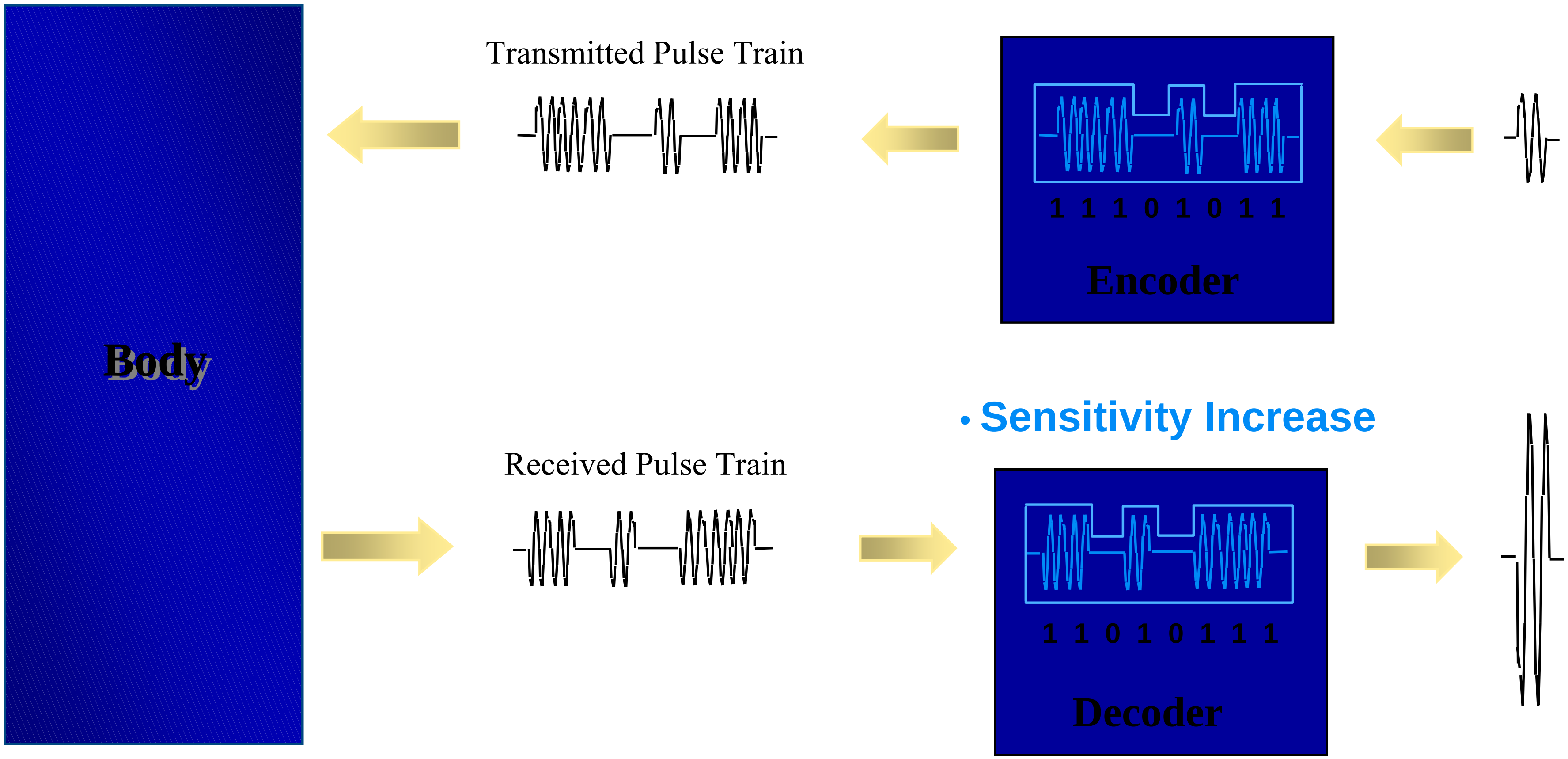
5.0MHz 1-D linear array - beam focused at 5 cm

Resolution / Penetration Dilemma



Longer pulse gains penetration but sacrifices resolution

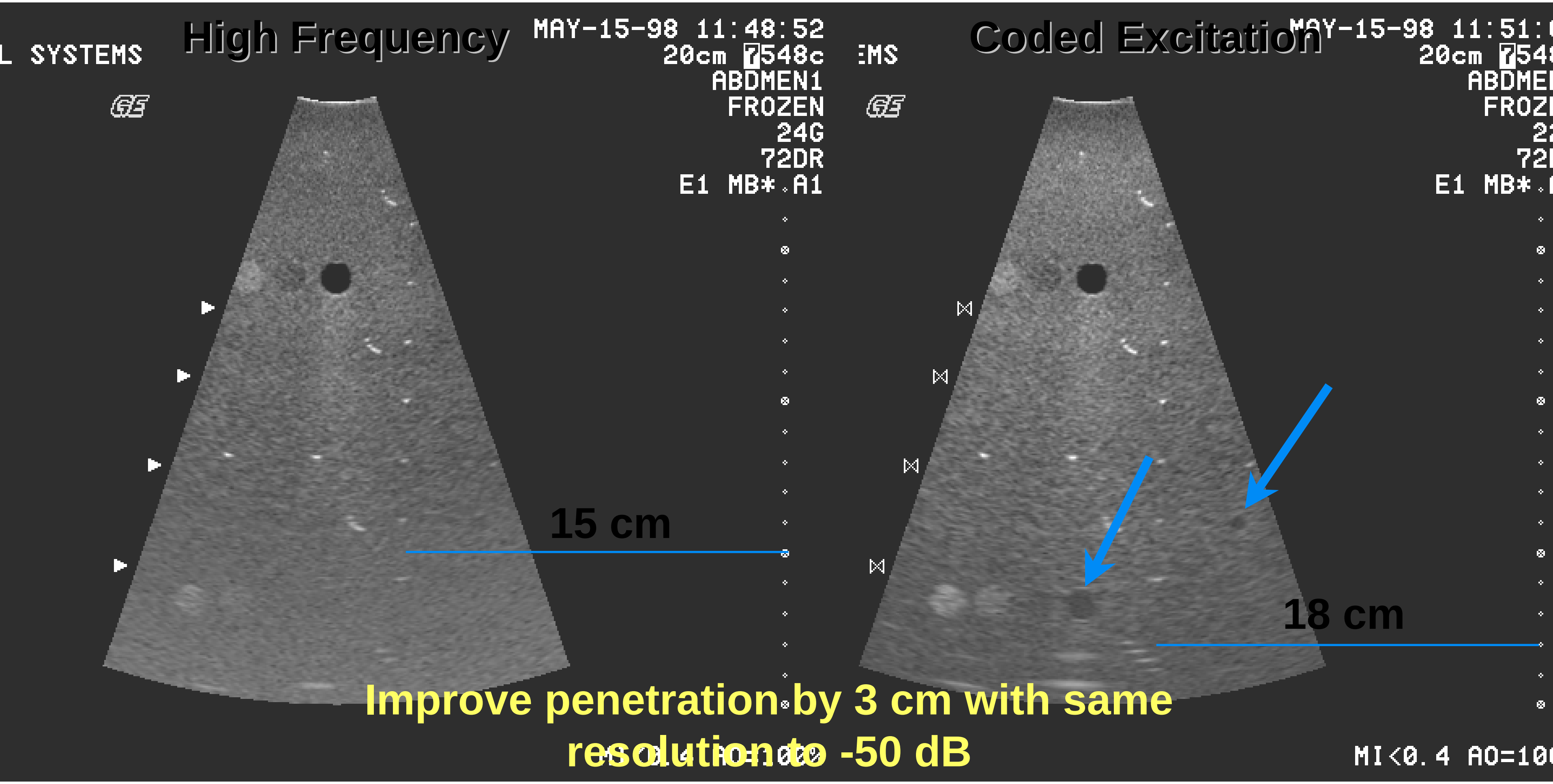
Coded Excitation



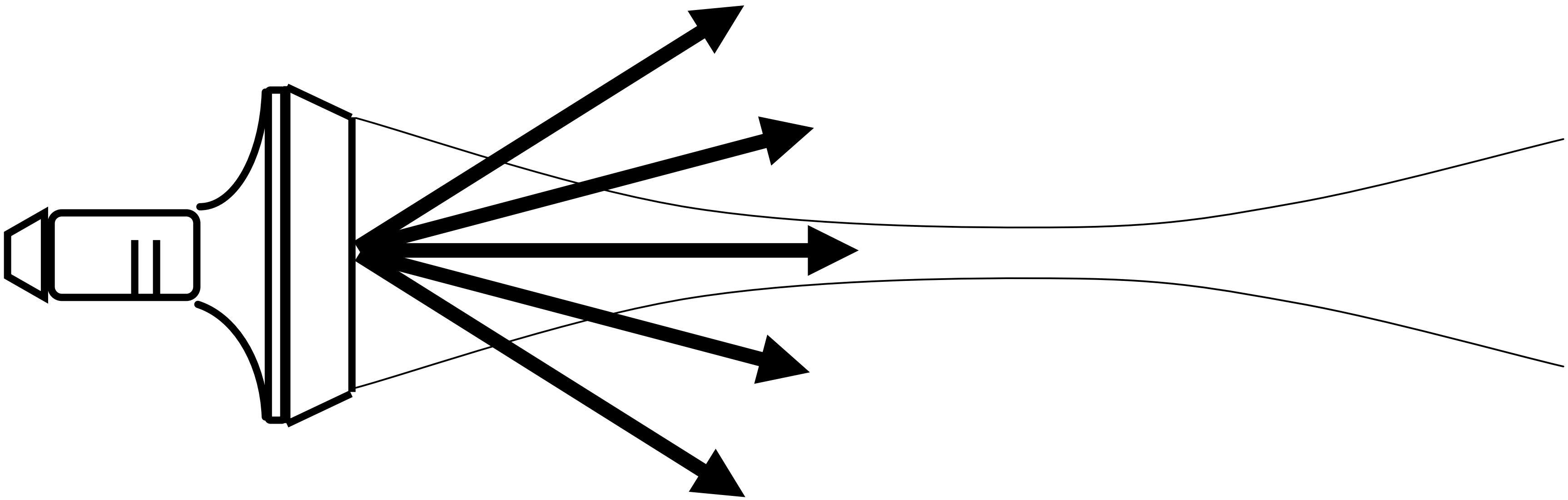
- Sensitivity Increase

Coded Excitation improves sensitivity without resolution tradeoff

Coded Excitation - Experiment



Compounding



- **Compounding:**
  - **suppress speckle to improve contrast resolution**
- **Spatial compounding:**
  - **combine images from multiple angles**
- **Frequency compounding**
  - **combine images from different frequencies**

What are we trying to image?

Medical ultrasound different from radar.

- volume scatterers
- very wide band
- near field

First level

- Gross anatomy
- basic measurements
  - e.g. fetal dimensions
- often tissue/fluid interfaces
- not very challenging

Second level

- soft tissue characteristics
  - attenuation
  - speckle size
- minimum acoustic noise
- beam performance critical

Third level

- 3D/4D volume & surface rendering
- Beam performance critical

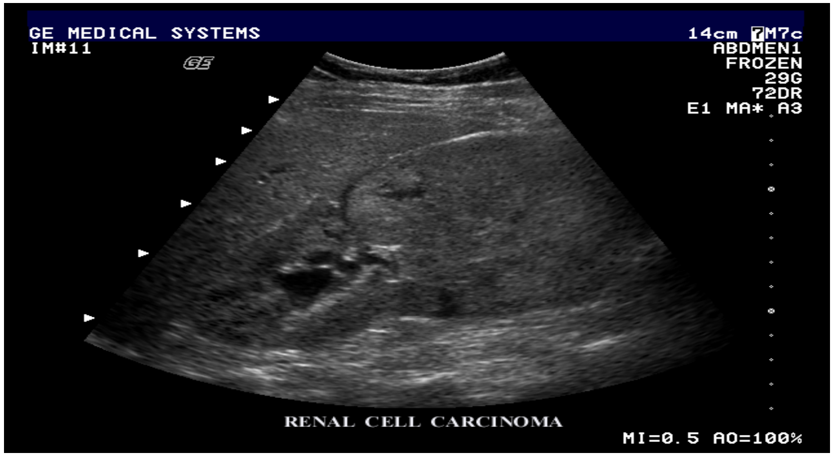
Imaging Examples

Image uniformity

- large depth of penetration
- reasonably uniform tissue texture

Ability to bring out subtle changes.

- minimal beam distortion
- minimal reverberant noise



Beamshapes, Focusing, and all that

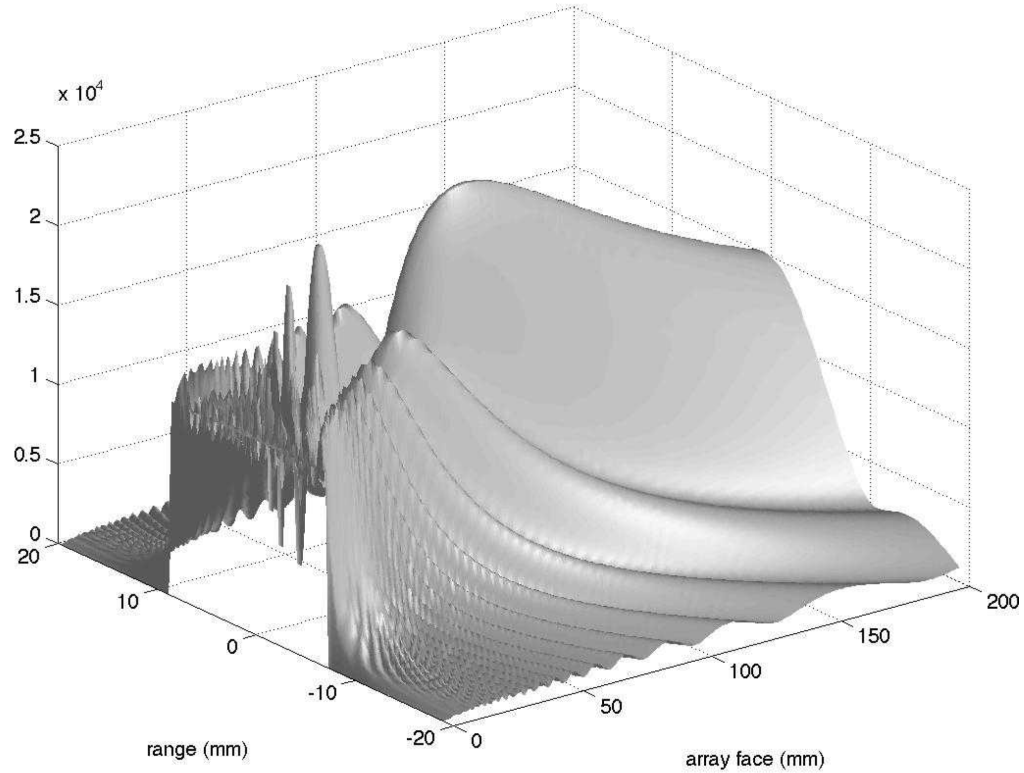
Anatomy of an ultrasound beam

Near field or Fresnel zone

Far field or Fraunhofer zone

Near-to-far field transition, L

$$L = \frac{D^2}{4\lambda}$$



Anatomy of an ultrasound beam

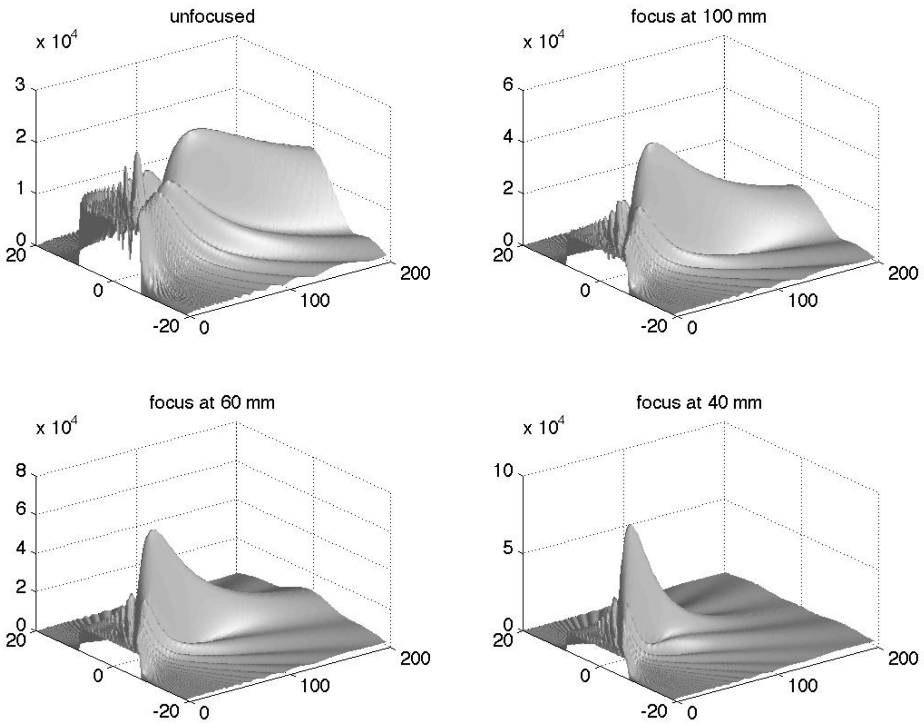
Spatial resolution, beamwidth

Depth of field (DOF)

F-number

$$f\# = \frac{F}{D}$$

$$bw = \frac{\lambda F}{D} = \lambda \left(f\# \right)$$

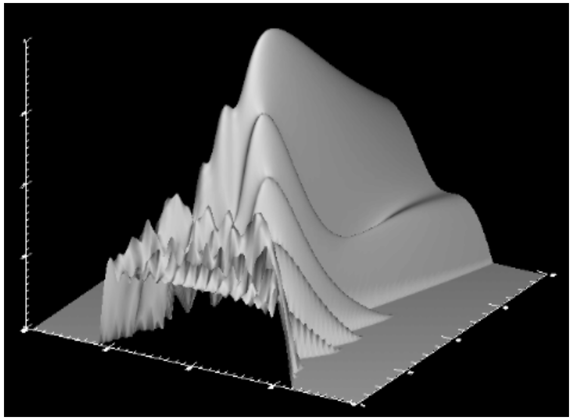


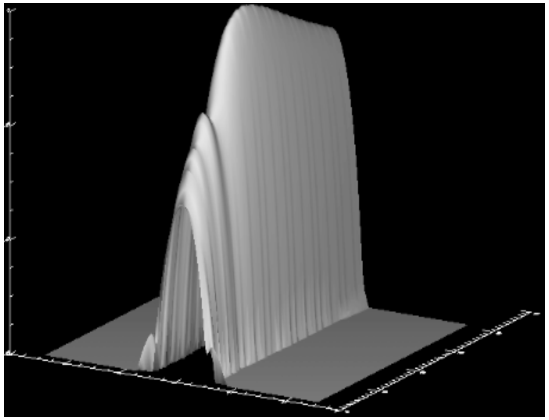
Closer focal locations have narrower beamwidths, shorter depths of field.

Summary of Beam Processing

Beam shape is improved by several processing steps:

- Transmit apodization
- Multiple transmit focal locations
- Dynamic focusing
- Dynamic receive apodization
- Post-beamsum processing





Upper frame: fixed transmit focus

Lower frame: the above steps.

Analysis of beamformation

Basic narrowband far-field analysis

- radar type analysis

Spatial impulse response method

- application to regulatory measurements

Angular spectrum methods

- propagation of beams
- harmonic imaging

Narrow-band Far Field Analysis

Narrowband far-field analysis

Totally unrealistic model

Amazingly useful results

will be used to introduce key points

Narrowband far-field analysis

Rayleigh Integral:

- relates:
  - velocity at array face
  - pressure at a point

Simplifications:

- far field: R will not vary by much as %
- $u = sin\theta = y / R_o$

The Upshot:

- field in Fraunhofer zone is the Fourier transform of *V(x)*

$$P(x,\omega) = \frac{jk\rho c}{2\pi} \int \frac{e^{-jkR}}{R} V(x,w) dS$$

$$P(x,\omega) = \frac{jk\rho c}{2\pi R} \int e^{-jkR} V(x,\omega) dS$$

$$R \approx R_o \left(1 - \frac{yx}{R_o^2} + \frac{x^2}{2R_o^2} \right) = R_o - \frac{yx}{R_o} + \frac{x^2}{2R_o}$$

$$f(x,u,\omega) = \int V(\mathbf{x},\omega) \exp\left[jk \left(xu - \frac{x^2}{2R_o} \right) \right] dS$$

$$f(x,u,\omega) = \int V(\mathbf{x},\omega) \exp[jkxu] dS$$

$$= \boldsymbol{F}\{\mathbf{V}(\mathbf{x},\omega)\}$$

Narrowband far-field analysis

Think of an array as:

- infinite array of point sources
- confined by a *rect*-function

Apply spatial Fourier relation

Beam pattern is an infinite train of sinc-functions

$$v(x) = rect\{L\} \cdot \sum_{n=-\infty}^{n=\infty} \delta(x - nd)$$

$$f(u) = F\{p(x)\}$$

$$= F\{rect[L]\} * F\left\{\sum_{n=-\infty}^{n=\infty} \delta(x - nd)\right\}$$

$$f(u) = \sum_{m=-\infty}^{m=\infty} \mathrm{sinc}\left[\left(\pi L / \lambda\right)\left(u - m\lambda / d\right)\right]$$

Narrowband far-field analysis

Illustration:

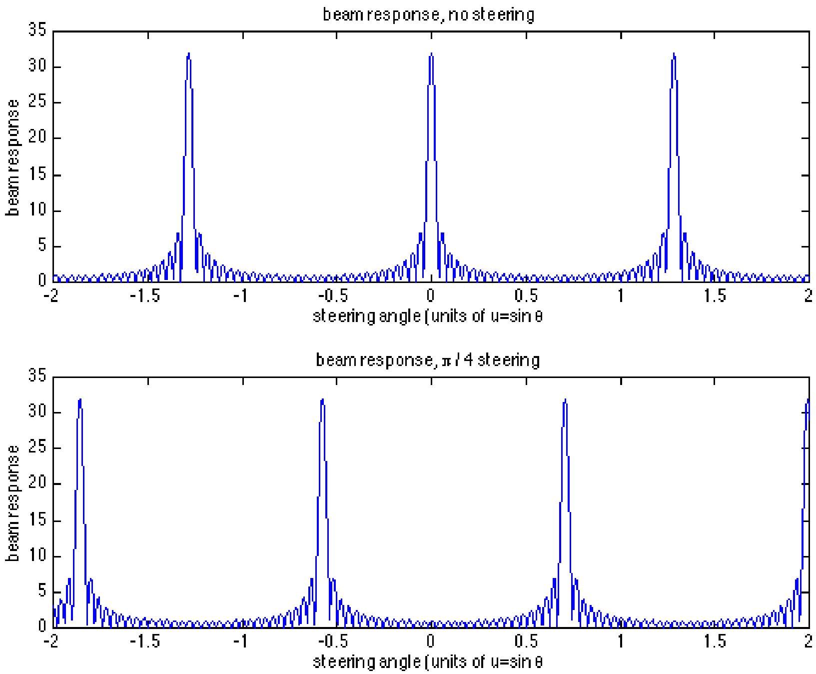
- 32 element array
- 3 MHz
- pitch *d* = 0.4 mm
- $\lambda = 0.51$ mm
- $L = N\,d = 13$ mm

NOTE: plot wrt to *u*!

Center beam is our main lobe.

Beamwidth:

- λ / L u-units



Narrowband far-field analysis

Adjacent beams:

- grating lobes

Separation:

- λ / d u-units

Beam steering:

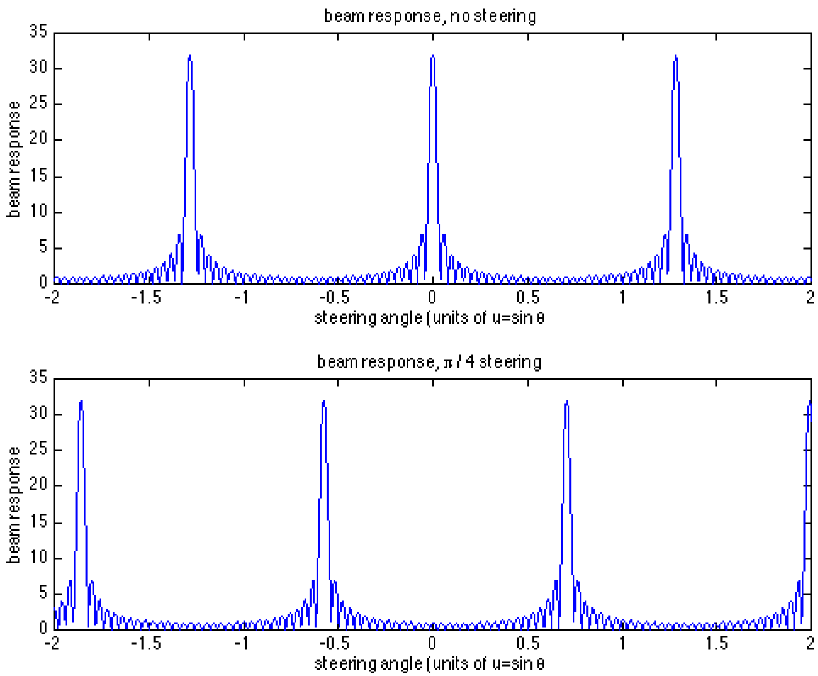
- apply τ_s phase tilt

Danger!

- Grating lobes move w. main

Visible region:

- ±0.707 u-units or ±45 degrees



$$\tau_s = \frac{x \sin(\theta)}{c}$$

Grating Lobes

Main concern w. phased arrays

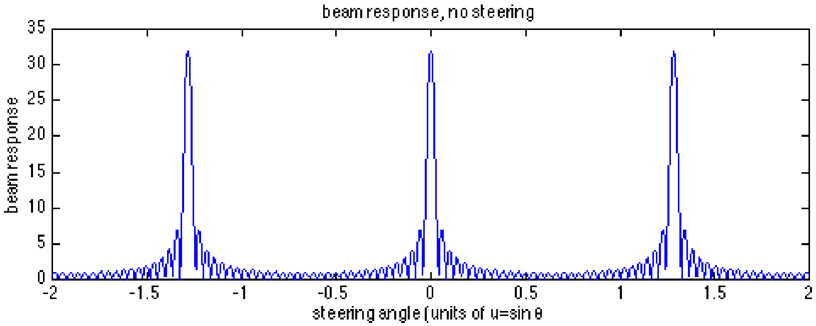
- **But** can show up in low f-# designs!

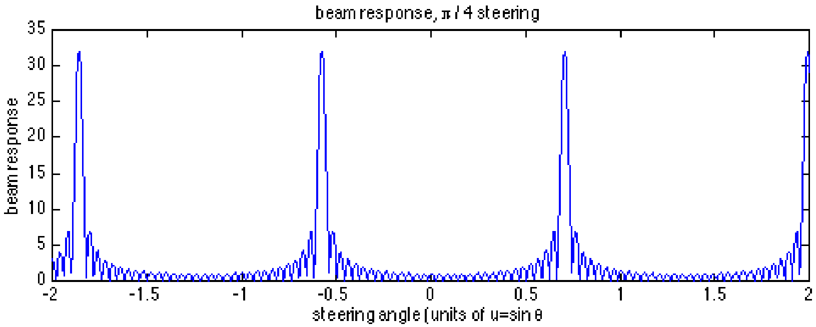
How to avoid:

- design for horizon-to-horizon safety
- safe pitch:
  - $d \le \lambda$ / 2

Other points:

- wideband case
- sparse arrays





$$d \le \frac{\lambda}{2}$$

Apodization

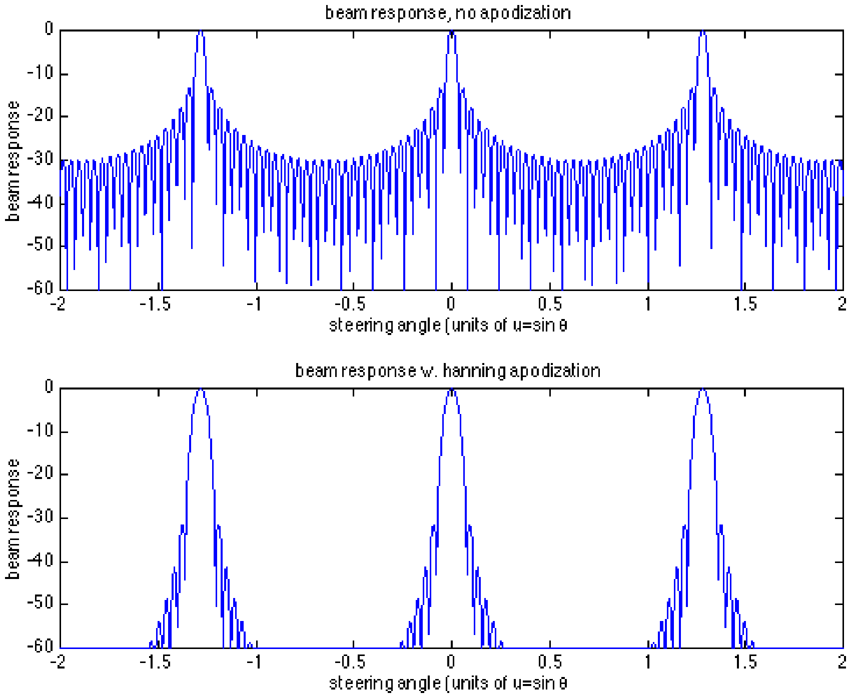
Same array:

- 32 element array
- 3 MHz
- pitch *d* = 0.4 mm
- λ = 0.51 mm
- $L = N\, d$ = 13 mm

With & w/o Hanning wting.

Sidelobes way down.

No effect on grating lobes.



A/D Converters & Dynamic Range

Major concern:

- how much SNR will we lose going digital?

Quantization error

$$\hat{x}(n) = Q[x(n)] = x(n) + e(n)$$

Under reasonable assumptions:

- SNR = 6*b* - 1.24 dB <u>at the 4 σ level</u>
- The 4σ rule is probably violated.
- Hence greater SNR's

$$\sigma_e^2 = \frac{\Delta^2}{12} = \frac{2^{-2b}}{12}$$

More Realistic Simulations

More Realistic Models

Far field, narrow band models are useful, though not very realistic.

We will discuss two types of models which come closer to reality:

- Spatial Impulse Response
  - Approach used in Field II code
- Angular Spectrum

And some examples of each.

Spatial Impulse Response

Velocity Potential

- particle velocity as gradient of a scalar
- *u(x,y,z) = grad*$(\phi(x,y,z))$

Such functions readily available.

$\phi(x,y,z,t)$ written as a convolution.

This has led to the concept of spatial impulse response.

$$\phi(\vec{\mathbf{r}},t) = \int_S \frac{v_n\left(r_2, t - \frac{|\vec{r}_1 - \vec{r}_2|}{c}\right)}{2\pi|\vec{r}_1 - \vec{r}_2|} dS$$

$$\phi(\vec{\mathbf{r}},t) = v_n(t) * \int_S \frac{\delta\left(t - t_2 - \frac{|\vec{r}_1 - \vec{r}_2|}{c}\right)}{2\pi|\vec{r}_1 - \vec{r}_2|} dS$$

$$h(\vec{r}_1,t) = \int_S \frac{\delta\left(t - \frac{|\vec{r}_1 - \vec{r}_2|}{c}\right)}{2\pi|\vec{r}_1 - \vec{r}_2|} dS$$

Spatial Impulse Response

Closed form expressions exist.

Think of field response to δ-function stimulus.

Pressure at any field point directly related.

Particle velocity at any field point related.

Differentiable transducer velocities can be use.

Field II is an excellent tool for analyzing ultrasound beams.

$$h(\vec{r}_1, t) = \int_S \frac{\delta\left(t - \frac{|\vec{r}_1 - \vec{r}_2|}{c}\right)}{2\pi|\vec{r}_1 - \vec{r}_2|} dS$$

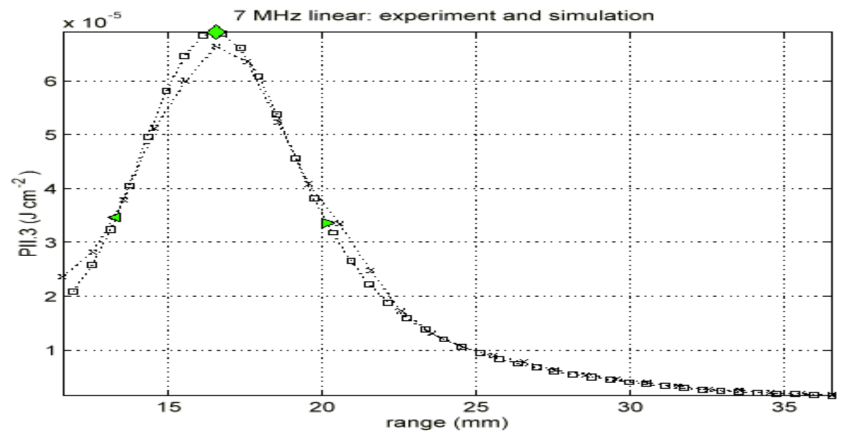
$$p(\vec{r}, t) = -\rho_o \frac{\partial \phi(\vec{r}, t)}{\partial t}$$
$$= -\rho_0 \frac{\partial v_n(t)}{\partial t} * h(\vec{r}_1, t)$$

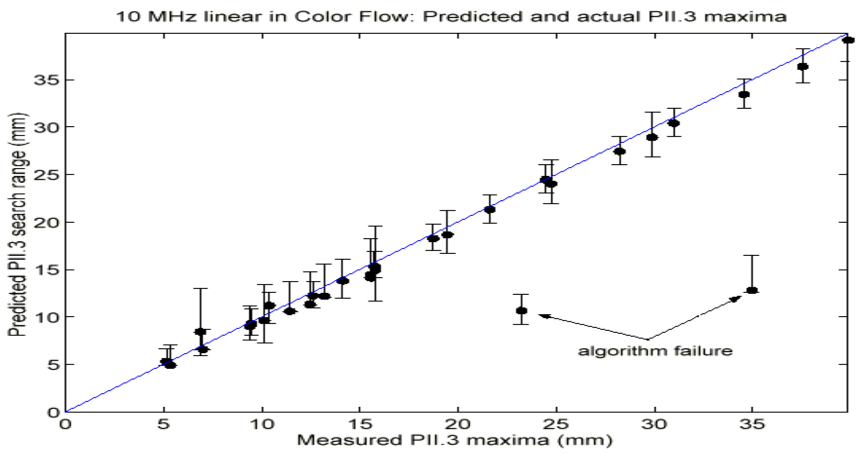
Spatial Impulse Response: Testing

Acoustic power testing.

For cases w. linear propagation, results are excellent.

All types of beamformation have been evaluated.





Angular Spectrum Method

We start w. velocity distribution at array.

We take the 2D FFT of it.

This amounts to splitting the source to plane waves.

$$A_o\left(f_x, f_y\right) = \iint\limits_{-\infty \to \infty} U(x, y, 0)\exp\left[-j2\pi\left(f_x x + f_y y\right)\right] df_x df_y$$

$$B(x, y, z) = \exp\left[j\frac{2\pi}{\lambda}(\alpha x + \beta y + \gamma z)\right]$$

$$A_o\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}\right) = \iint\limits_{-\infty \to \infty} U(x, y, 0)\exp\left[-j2\pi\left(\frac{\alpha}{\lambda}x + \frac{\beta}{\lambda}y\right)\right] df_x df_y$$

Angular Spectrum Method

The plan is to figure out how to propagate this spectrum to a new plane.

This can be done with the help of the Helmholtz Equation.

$$U(x,y,z) = \iint_{-\infty\to\infty} A_o\left(\frac{\alpha}{\lambda},\frac{\beta}{\lambda};z\right)\exp\left[j2\pi\left(f_x x + f_y y\right)\right] d\frac{\alpha}{\lambda}\, d\frac{\beta}{\lambda}$$

$$\nabla^2 U + k^2 U = 0$$

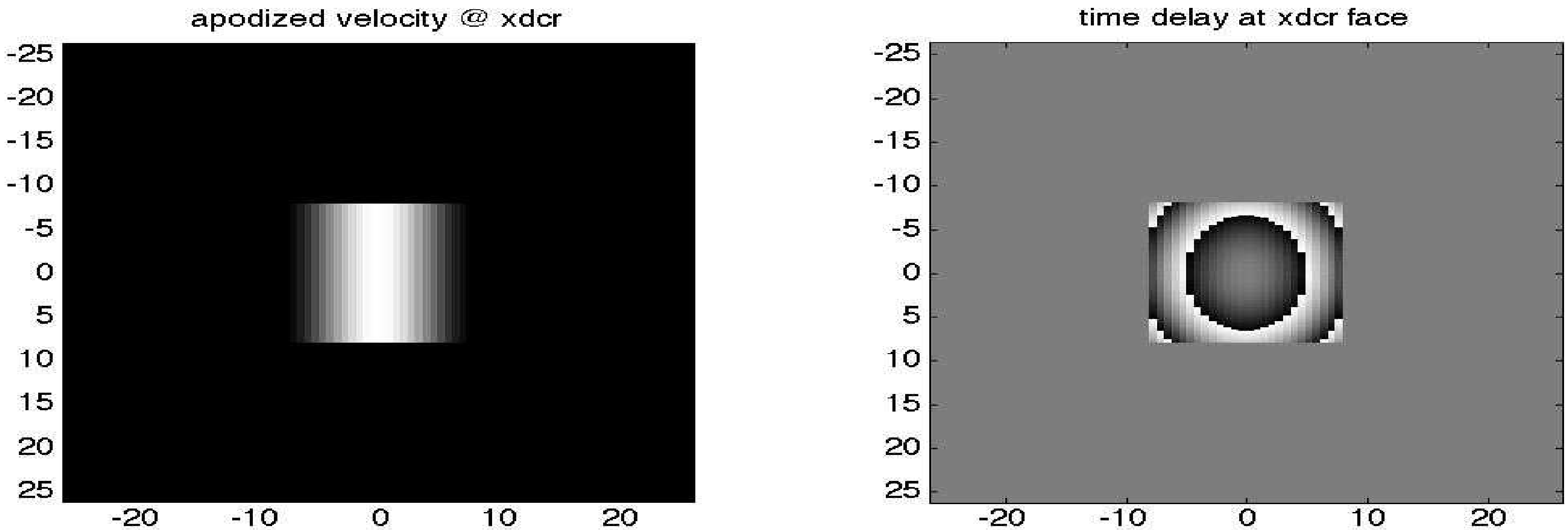
$$A\left(\frac{\alpha}{\lambda},\frac{\beta}{\lambda};z\right) = A_o\left(\frac{\alpha}{\lambda},\frac{\beta}{\lambda}\right)\exp\left(j\frac{2\pi}{\lambda}\sqrt{1-\alpha^2-\beta^2}\,z\right)$$

Computer Experiments

Consider a linear array, apodized and unapodized cases.

Roughly 16 by 16 mm aperture

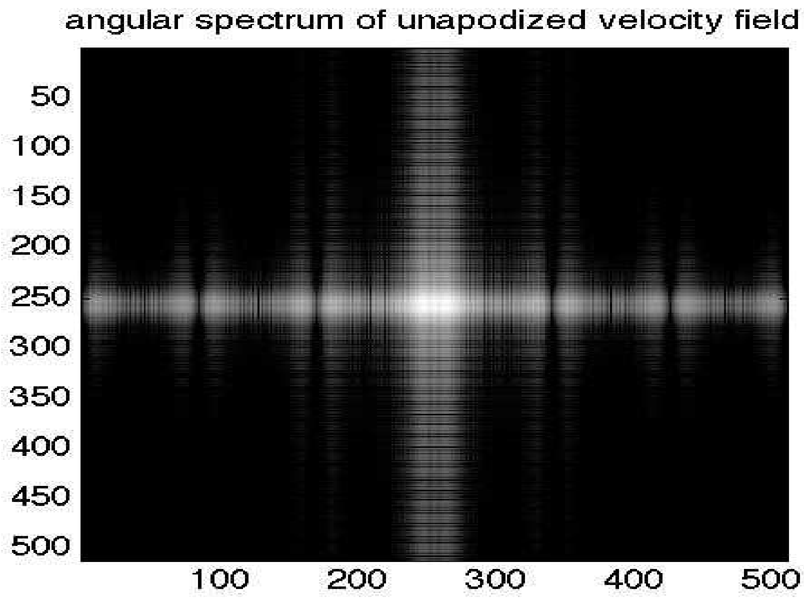
Azimuthal focus at 40, elevation at 60 mm

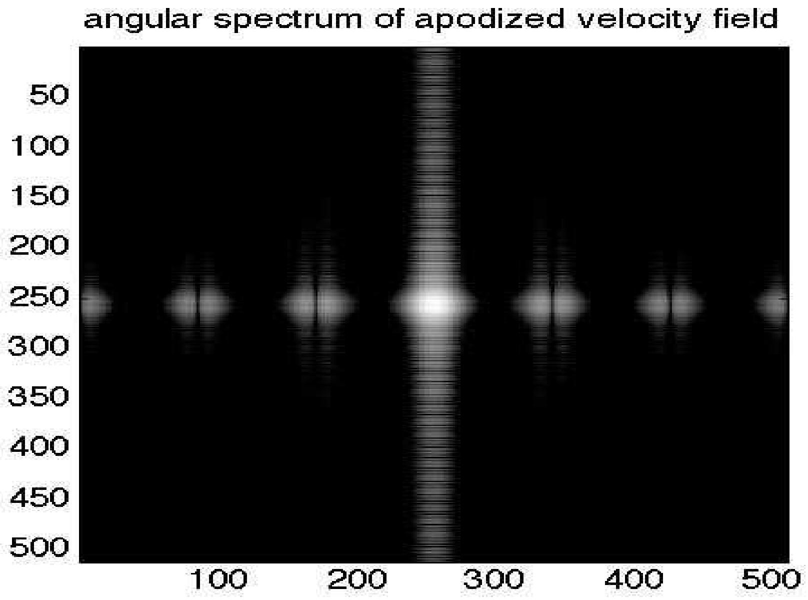


Angular spectra due to apertures

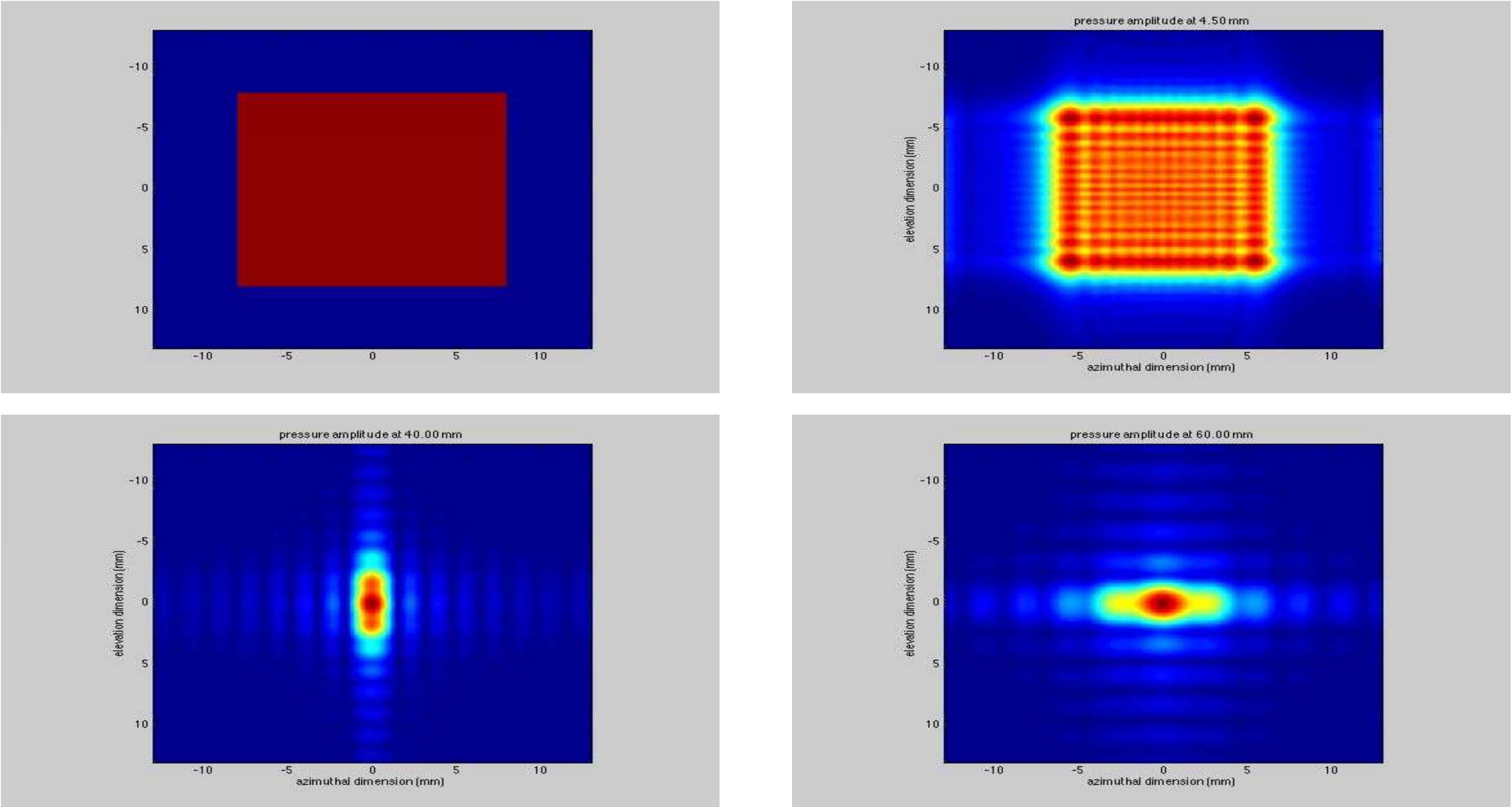
Think of the resulting spectra as pin cushions.

Wherever there is energy, there is a plane wave moving in that direction.

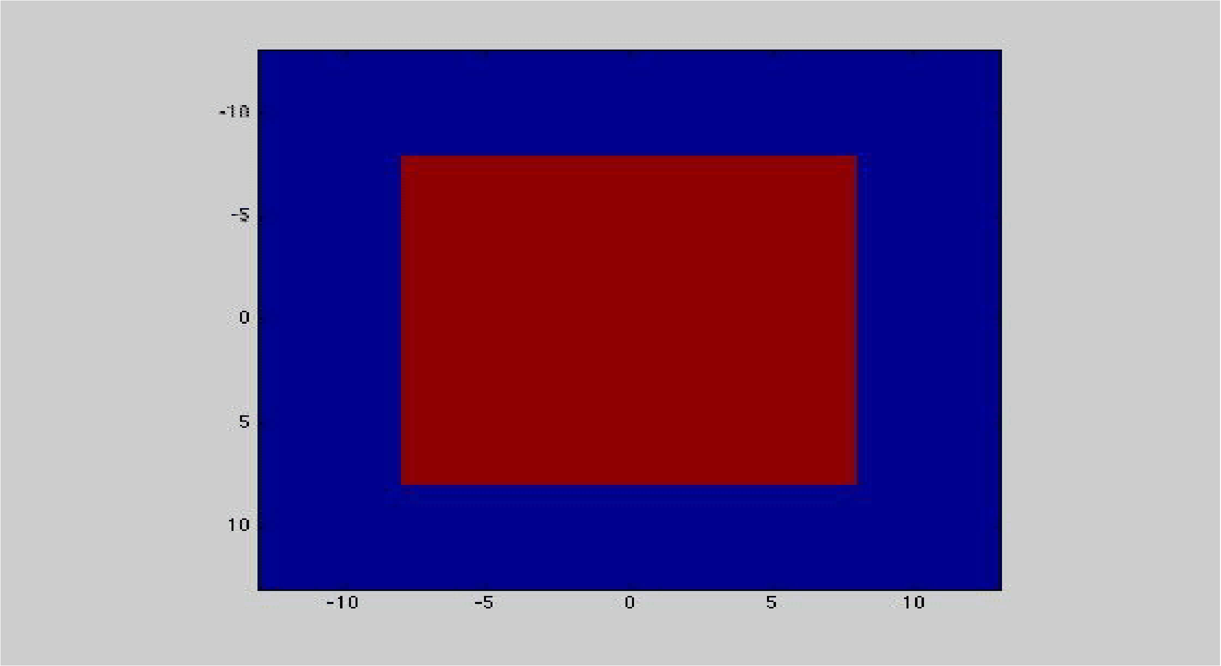




Propagation of Beam from Array



Movie of Propagating Beam



Utility of Models

Why bother?

- Beamformer design validation before going to hardware.
  - How good a beam results from the design choices made?
  - New modes (RT3D) and new instruments (laptop ultrasound)
- Reduction of regulatory measurement work load.
- Analysis of new topics such as:
  - contrast agent performance
  - harmonic imaging.
  - aberration correction

Recent Advances in Simulation

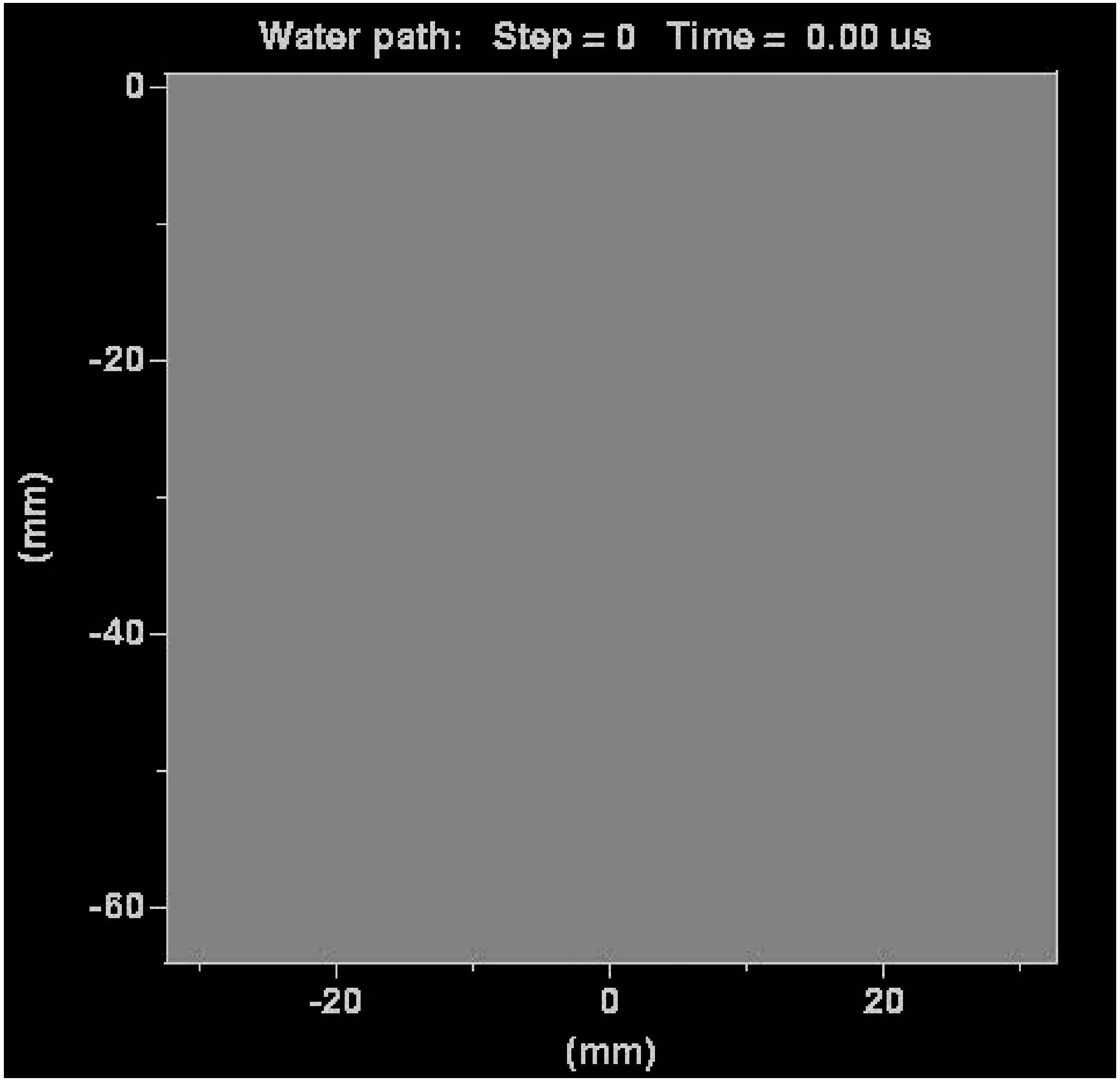
Much of the work reported has been done with finite difference methods.

These are limited in their ability to estimate the derivatives.

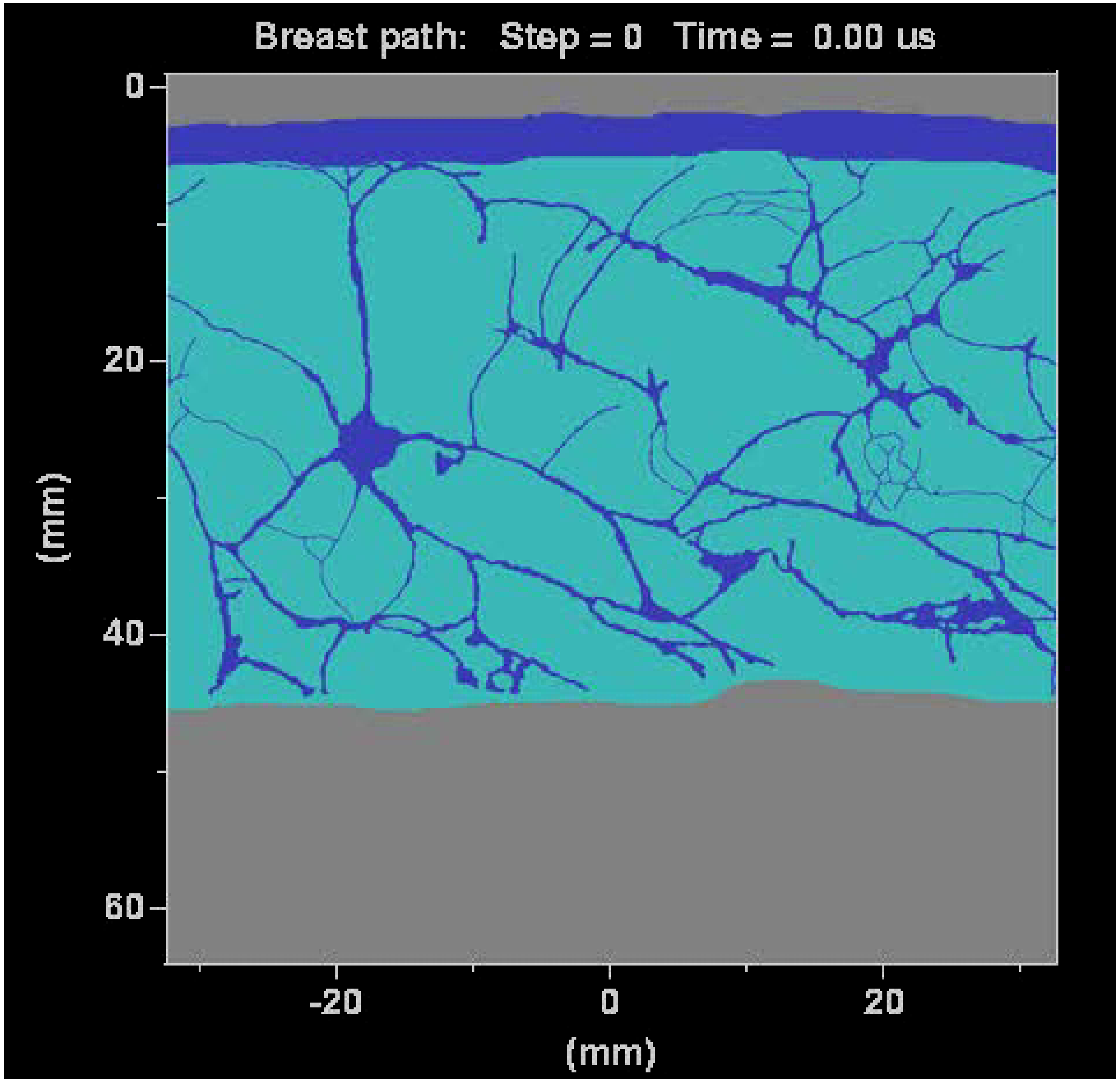
Improvements exist mainly with FFT estimation of derivatives:

- pseudospectral methods (Weidlinger)
  - example: previous transducer/beam movie
- k-space methods (U. of Rochester)
  - examples to be shown.

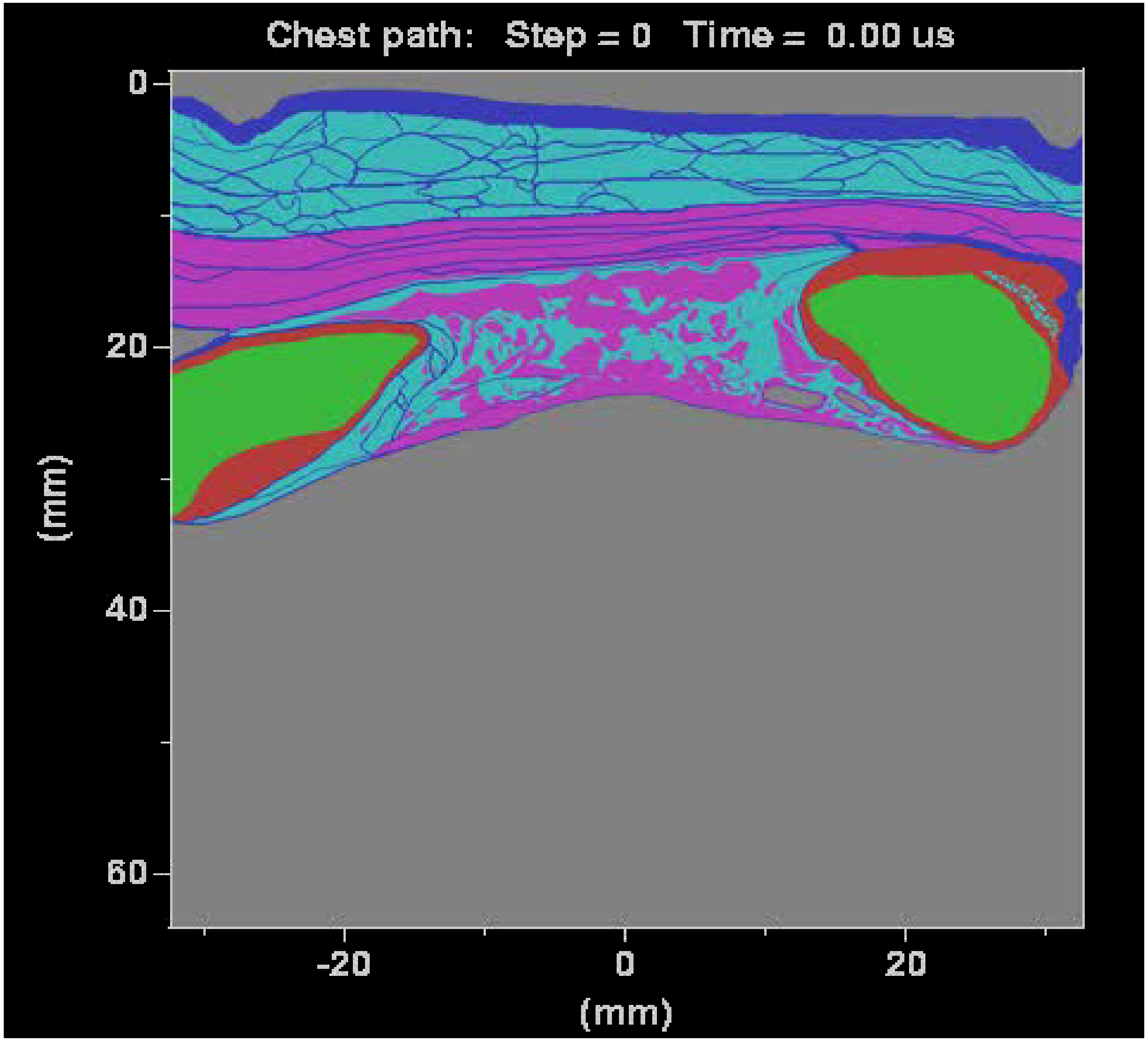
Sound propagation in water



Sound propagation in breast tissue



Propagation through chest wall



Harmonic Imaging

Harmonic Imaging

Perhaps the most important innovation of the last five years.

- Now default mode in most cardiac scanners

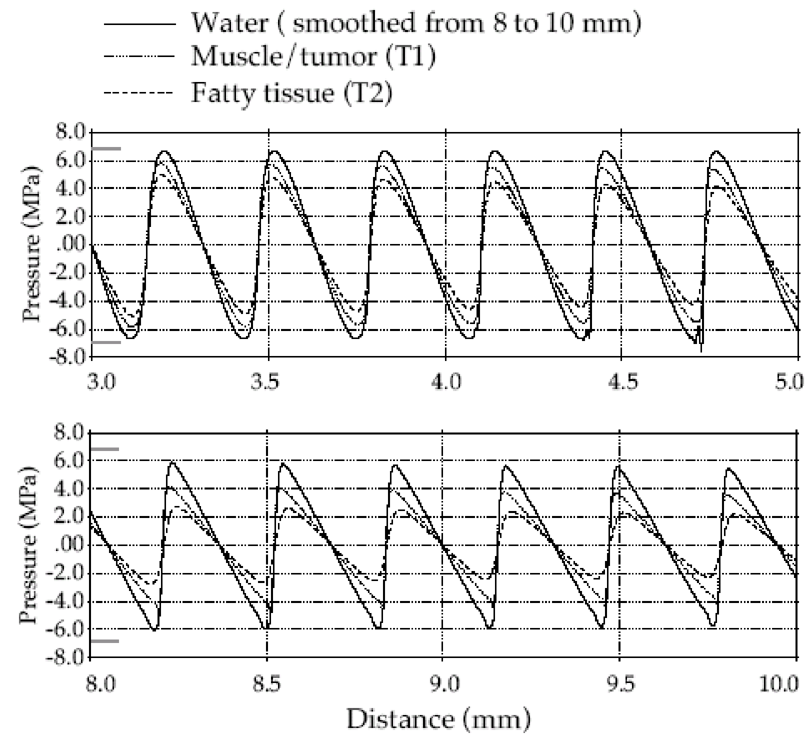
Discovery due to two major sources:

- harmonic imaging for contrast agents
- transducer bandwidth increases

Arises from pressure dependence of sound speed

- compressional wave is faster than rarefactional

Need to understand via simulations.



Wojcik et al., IEEE95

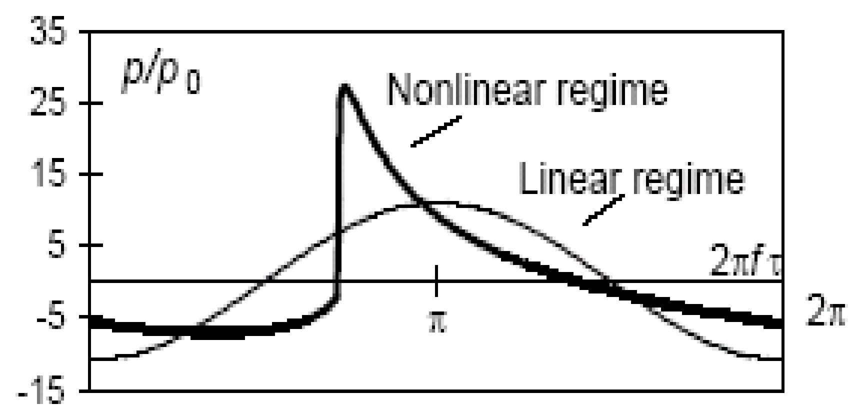


Fig. 1. Acoustic waveform in the geometrical focus.

http://www.akin.ru/Docs/Rao/Ses10/Me4.pdf

Angular Spectrum, Operator splitting

Evolution type partial differential equation

L_{total} accounts for the effect of various factors on propagation.

$L_{total} = 0$ is the case of a plane wave in an ideal medium.

In the linear case, we have diffraction and attenuation.

L_{diff} and L_{attn} are embedded in angular spectrum simulation.

Burgers' Equation can be used to give the expression for L_{nonl}.

$$\frac{\partial u}{\partial z} = L_{total}[u]$$
$$= \mathbf{L_{diff}[u] + L_{attn}[u] + L_{nonl}[u]}$$

$$\frac{\partial u}{\partial z} = L_{diff}[u] + L_{attn}[u]$$

$$L_{nonl}[u] = \frac{\beta \omega_o}{c_o^2} u \frac{\partial u}{\partial \tau}$$

Christopher's Approach

In effect an operator splitting approach, but:

- use angular spectrum to determine role of diffraction.
  - take 2D FFT of velocity field at $z = z_1$
  - multiply by propagation filter to get to $z_1 + \Delta z$
  - take inverse 2D FFT to get back to velocity
- apply the attenuation operator as part of the linear diffraction step (multiplication by propagation filter)
- express u-field at each point as a Fourier series, plug into Burgers' Equation, which gives:

$$U_n(z+\Delta z) = U_n(z) + \left[i \frac{\beta \omega_o}{c_o^2} \left(\sum_{j=1}^{n-1} j U_j U_{n-j} - \sum_{j=n}^{\infty} n U_j U_{j-n}^* \right) \right] \Delta z$$

Nonlinear Propagation

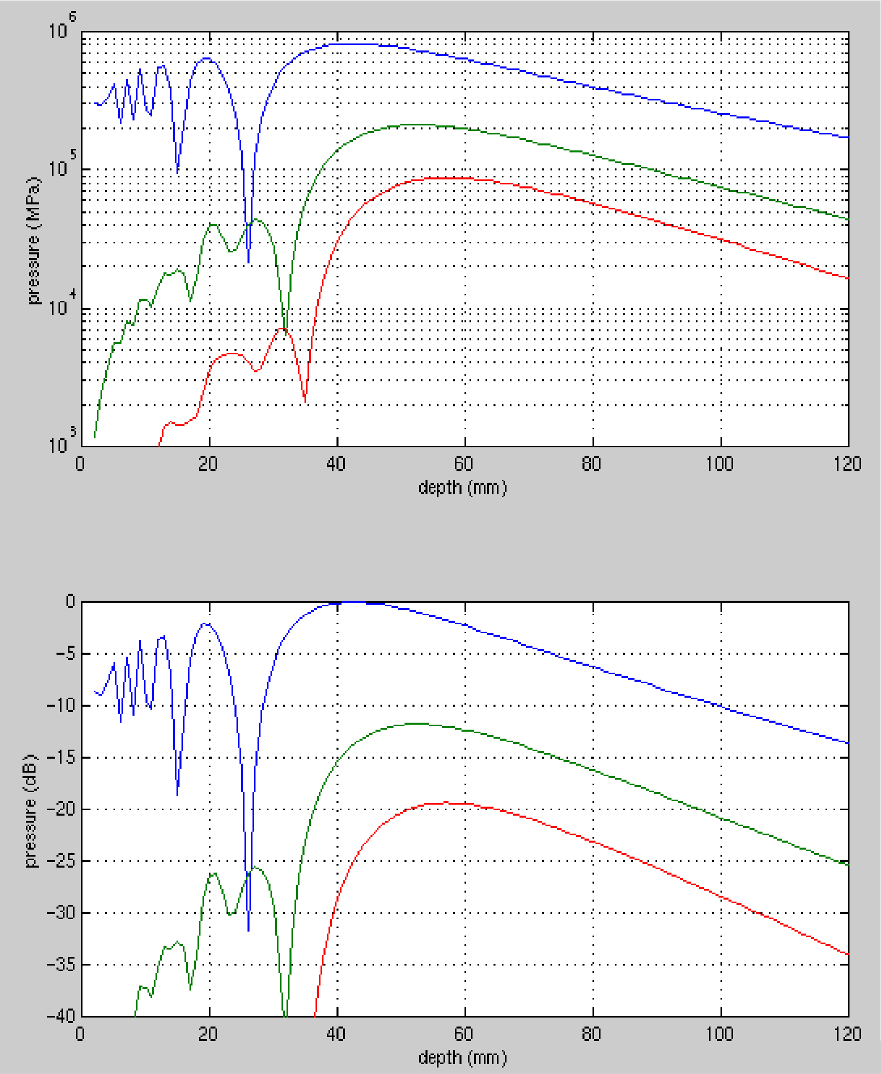
During propagation, harmonics are formed.

Rate of generation of 2nd harmonic proportional to p^2.

This is equivalent to having an extra beamformer to narrow the beam shape.

Beamformer requirements:

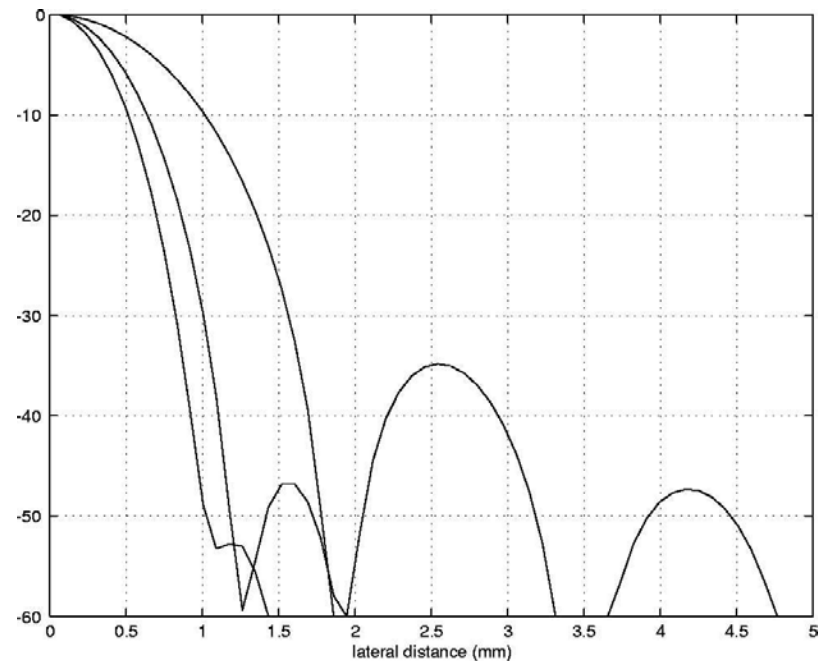
- added transmit flexibility
- increased filtering capacity



Why are harmonic images so good?

Several reasons:

- harmonics formed at main lobe
  - narrower beams
  - lower sidelobes
- much acoustic noise generation at fundamental
  - refraction from fat layers
  - reverberations near fat/muscle layers

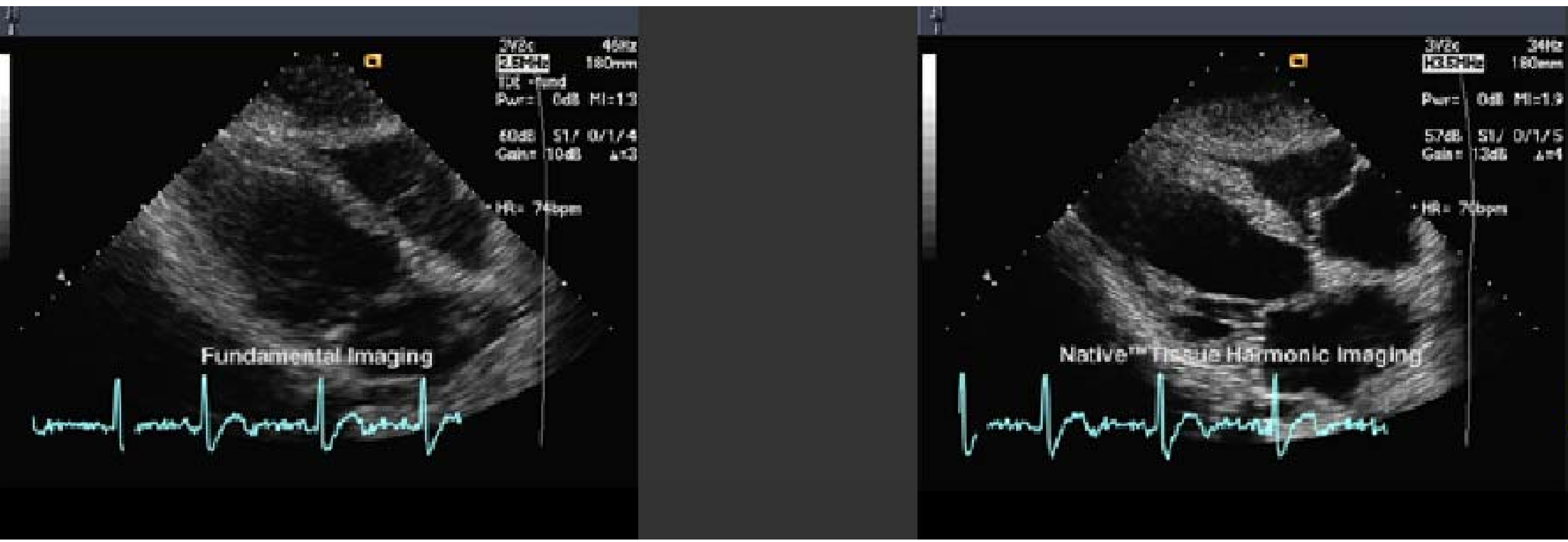


Optimization of beamformers may be necessary.

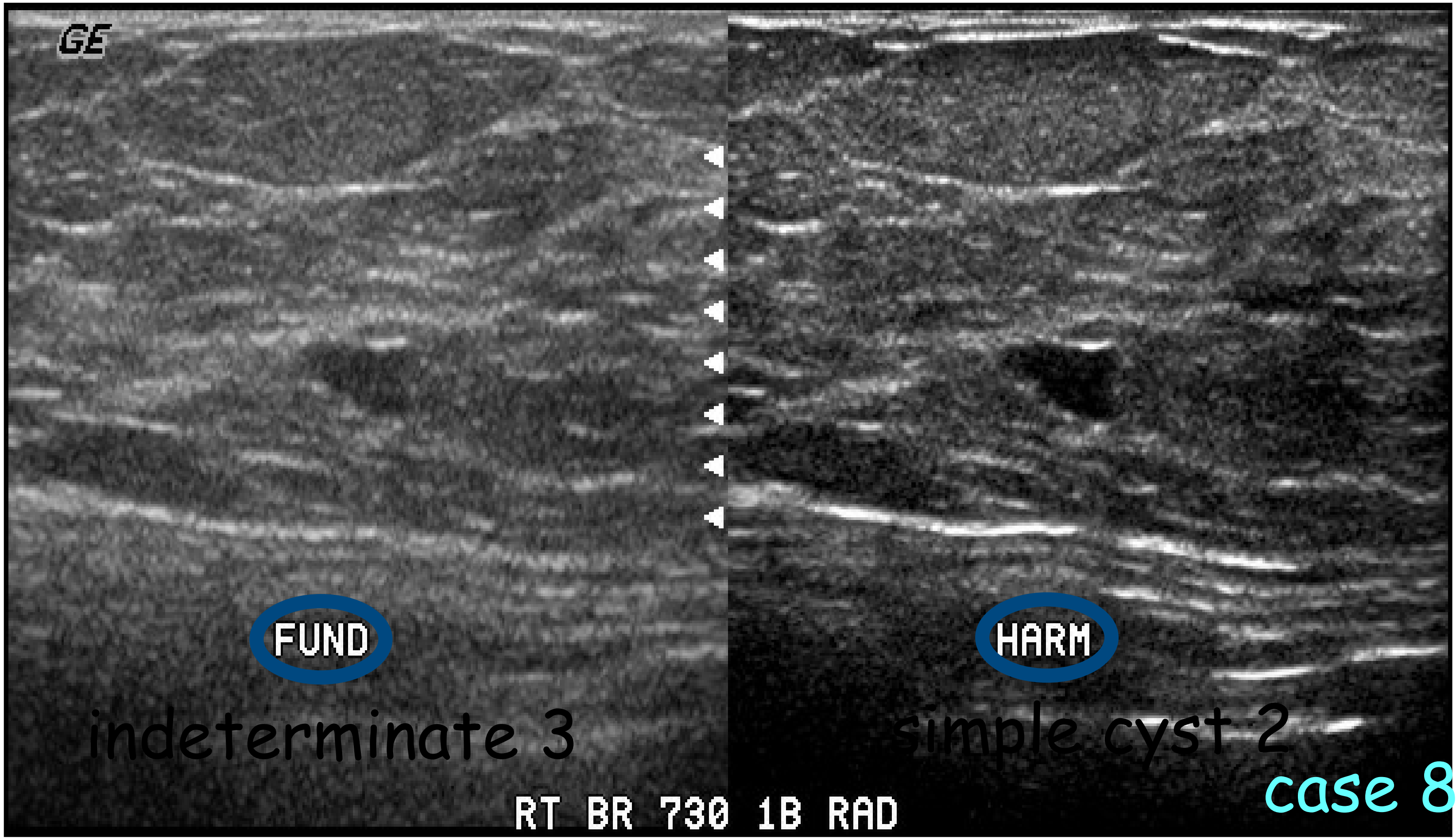
Harmonic Imaging

Below are two images from Acuson’s web site

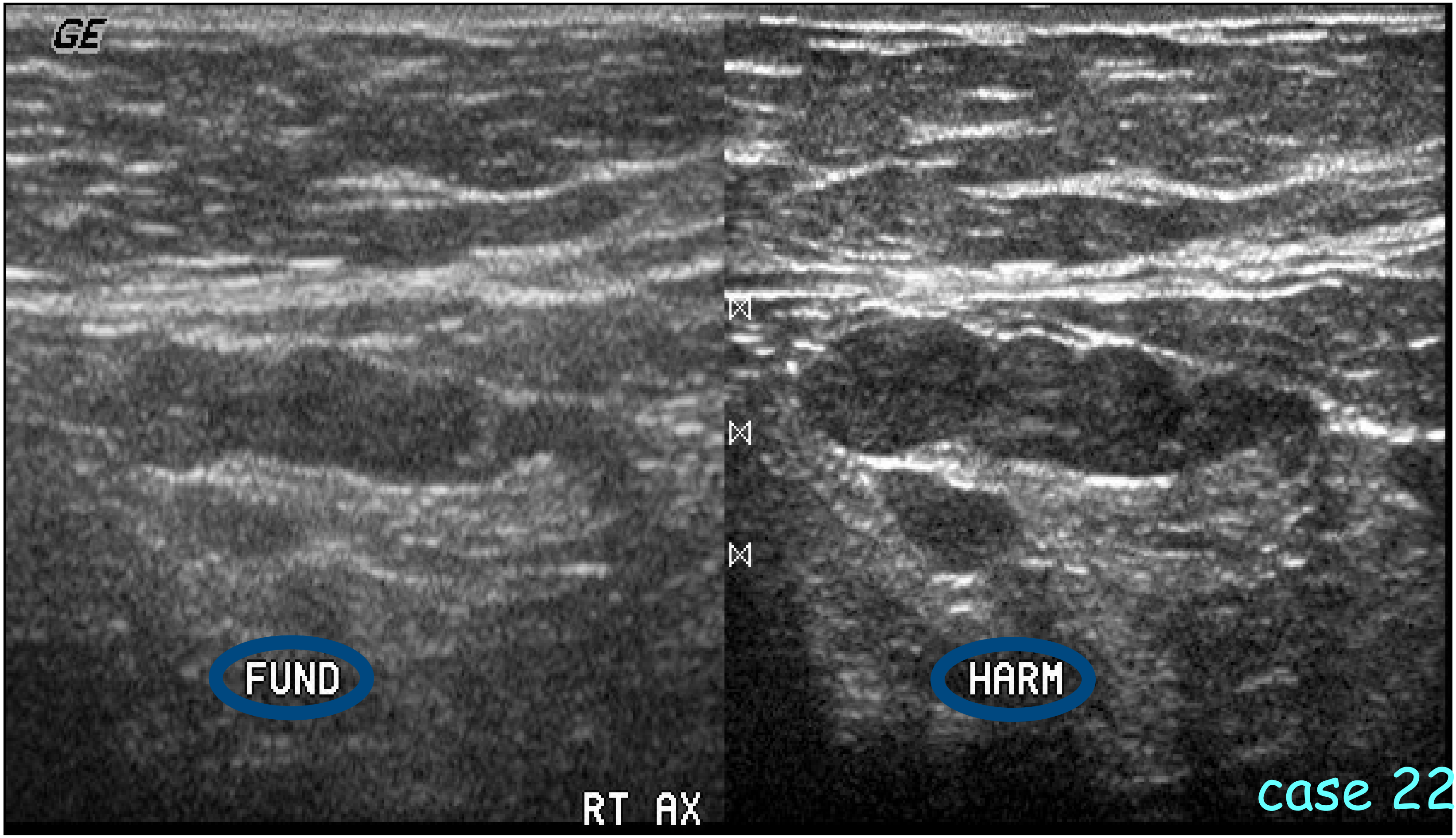
Clearly the cardiac structures are far clearer and blood pool areas have reduced noise.



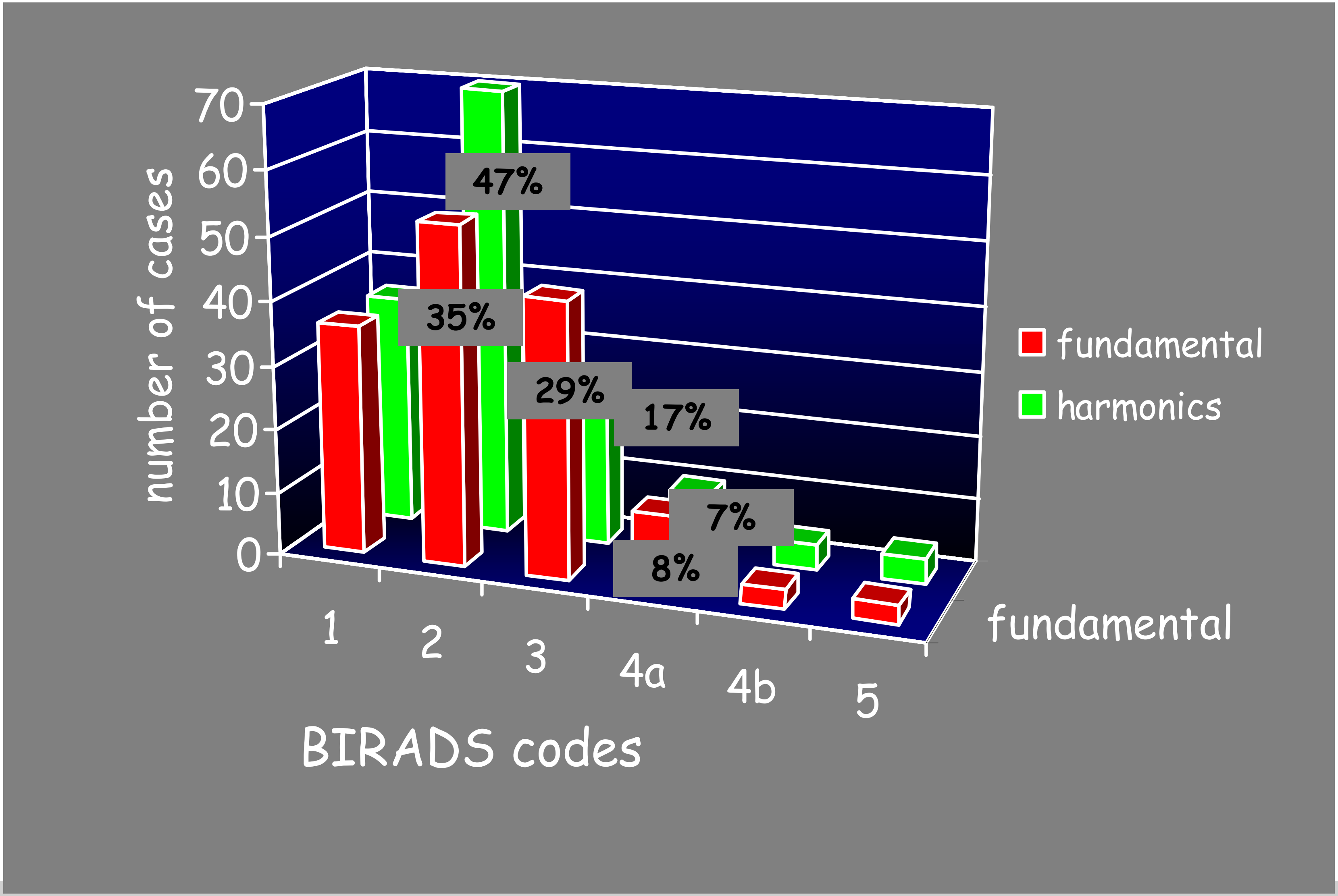
Indeterminate vs simple cyst



Axillary lymph nodes more hypoechoic



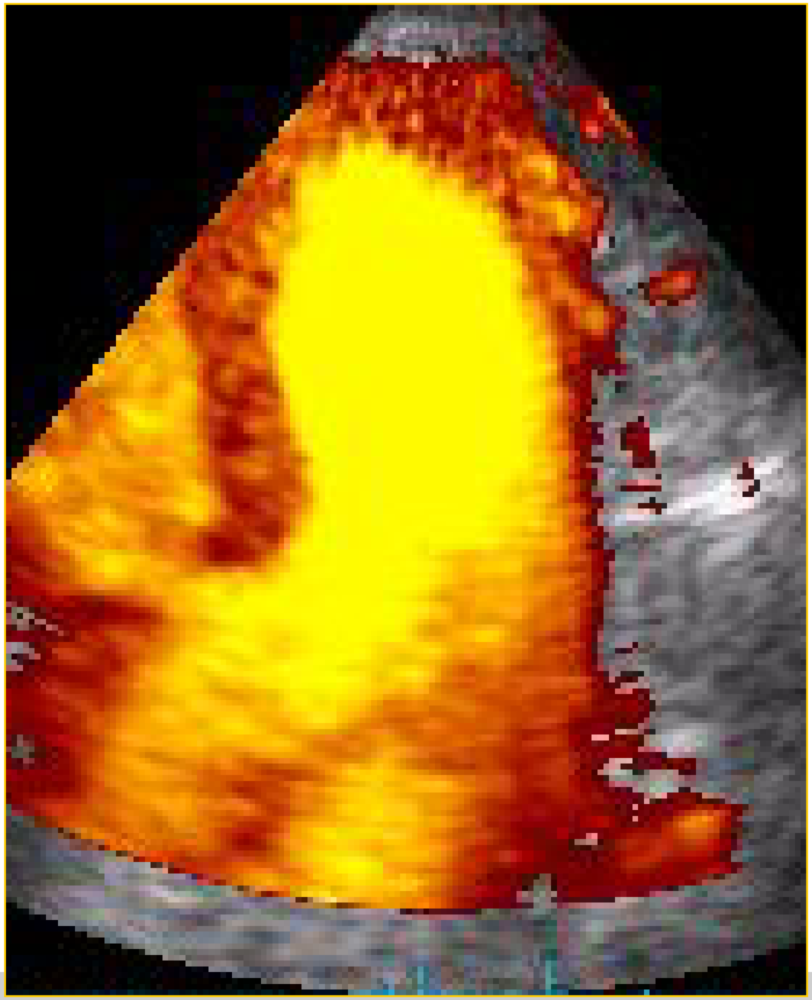
BI-RADS codes fundamental / harmonics



Contrast Agent Harmonic Imaging

Ultrasound contrast

- Gas filled microbubbles
- Strong harmonic response
- Main clinical goal: perfusion
  - Myocardial viability
  - Presence of tumors
- Tissue harmonics confuse the issue
- Trend toward low frequency (1.5 MHz) operation



Beamformation & Harmonics

Tissue Harmonics

- Goal: best tissue images
- Methods:
  - Maximize harmonic energy
  - Higher f-numbers to allow harmonic energy to accumulate
  - Consider non-spherical focusing

Contrast Harmonics

- Goal: Show distribution of contrast agents
- Methods:
  - Minimize propagation harmonic energy
  - Transmit harmonic energy that cancels propagation related harmonics.
  - Alternative phasing schemes

Two cases with diametrically opposed goals

Channel Count Issues

Whither Channel Count?

First 128 channel system introduced in 1983.

- Huge majority of high-end systems are still at 128 channels.

Does it make sense to go higher?

- What's the cost/benefit trade-off?
- Will the performance improve proportionately to the cost?

What are some of the reasons for increasing it?

- Elevation focusing
- Real-time 3D/4D
- Aberration correction

Rationale for Elevation Beamformation

Limited performance available with 1D designs

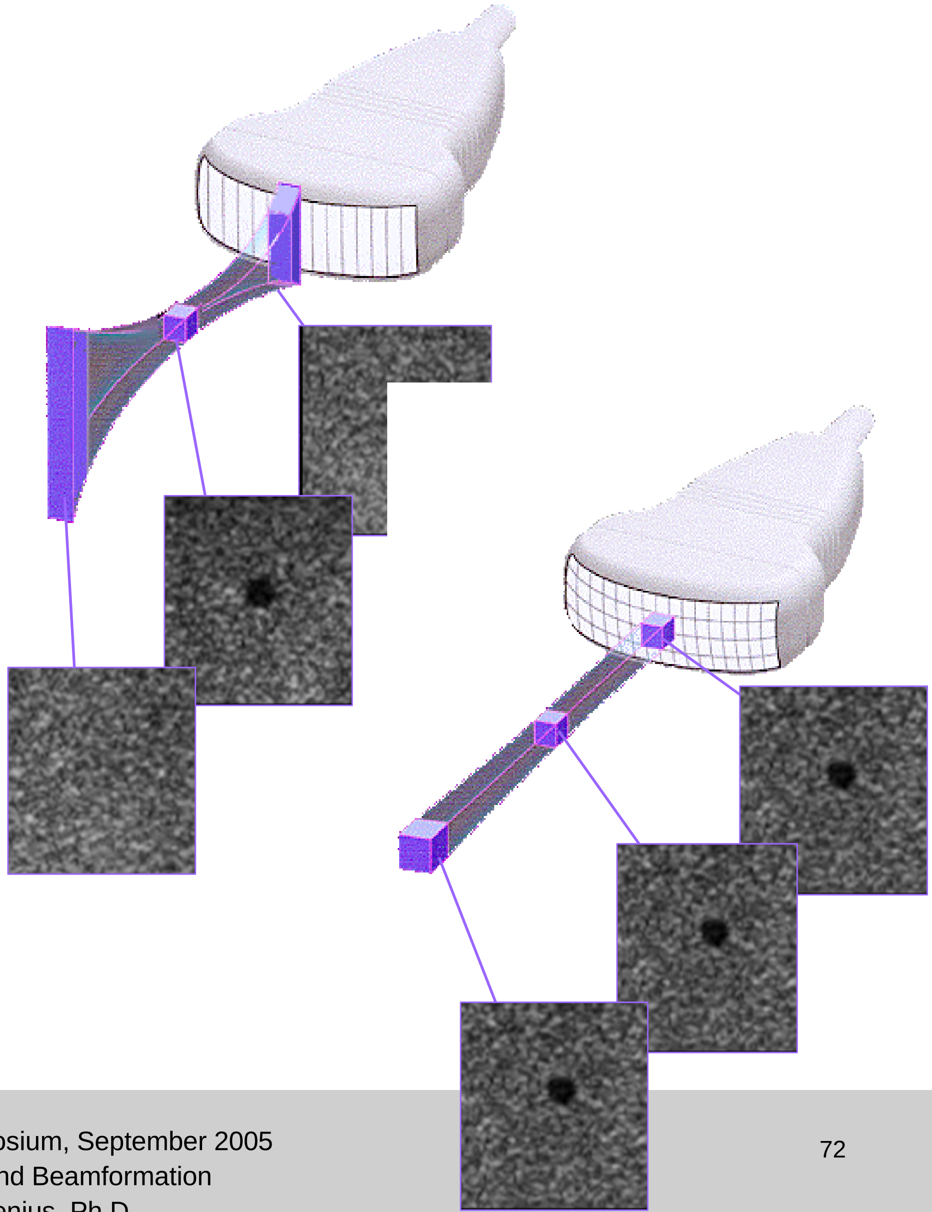
- Poor beamformation away from elevation focus.
  - Fixed focus hurts performance
- Limits on size of elevation aperture due to fixed focus.
  - Depth of focus inversely related to aperture size.

Slice thickness improvement throughout image

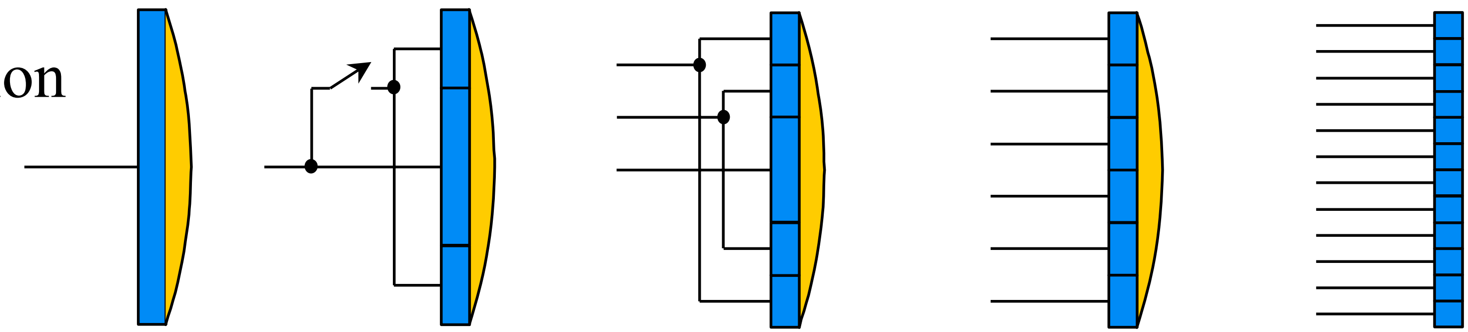
- Expanding aperture, dynamic focusing in elevation

Greater acoustic power control.

- I_{spta} location becomes more controllable.

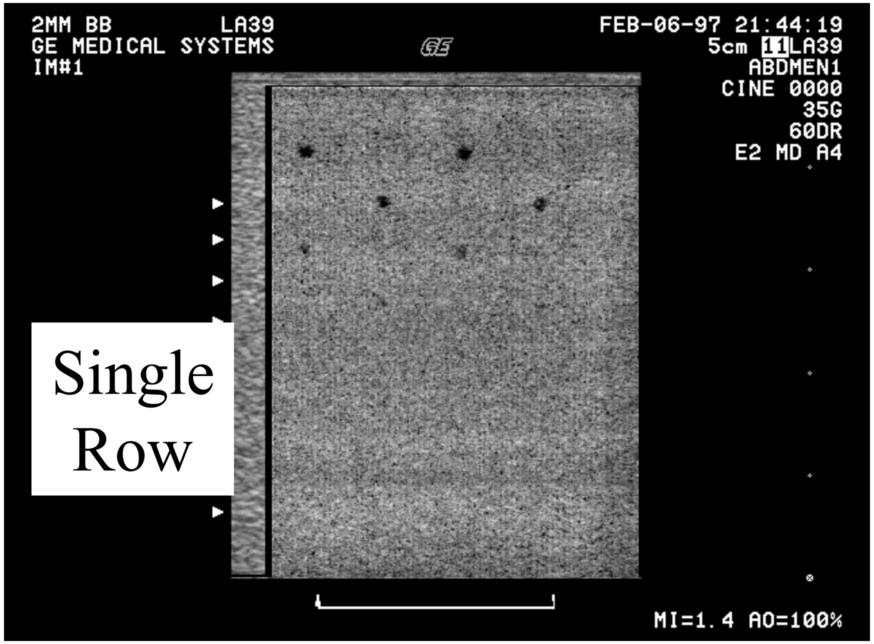


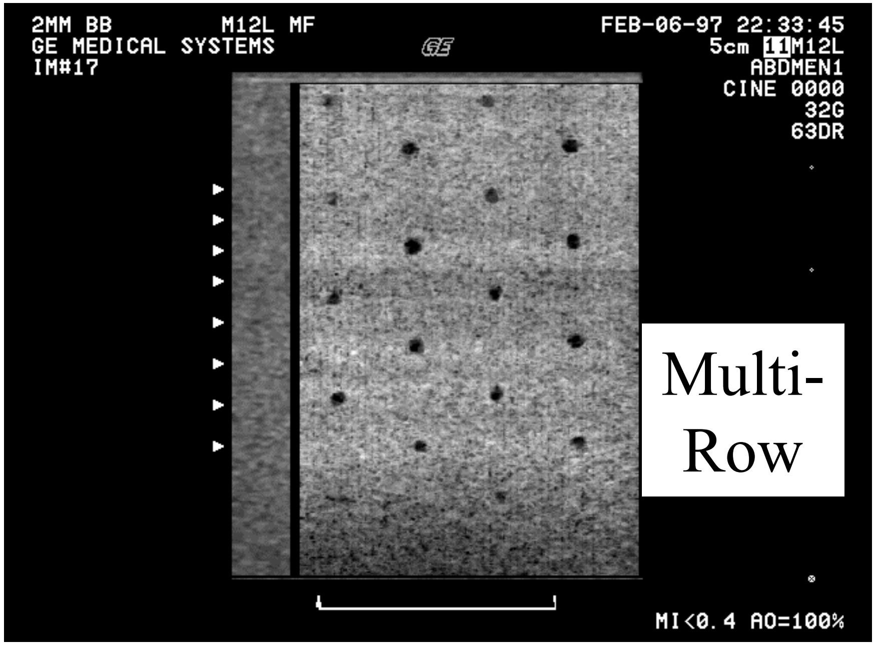
Transducer Array Taxonomy



	1D	1.25D	1.5D	1.75D	2D
Elevation					
Aperture	Fixed	Discrete	Dynamic	Dynamic	Dynamic
Focus	Static	Static	Dynamic, Symmetric	Dynamic, No Symmetry Constraint	Dynamic, Steerable

Single- vs. Multi-Row Arrays





Phantom with 2 mm Spherical Cysts

Channel Count Requirements

Channel counts for elevation focused systems.

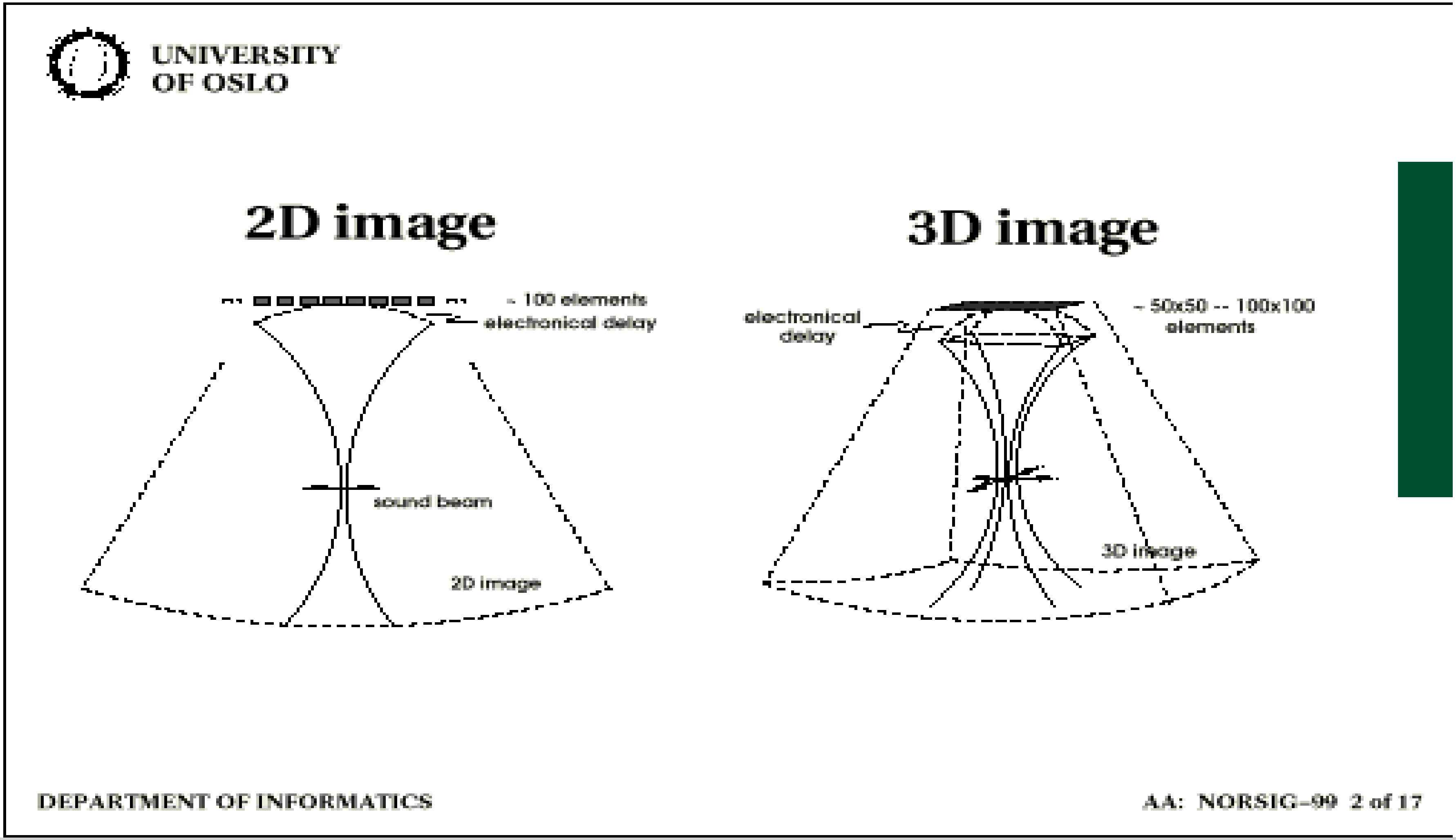
Let N = azimuthal channel count desired, e.g. 128.

- 1.25D no increase over N.
- 1.5D assume 5 rows (3 independent), therefore 3N channels required
- 1.75D with 5 rows, 5N channels required
- 2D sparse arrays w. 256 channels currently available, heading for 3D/4D imaging.

But, for ergonomic scanning, limit to no. of cables is 256 – 512.

3D/4D Challenges

Realtime 3D Beamformation



Physics Constraints

Speed of sound in body = 1540 m/sec

Image quality, Field of view, Volume update rate

- Can have any 2, not all 3

Example:

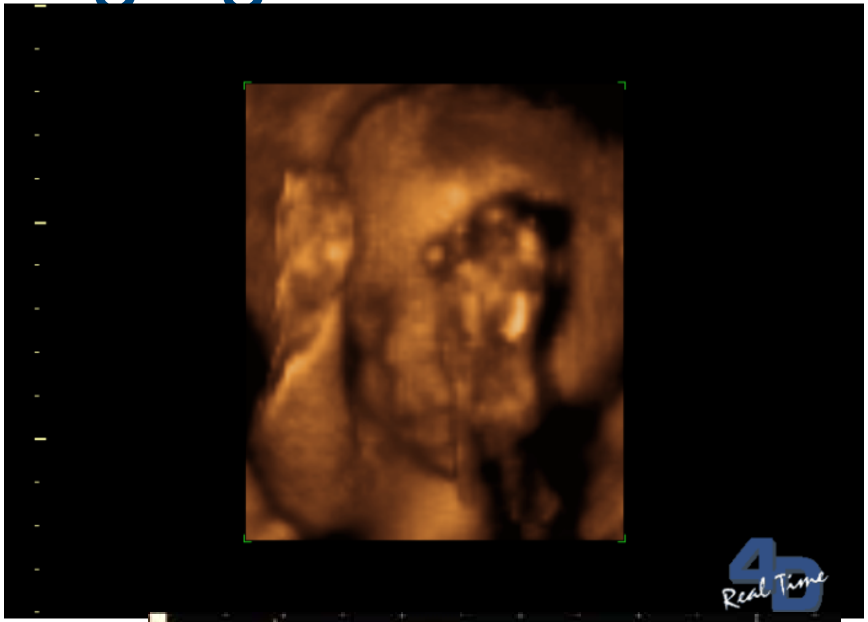
- 60° x 60° x 12 cm pyramid volume
- 1° beam spacing $\Rightarrow$ 3600 beams
- 12 cm x 2 / 1540 m/s = 160 μsec per beam
- $\Rightarrow$ 1.7 volumes / sec

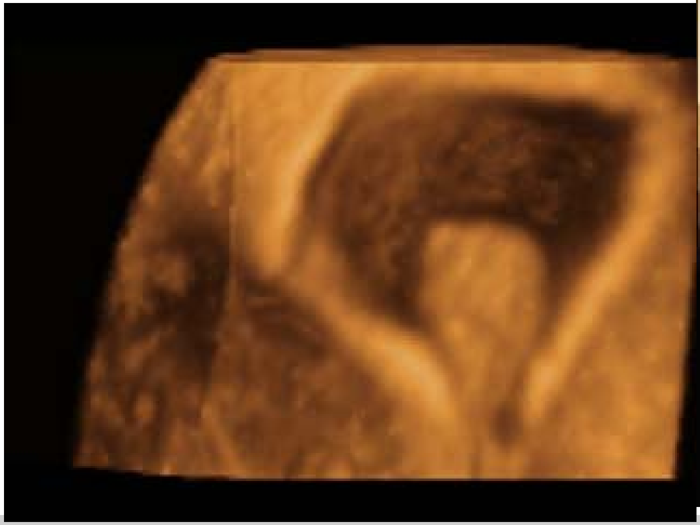
Mechanical 3D/4D Imaging

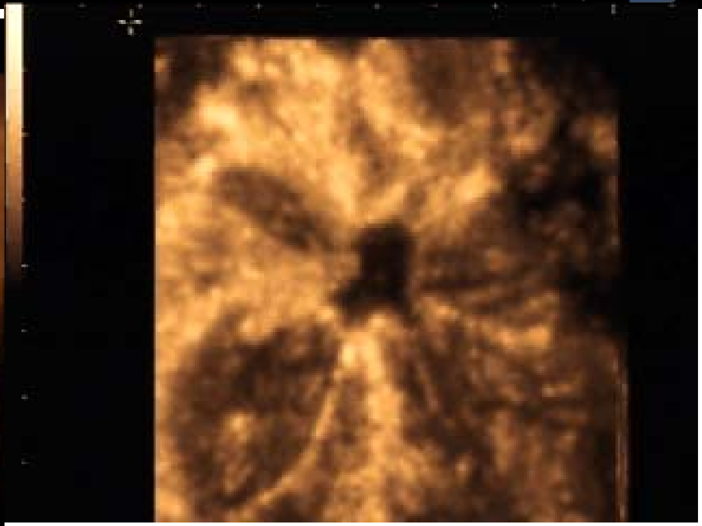
Attached clip with a mechanically scanned array.

8 – 16 vol/sec possible.

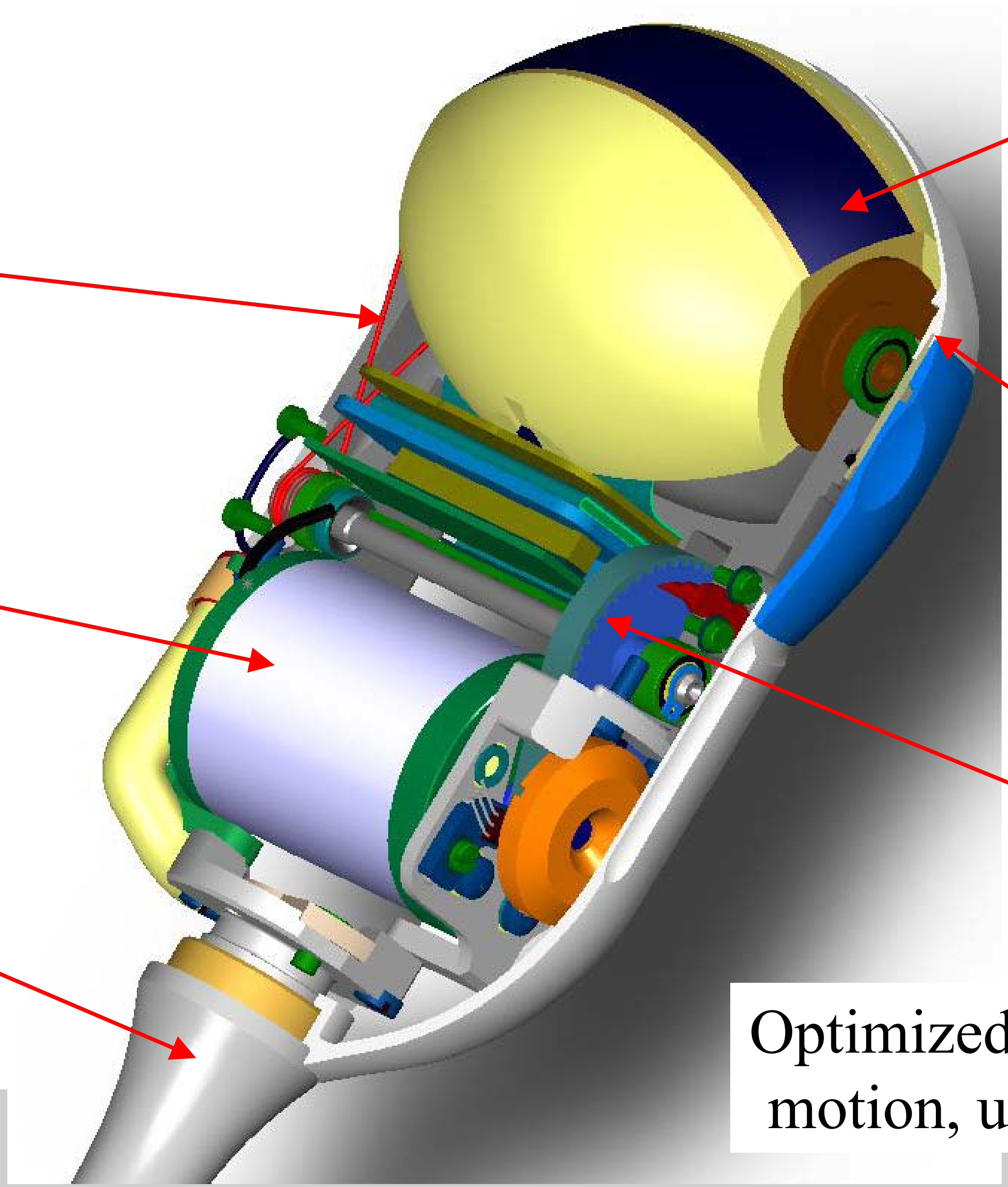
No compromise on 2D image quality necessary.







Mechanical 4D Probe



Optimized for high-speed motion, up to 18 vol/sec

Multi-line Acquisition

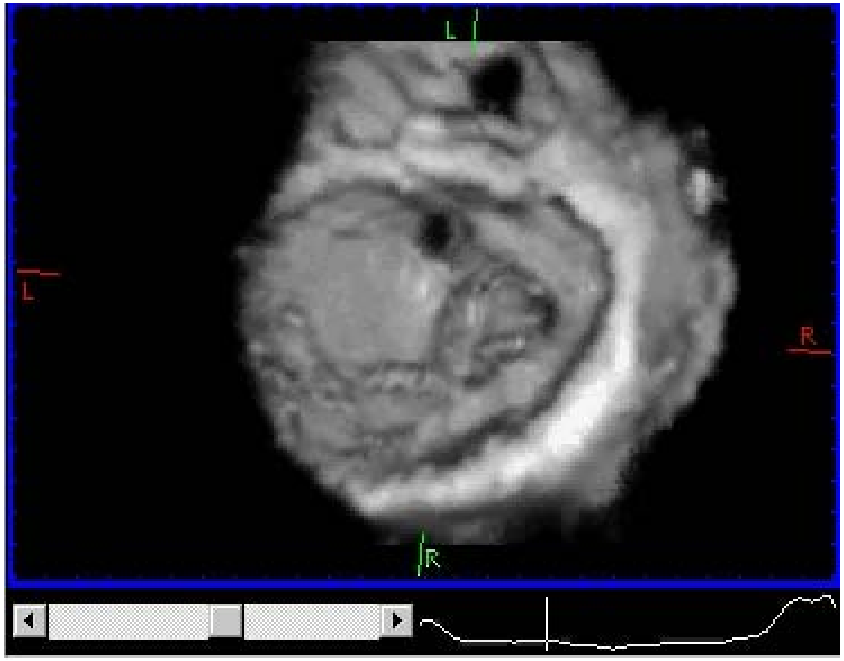
Transmit beam is broader than receive beam

- transmit is static focus, usually high f-number for max depth of field

Create 2 – 16 simultaneous receive beams
within the transmit beam

Substantial increase in volume rate!

Essential for effective 4D imaging



Electronic 4D with 2D Arrays

2D array can fire beams in any direction,
in any sequence

Symmetric beamforming & image quality

Multi-line imaging for faster volume rates

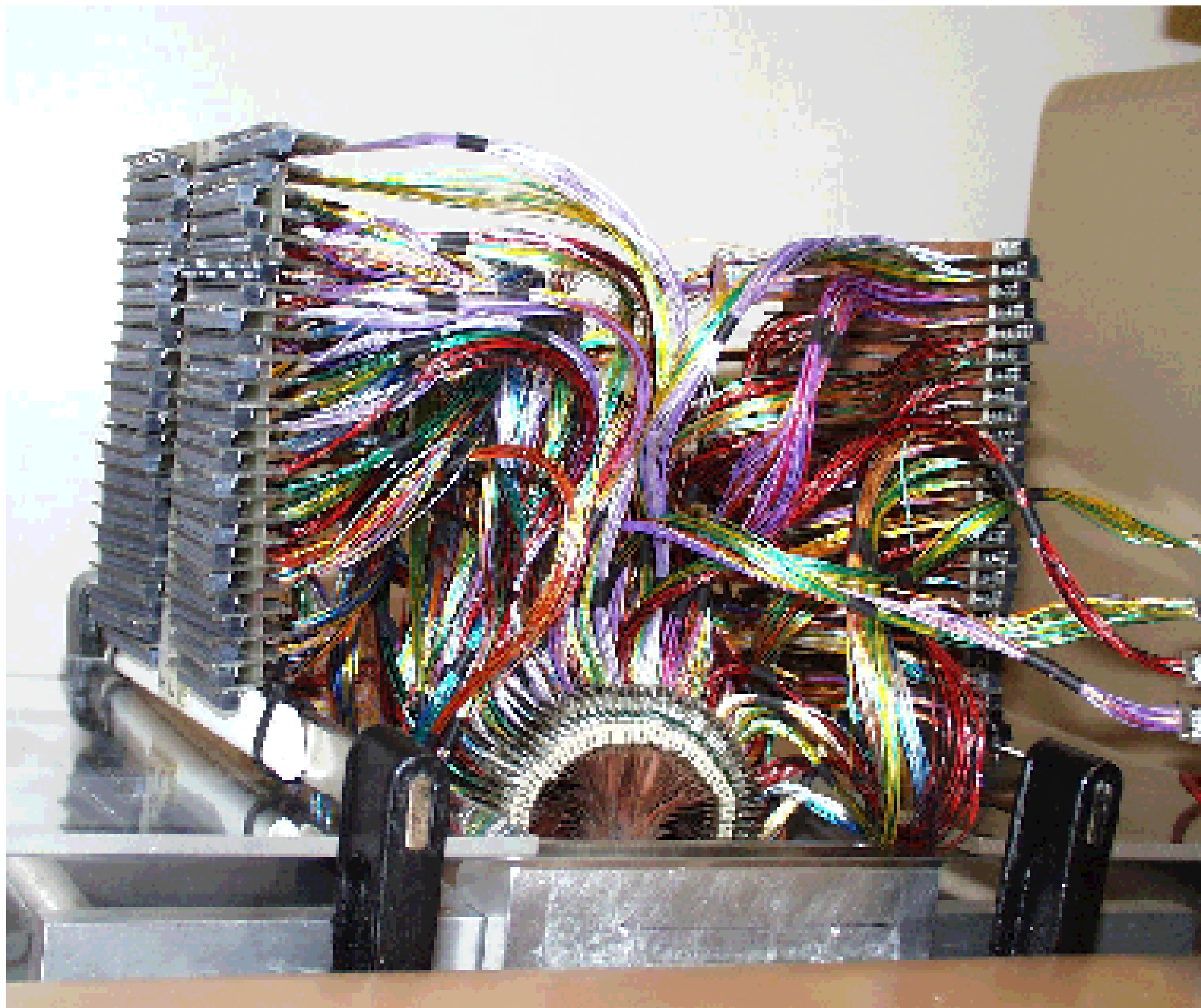
Thousands of transducer elements needed.

- Cabling constraints severely limit options.

Novel solutions needed.

Fully connected 50 by 50 array

UNIVERSITY
OF OSLO



DEPARTMENT OF INFORMATICS

AA: NORSIG-90 16 of 17

Sparse Array Solution

2D arrays needed

- consider 50 by 50 design
- we are not ready yet for a 2,500 channel system, have to settle for less.
- hence, have to make these sparse arrays
- consider 500 channels

An optimal search: 10^{551} possibilities

- there are 10^{80} electrons in the universe
- Unlikely to get the true optimum.

Solutions not very competitive …

Numerous compromises still have to be made

One Possible Solution

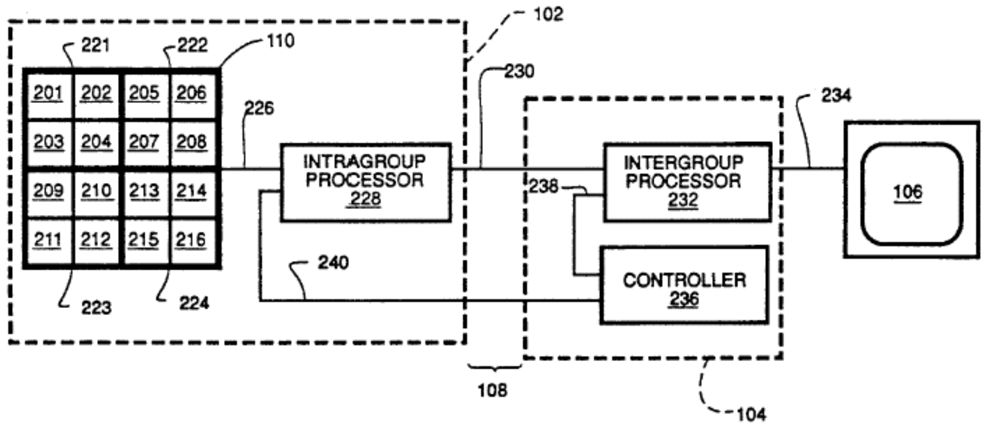
Migrate beamformer components to handle.

With multi-row probes, muxing is in the handle.

Patent by Larson from 1993

- group 2D array elements into subarrays
- combine echoes from subarrays and send summed signals
- cable count reduced w. reasonable spatial sampling.

Look for more system changes along these lines



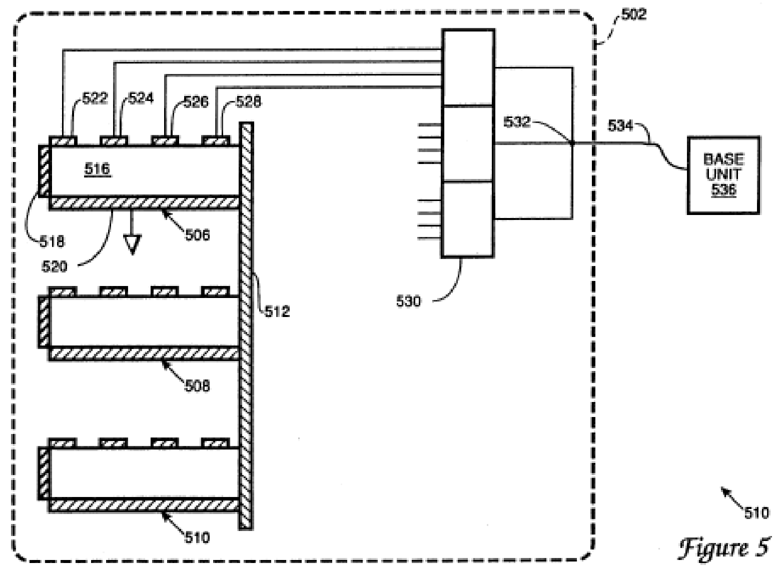
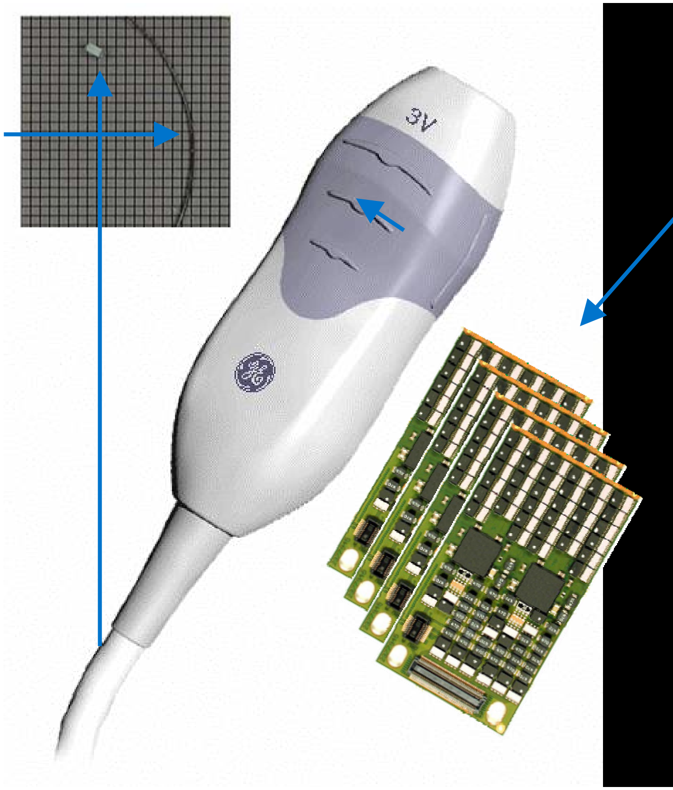
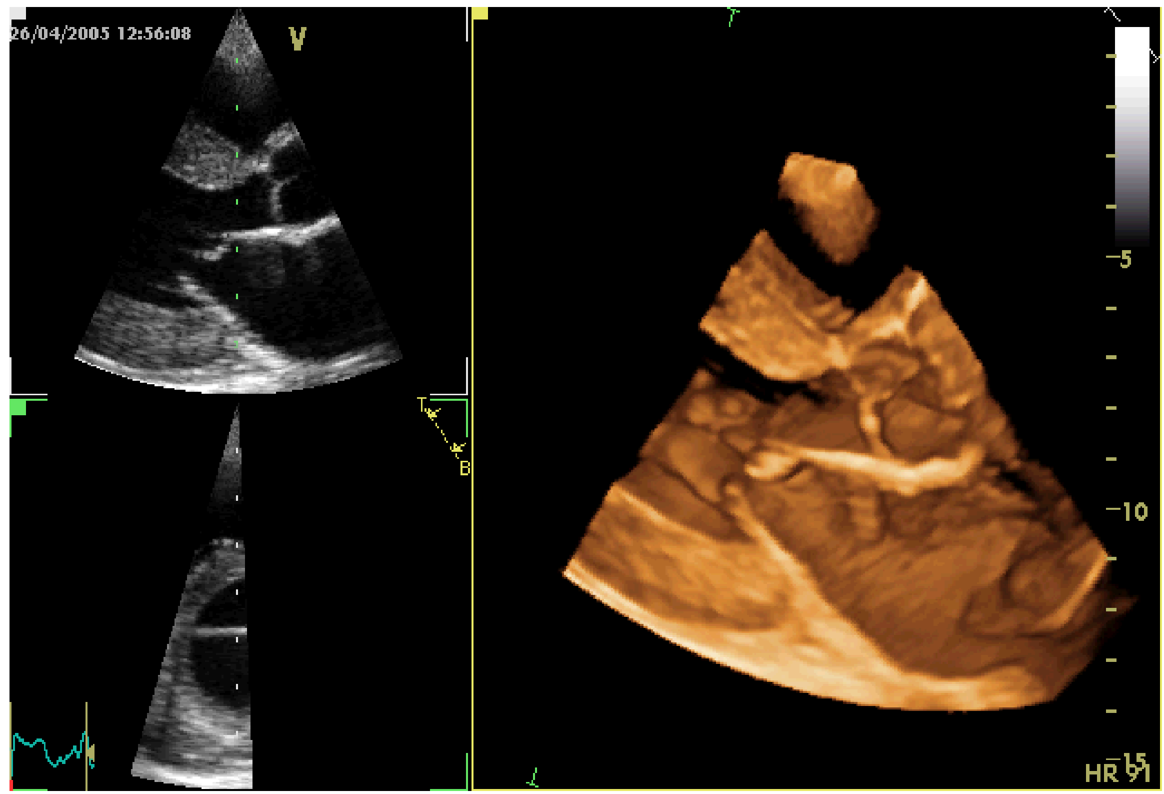


Figure 5

Migration of Beamformation to Handle

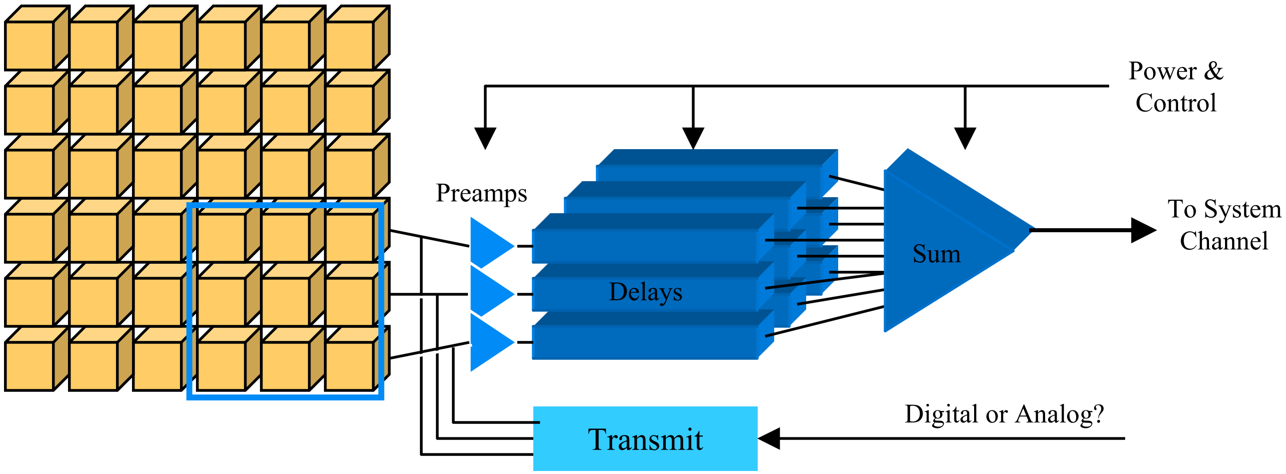


Modular Beamformer
in Probe Handle



2D Transducer Array
(vs. human hair)

Sub-Array Beamformer in Probe



Connects a group of transducer elements to each system channel

Low-power analog beamformer: Phase rotation or Delay lines

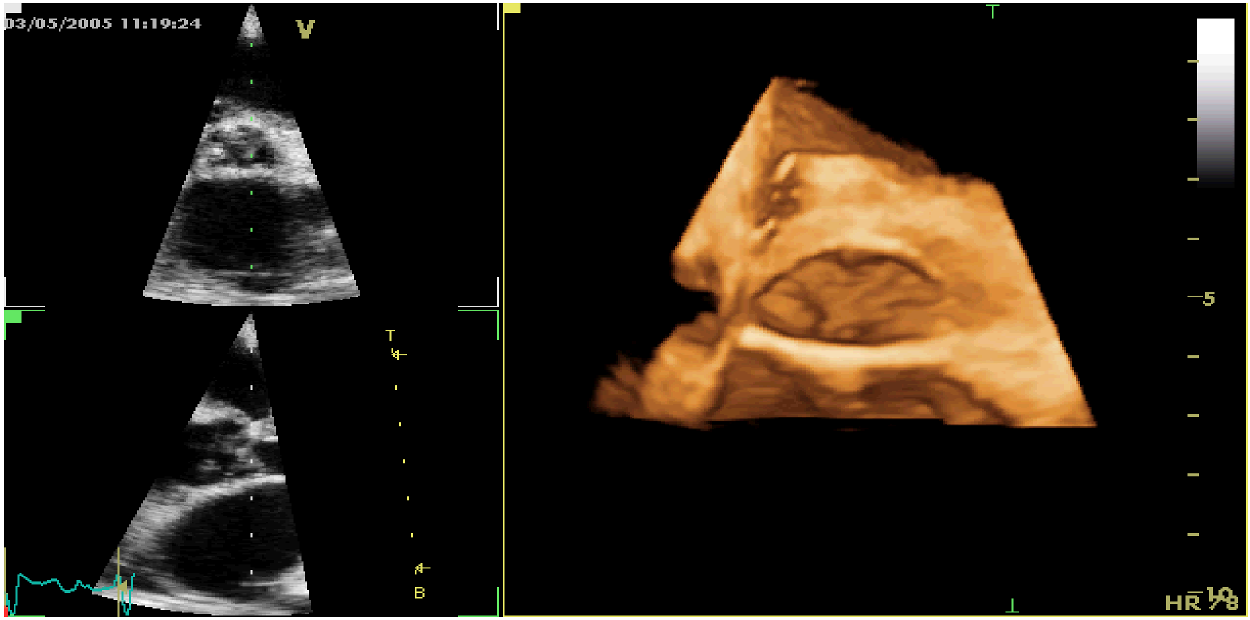
Small delays only: static steering of small sub-aperture

Dynamic focusing & full-aperture delays by system beamformer

Real-time 3D/4D Imaging

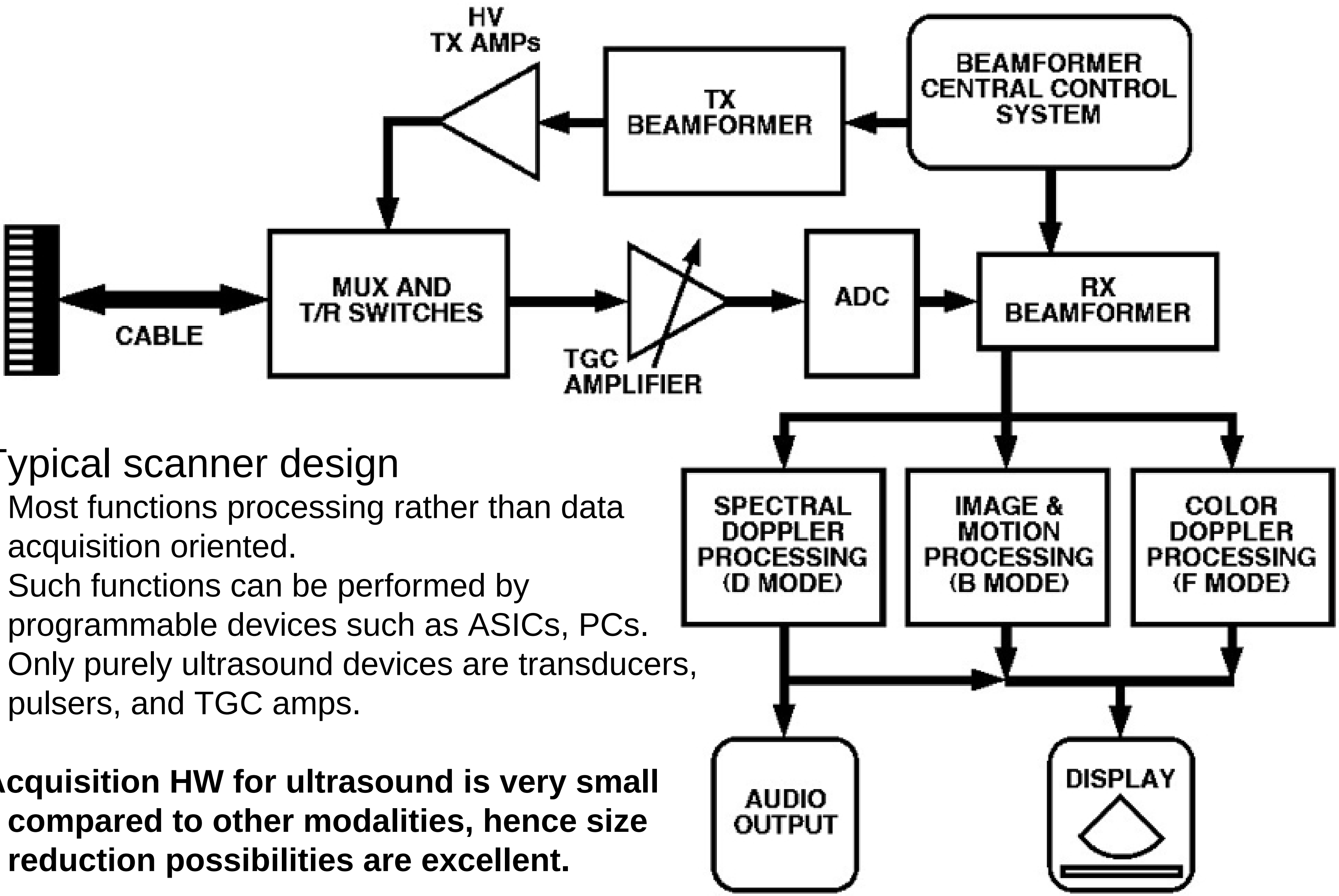
RT3D promises to be yet another exciting stage for ultrasound.

Much work is on-going on defining clinical apps.



Miniaturization

Miniaturization in Ultrasound: Trends

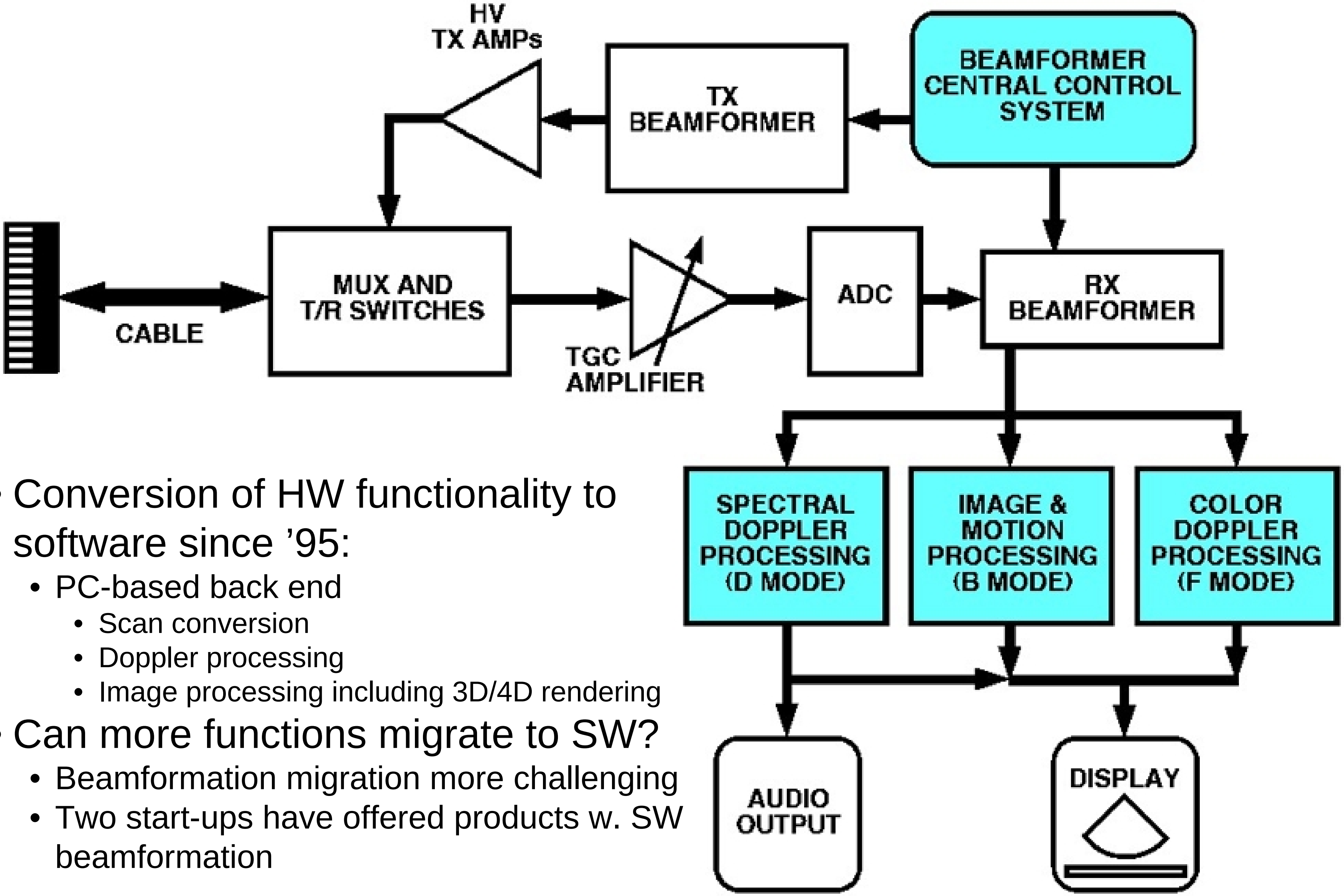


Typical scanner design

- Most functions processing rather than data acquisition oriented.
- Such functions can be performed by programmable devices such as ASICs, PCs.
- Only purely ultrasound devices are transducers, pulsers, and TGC amps.

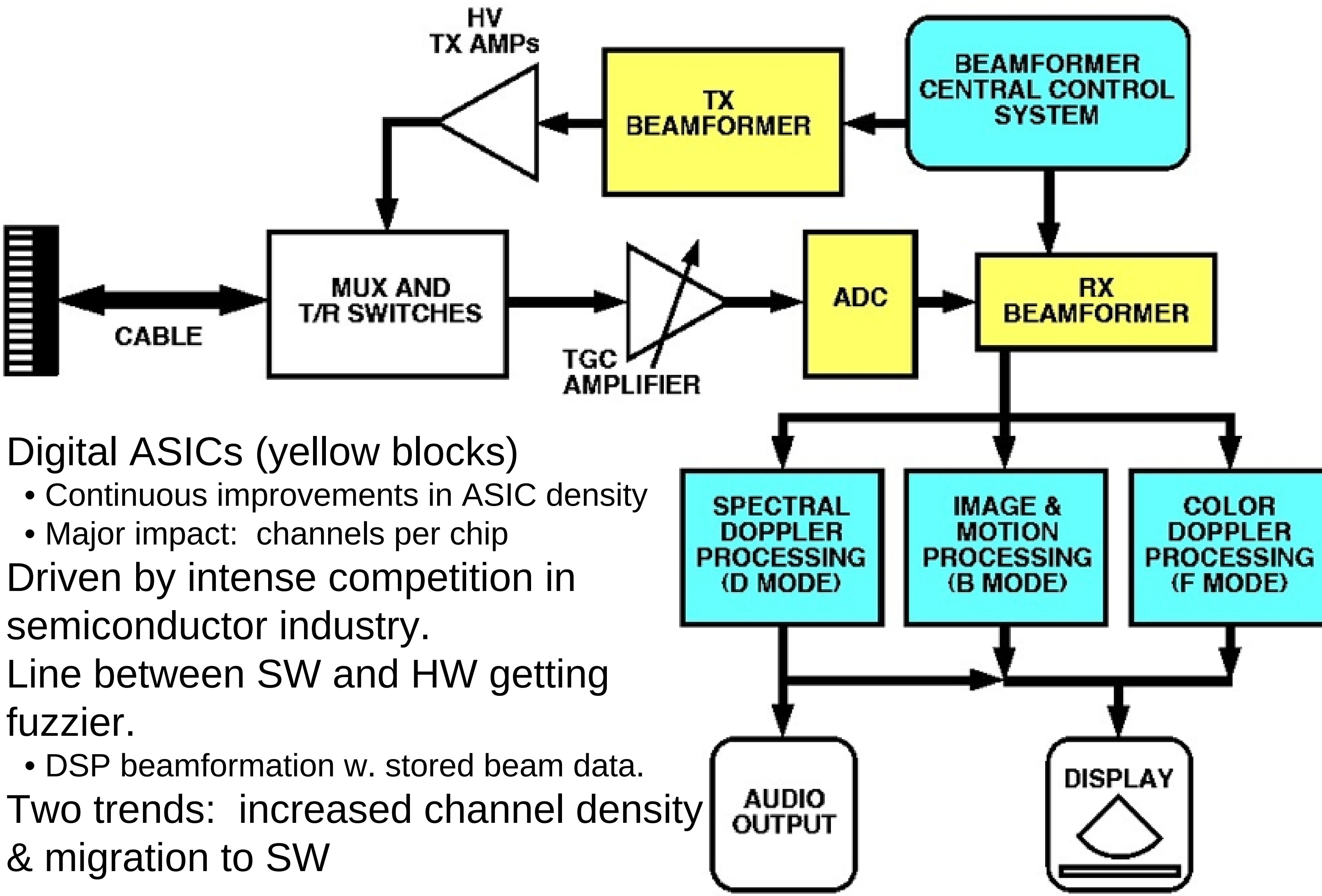
Acquisition HW for ultrasound is very small compared to other modalities, hence size reduction possibilities are excellent.

Migration of HW Functionality to SW



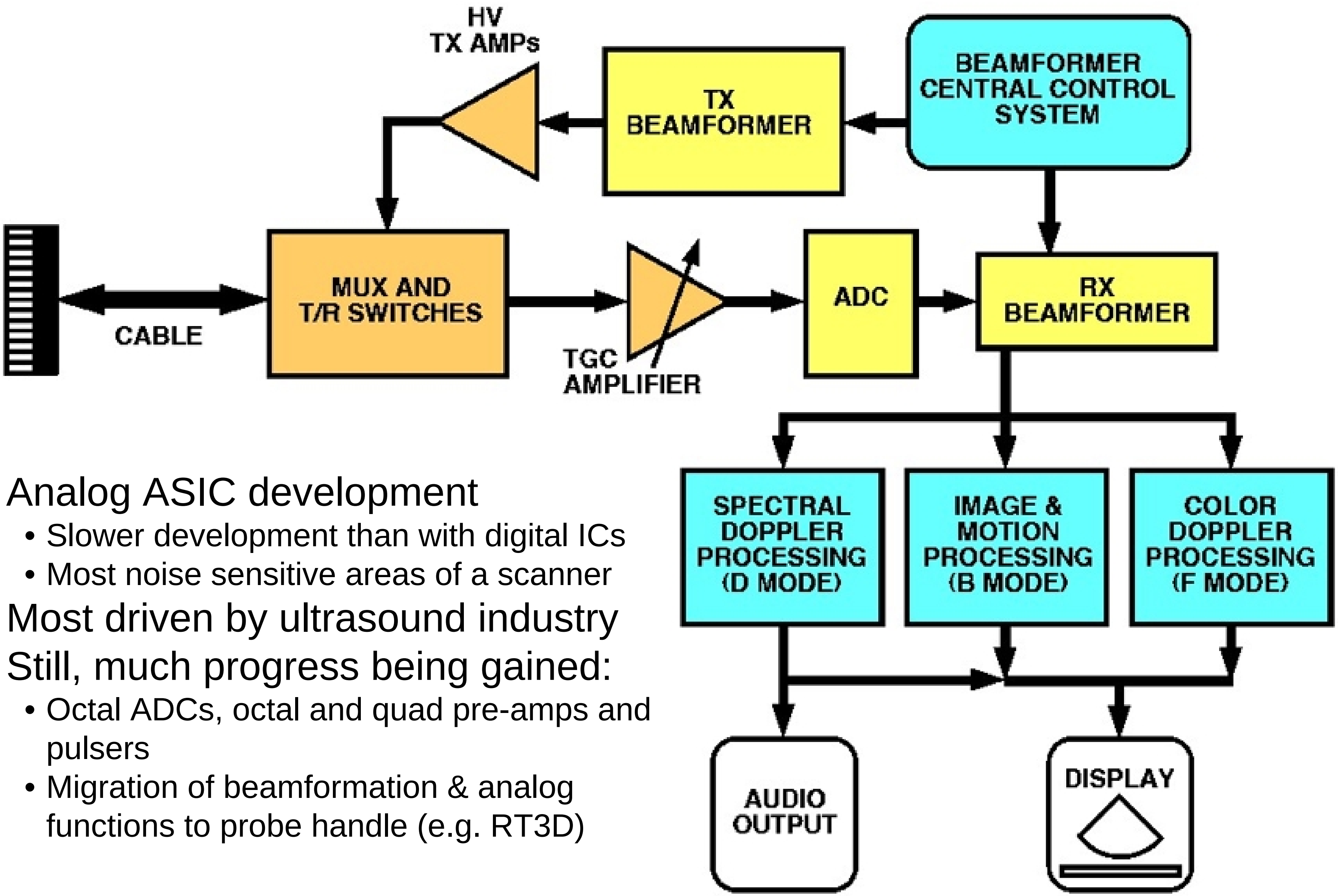
- Conversion of HW functionality to software since '95:
  - PC-based back end
    - Scan conversion
    - Doppler processing
    - Image processing including 3D/4D rendering
- Can more functions migrate to SW?
  - Beamformation migration more challenging
  - Two start-ups have offered products w. SW beamformation

Beamformation Miniaturization: Digital ASICs



- Digital ASICs (yellow blocks)
  - Continuous improvements in ASIC density
  - Major impact: channels per chip
- Driven by intense competition in semiconductor industry.
- Line between SW and HW getting fuzzier.
  - DSP beamformation w. stored beam data.
- Two trends: increased channel density & migration to SW

Analog Components



- Analog ASIC development
  - Slower development than with digital ICs
  - Most noise sensitive areas of a scanner
- Most driven by ultrasound industry
- Still, much progress being gained:
  - Octal ADCs, octal and quad pre-amps and pulsers
  - Migration of beamformation & analog functions to probe handle (e.g. RT3D)

Summary of Trends in Miniaturization

Probe → Analog Front End → Digital Beamformation & Processing → PC

Probe

- **Migration of electronics to handle:**
  - Multiplexers
  - Analog beamformation or SAPs
- **Silicon Transduction**

Analog Front End

- **Increases in analog circuit density**
  - Functions per chip

Digital Beamformation & Processing

- **Increased ASIC Density**
  - Increased channels per chip
- **Potential of SW beamformation at low end**

PC

- **Many traditional HW roles converted to SW**
- **Much of new functionality SW based:**
  - 3D/4D rendering
  - Networking
  - CAD

> Long term trends: Analog electronics to probe, Digital electronics to SW, Moore's Law everywhere.

Examples

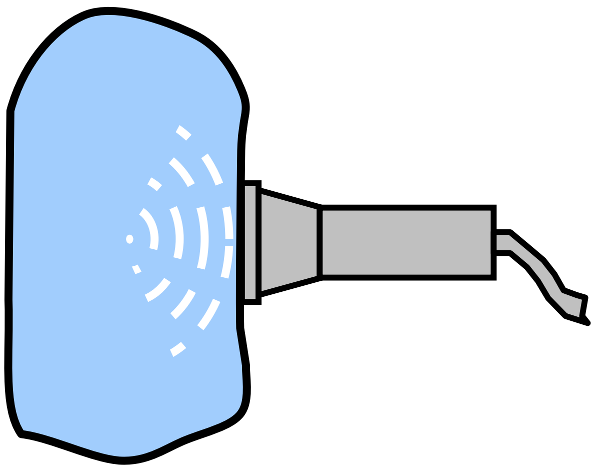
Status today:

- Nearly fully-featured handheld systems are available.
- Design issues:
  - Level of compromise in performance required
    - Channel count reduction
    - Coarser sampling
    - Folded architectures
  - Clinical utility realized
    - Portability is good but is the diagnosis?

Aberration Correction

State-of-the-Art in Ultrasound Imaging

Focusing = Geometry, or…

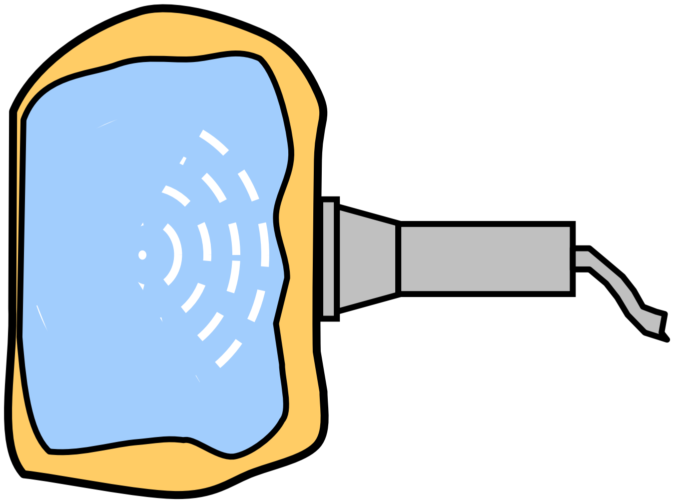


People are just bags of water

It's a Crude Approximation

Real-World Imaging

Fat and Muscle Layers Degrade the Image



Time-delay Errors from the Abdominal Wall are *10-50 Times Larger than beamformer delay quanta.*

Digital Beamformer Accuracy is Wasted

Aberration Correction

All beamformers use an assumption of constant speed of sound.

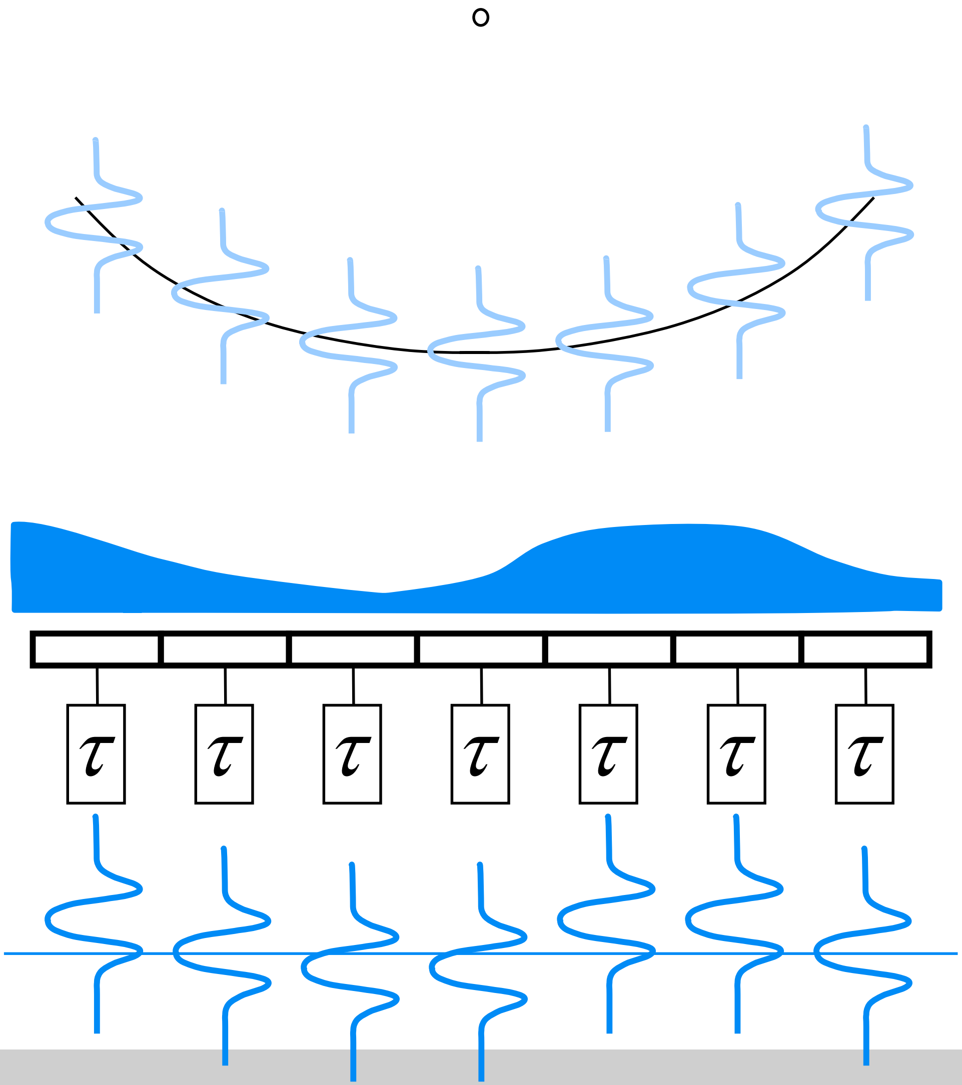
This assumption is not valid.

In soft tissues, we have these speeds:

- fat 1440 m/s
- liver 1510
- kidney 1560
- muscle 1570 (skeletal)
- tumors 1620

This variation limits further spatial & contrast resolution improvements.

Beamforming With Aberration



Point-like scatterer

Spherical wavefronts

Aberrating Layer, $c \neq c_0$

Transducer

Geometric beamforming delays

Channel data poorly aligned

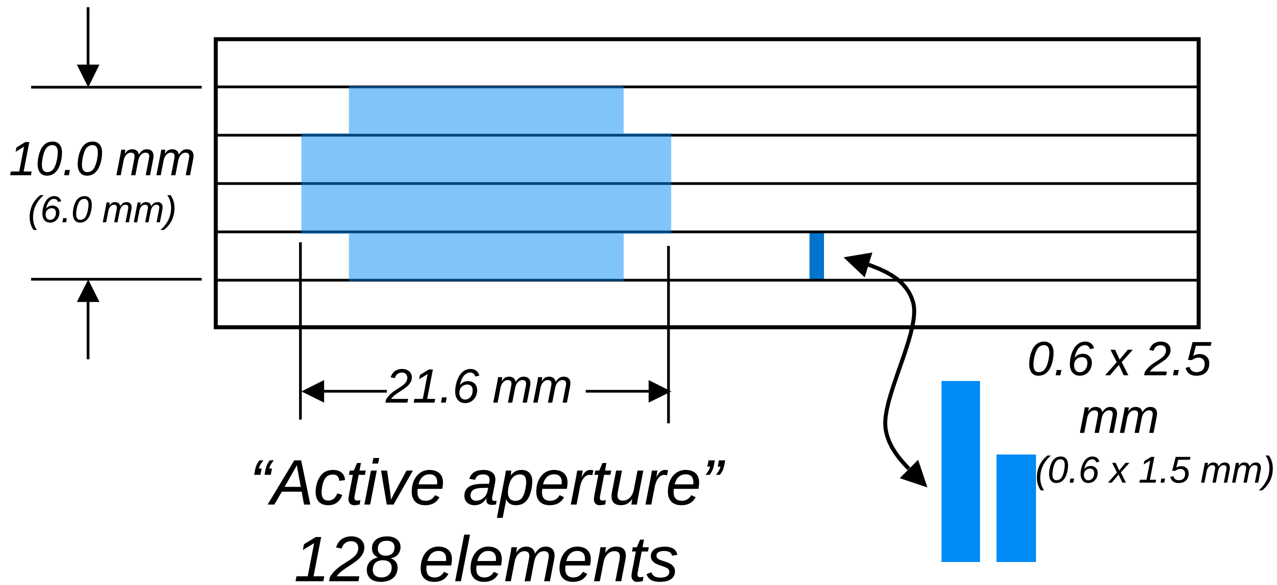
Multirow Transducer

6 x 96 elements

Independent time delay for each element

Elevational lens

3.5 MHz center frequency



Possible solutions

Three main thrusts:

- phase screen models
  - all aberrating sources near skin line
  - deaberration can occur via time shifting of the echoes
  - amount of shift determined by correlations.
- distributed aberrators
  - aberrating sources away from skin (as well as near it). Interference among refracted beams occurs.
  - far more complex deaberration methods than time shifting is needed.
- inverse filtering
  - Assume a common source to all echoes
  - Blind systems identification

Time Delay Estimation

$$C_{ij} = \frac{\sum_k B_j^*(k) s_{ij}(k)}{\sqrt{\sum_k |B_j(k)|^2 \sum_k |s_{ij}(k)|^2}}$$ *channel i, beam j*

Baseband beamsum signal $B(k) = |B(k)| e^{-j\theta_B(k)}$

channel signal $s(k) = |s(k)| e^{-j\theta_s(k)}$

Average phase difference over range gates...

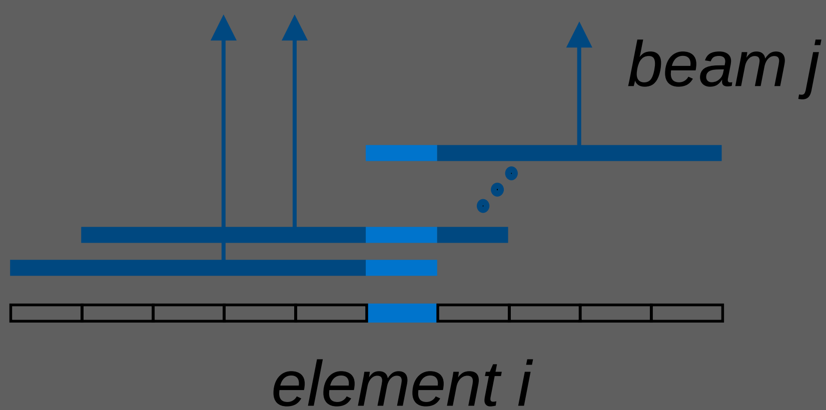
$$C_{ij} \propto \sum_k |B| \, |s| \, e^{j[\theta_B(k) - \theta_s(k)]}$$

Arrival time error $\tau_{ij} = (2\pi f)^{-1} Phase\{C_{ij}\}$

Time Delay Estimation

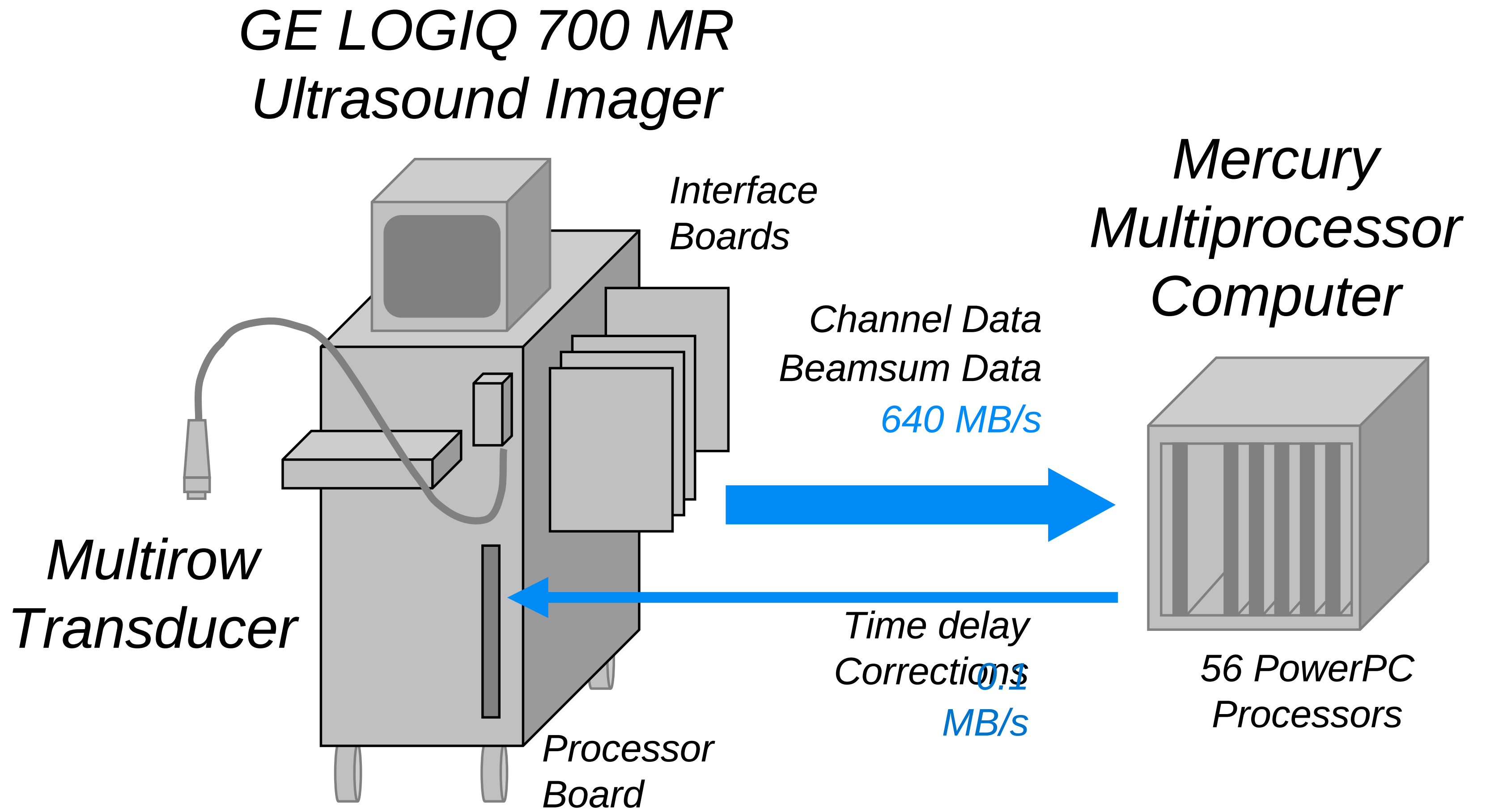
Arrival time error $\tau_i = (2\pi f)^{-1} \, Phase\{\overline{C}_i\}$

Average C_{ij} over all beams j to which element i contributes

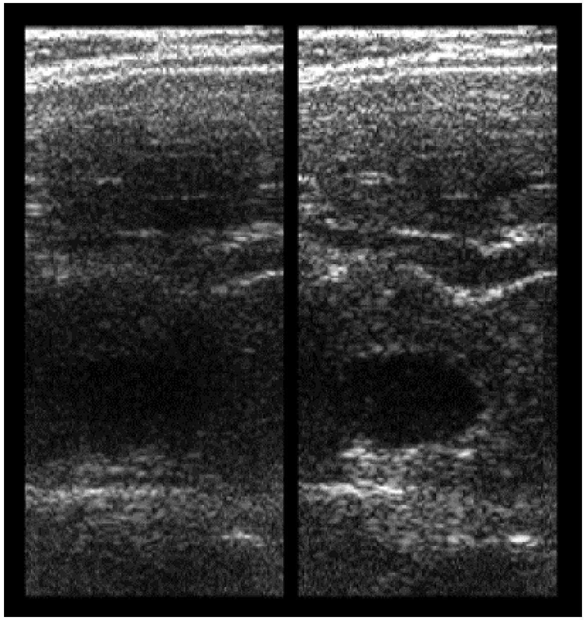


For thin aberrating layer, time delay for a given element is independent of beam

Adaptive Imager



Liver with Model Aberration

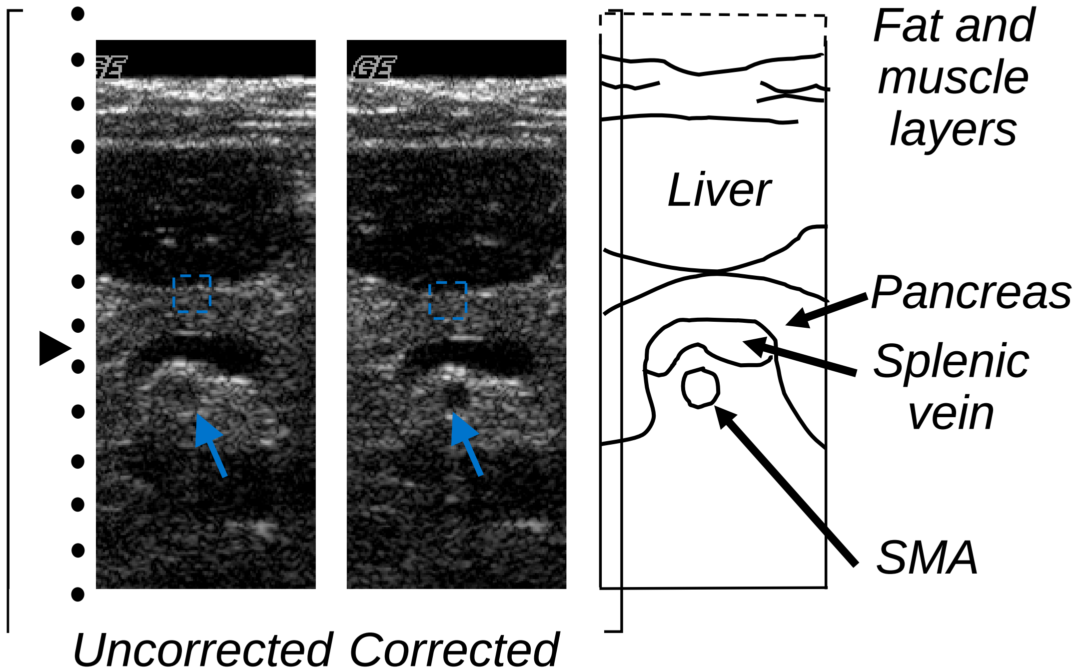


Uncorrected *Corrected*

Arrival Time Error Estimates

In-Vivo Time Delay Correction

Pancreas and
Superior Mesenteric Artery



SMA 4.4 dB darker, pancreas 1.4 dB brighter

Aberration Correction

Perhaps the major beamformer related challenge today.

Several groups throughout the world are addressing this issue.

Stay tuned.

Summary: New areas of interest

Hand held systems

- how small can we make a beamformer?

How can we increase channel count w/o major cost increase?

- Will clinical benefits justify increased costs?
- Search for new methods of beamformation, e.g.
  - Delta-sigma beamformation

Realtime 3D/4D

- Migration of beamformer functions to probe handle

Methods of combating slow speed of sound

- Multi-line strategies

Conclusions

Major trends in beamformers:

- increased channel count is highly likely
  - real-time 3D
  - elevation beamforming
  - sparse arrays
- to accomplish this, several approaches may be possible:
  - migration of beamformer functions to probe handle
  - increased channel density per board
  - synthetic aperture schemes
  - novel beamformation approaches
- new applications, directions
  - taking advantage of nonlinear propagation effects
  - contrast agents

Bibliography

F. Anderson, ``3D ellipsoidal backprojection images from large arrays", 1992 IEEE Ultrasonics Symposium Proc., pp. 1223-1226, (1992).

W.A. Anderson, et al., ``A new real time phased array Sector Scanner for imaging the entire adult human heart", {Ultrasound in Medicine}, 3B Edition, pp. 1547-1558, (1977).

Austeng and S. Holm, " Sparse Arrays for Real-time 3D Imaging, Simulated and Experimental Results," in Proc. IEEE Ultrasonics Symp.2000, San Juan, Puerto Rico, Oct 2000

K.N. Bates, ``Tolerance analysis for phased arrays", {Acoustic Imaging}, Vol. 9, edited by K. Wang, pp. 239-262, Plenum Press, New York, (1980).

W.L. Beaver, ``Phase error effects in phased array beam steering", 1977 IEEE Ultrasonics Symposium Proc., pp. 264-267, (1977).

N. Bom, C.T. Lancee, and J. Honkoop, ``Ultrasonics viewer for cross-sectional analysis of moving cardiac structures", Bio-med Engng 6:500, (1971).

C.B. Burckhardt, P.-A. Grandchamp, and H. Hoffman, ``An experimental 2 MHz synthetic aperture sonar system intended for medical use", IEEE Trans. Son. Ultrason. vol. 21, pp. 1-6, (1974).

C.B. Burckhardt, P.-A. Grandchamp, H. Hoffman, and R. Fehr, ``A simplified ultrasound phased arrays sector scanner", {Echocardiology}, ed. C.T. Lancee, pp. 385-393, (1979).

C.R. Cooley and B.S. Robinson, ``Synthetic focus imaging using partial datasets", 1994 IEEE Ultrasonics Symposium Proc., vol.94CH3468-6, pp. 1539-1542, (1994).

Daft, CMW, Leue, WM, Thomenius, KE, Macdonald, MC, Odegaard, LA, "Comprehensive Imager Simulation for Improved Acoustic Power Control," 1999 IEEE Ultrasonics Symposium, pp. 1571 – 1757, 1999.

C.M.W. Daft, D.G. Wildes, L.J. Thomas, L.S. Smith, R.S. Lewandowski, W.M. Leue, K.W. Rigby, C.L. Chalek, and W.T. Hatfield, "A 1.5D transducer for medical ultrasound", 1994 IEEE Ultrasonics Symposium Proceedings, pp.~1491-1495.

R. E. Davidsen, J. A. Jensen and S. W. Smith, ``Two dimensional random arrays for real time volumetric imaging," Ultrason. Imag., vol 16, pp 143-a63, 1994.

M.D. Eaton, R.D. Melen, and J.D. Meindl, ``A flexible, real-time system for experimentation in phased-array ultrasound imaging", {Acoustic Imaging}, Vol. 8, edited by A.F. Metherell, pp. 55-67, Plenum Press, New York,(1980)

S. Freeman, P.-C. Li, and M. O'Donnell, ``Retrospective dynamic transmit focusing", Ultrasonic Imaging, vol. 17, pp. 173-196, (1995).

S.M. Gehlbach and R.E. Alvarez, ``Digital ultrasound imaging techniques using vector sampling and raster line reconstruction", Ultrasonic Imaging, vol. 3, pp. 83-107, (1981).

R.T. Hoctor and S.A. Kassam, ``The unifying role of the coarray in aperture synthesis for coherent and incoherent imaging", IEEE Proc., vol. 78, pp. 735-752, (1990).

S. Holm, "Sparse and irregular sampling in array processing," Proc. IEEE Int. Conf. Acoust., Speech, Sign. Proc. 2000, Istanbul, Turkey, June 2000

K. Jeon, M.H. Bae, S.B. Park, and S.D. Kim, ``An efficient real time focusing delay calculation in ultrasonic imaging systems", Ultrasonic Imaging, vol. 16, pp. 231-248, (1994).

M. Karaman, A. Atalar, and H. Koymen, ``VLSI circuits for adaptive digital beamforming in ultrasound imaging", IEEE Trans. Med. Imaging, vol. 12, pp. 711-720, (1993).

M. Karaman, P.-C. Li, and M. O'Donnell, ``Synthetic Aperture Imaging for Small Scale Systems", IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control UFFC-42, 429-442 (1995)

H.E. Karrer, J.F. Dias, J.D. Larson, R.D. Pering, ``A phased array acoustic imaging system for medical use", 1980 Ultrasonics Symposium Proceedings, pp.757-762, IEEE 80CH1602-2, (1980).

J.H. Kim, T.K. Song, and S.B. Park, ``A pipelined sampled delay focusing in ultrasound imaging systems", Ultrasonic Imaging, vol. 9, pp. 75-91, (1987).

D.L. King, ``Real-time cross-sectional ultrasonic imaging of the heart using a linear array multi-element transducer", J. Clin. Ultrasound, vol. 2, p. 222, (1974).

W.C. Knight, R.G. Pridham, and S.M. Kay, ``Digital Signal Processing for Sonar", Proc. IEEE, vol. 69, pp. 1451-1507, (1981).

J.D. Larson, III, "2-D Phased array ultrasound imaging system with distributed phasing", US Patent, no. 5,229,933, Jul. 20, 1993.

P.-C. Li and M. O'Donnell, ``Synthetic aperture imaging using a Lagrange based filtering technique", Ultrasonic Imaging, vol. 14, pp. 354-366, (1992).

G. R. Lockwood, P. C. Li, M. O'Donnell, and F. S. Foster, ``Optimizing the radiation pattern of sparse periodic linear arrays", IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control UFFC-43, pp.7-14 (1996).

G.

Bibliography

R. Lockwood and F. S. Foster, ``Optimizing the radiation pattern of sparse periodic two dimensional arrays", IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control UFFC-43, pp. 15-19 (1996).

G.R. Lockwood and F.S. Foster, ``Design of sparse array imaging systems", 1995 IEEE Ultrasonics Symposium Proceedings, vol. 95CH35844, pp. 1237-1243,(1995).

J.-Y. Lu and J.F. Greenleaf, ``Nondiffracting X waves-exact solutions to free-0space scalar wave equation and their finite aperture realizations",IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control UFFC-39, pp. 19-31 (1992).

R.M. Lutoff, A. Vieli, and S. Basler, ``Ultrasonic phased array scanner with digital echo synthesis for Doppler echocardiography", IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control, vol. UFFC-36, pp. 494-506, (1989).

P.A. Magnin, O.T. von Ramm, and F. Thurstone, ``Delay quantization error in phased array images", IEEE Trans. Sonics Ultrasonics, vol. SU-28, pp. 305-310, (1981)

G.F. Manes, C. Atzeni, and C. Susini, ``Design of a simplified delay system for ultrasound phased array imaging", IEEE Transactions of Sonics Ultrasonics, vol. SU-30, pp. 350-354, (1983).

R.E. McKeighen and M.P. Buchin, ``New techniques for dynamically variable electronic delays for real time ultrasonic imaging", 1977 Ultrasonics Symposium Proceedings, pp. 250-254, IEEE 77CH1264-1, (1977).

R.A. Mucci, ``A comparison of efficient beamforming algorithms", IEEE Trans. Acoust. Speech, Signal Proc., vol. 32, pp. 548-558,(1984).

R.A. Mucci and R.G. Pridham, ``Impact of beam steering errors on shifted sideband and phase shift beamforming techniques", JASA vol. 69, pp. 1360-1368, (1981).

K. Nagai, ``A new synthetic-aperture focusing method for ultrasonic B-scan imaging by the Fourier transform", IEEE Transactions Son.Ultrason. vol. 32, pp. 531-536, (1985).

M. Nikoonahad, ``Synthetic focused image reconstruction in the presence of a finite delay noise", 1986 IEEE Ultrasonics Symposium, IEEE 86CH2375-4, pp. 819-824, (1990).

L.F. Nock and G.E. Trahey, ``Synthetic receive aperture imaging with phase correction for motion and for tissue inhomogeneities - Part I: Basic Principles", IEEE Trans. Ultrason., Ferroelectr.,Freq. Control, vol. 39, pp. 489-495, (1992).

M. O'Donnell, ``Applications of VLSI circuits to medical imaging", Proc. IEEE, vol. 76, pp. 1106-1114, (1988).

M. O'Donnell et al., ``Real-time phased-array imaging using digital beamforming and autonomous channel control", 1990 IEEE Ultrasonics Symposium, pp. 1499-1502, (1990).

M. O'Donnell and L.J. Thomas, ``Efficient synthetic aperture imaging from a circular aperture with possible application to catheter-based imaging", IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control UFFC-39, pp. 366-380, (1992).

M. O'Donnell, B. M. Shapo, M. J. Eberle and D. Stephens, ``Experimental studies on an efficient catheter array imaging system", Ultrasonic Imaging 17, pp. 83-94, (1995).

D.K. Peterson and G.S. Kino, ``Real-time digital image reconstruction: A description of imaging hardware and an analysis of quantization errors", IEEE Trans. Sonics Ultrason., vol. SU-31, pp. 337-351,(1984).

Reid, J.M, and Wild, J.J., ``Current developments in ultrasonic equipment for mechanical diagnosis", in {Proc. Nat. Electronics Council}, vol. 12, pp. 44-58, 1956.

K. W. Rigby, C. L. Chalek, B. H. Haider, M. O'Donnell, R. S. Lewandowski, M. O'Donnell, L. S. Smith and D. G. Wildes, "Improved In Vivo Abdominal Image Quality Using Real-time Estimation and Correction of Wavefront Arrival Time Errors," 2000 IEEE Ultrasonics Symposium.

K. W. Rigby, "Real-time Correction of Beamforming Time Delay Errors in Abdominal Ultrasound Imaging," SPIE Medical Imaging 2000, February 12-18, 2000, San Diego, CA

B.J. Savord, “Beamforming methods and apparatus for three-dimensional ultrasound imaging using two-dimensional transducer array”, US Patent, no. 6,013,032, Jan. 11, 2000.

T.A. Shoup and J. Hart, ``Ultrasonic imaging systems", 1988 IEEE Ultrasonics Symposium, pp. 863-871, (1988).

S. W. Smith, G. E. Trahey, and O. T. von Ramm, ``Two dimensional arrays for medical ultrasound", Ultrasonic Imaging 14, 213-233 (1992).

J.C. Somer, ``Electronic sector scanning for ultrasonic diagnosis", Ultrasonics 6:153 - 159, (1968).

Bibliography

T.K. Song, and S.B. Park, ``A new digital phased array system for dynamic focusing and steering with reduced sampling rate", Ultrasonic Imaging, vol. 12, pp. 1-16, (1990).

B.D. Steinberg, Principles of Aperture and Array System Design, J. Wiley and Sons, New York, NY, (1976)

B.D. Steinberg, ``Digital beamforming in ultrasound", IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control UFFC-39, pp. 716-721, (1992).

R.H. Tancrell, J. Callerame, and D.T. Wilson, ``Near-field, transient acoustic beamforming with arrays", 1978 Ultrasonics Symposium Proceedings, pp.339-343, IEEE 78CH1344-ISU, (1978).

K.E. Thomenius, "New Directions for beamformation in medical ultrasound," Proc. SPIE, vol. 3664, San Diego, CA, 1999.

F.L. Thurstone and O.T. von Ramm, ``Electronic beam steering for ultrasonic imaging" in {Ultrasound in Medicine}, ed. M. deVlieger et al. pp. 43 - 48, American Elsevier Publishing Co., New York (1974).

P. Tournois, S. Calisti, Y. Doisy, J.M. Bureau, F. Bernard, "A 128*4 channels 1.5D curved Linear array for medical imaging", Proc. of 1995 IEEE Ultrasonics Symposium, pp.~1331-1335.

O.T. von Ramm and F.L. Thurstone, ``Thaumascan: Improved image quality and clinical usefulness", in {Ultrasound in Medicine}, vol. 2, p. 463, Plenum Press, NY, NY, (1970)

J.T. Walker and J.D. Meindl, ``A digitally controlled CCD dynamically focused phased array", 1975 Ultrasonics Symposium, pp. 80-83, (1975).

P. K. Weber, R. M. Schmitt, B. D. Tylkowski, J. Steck, ``Optimization of random sparse 2-D transducer arrays for 3-D electronic beam steering and focusing," in Proc. 1994 IEEE Ultrason. Symp., pp 1503-1506.

D. Wildes, et al., ``Elevation performance of 1.25D and 1.5D transducer arrays", IEEE Trans. UFFC, vol. 44, pp. 1027 - 1037, 1997.

J. Wright, ``Resolution issues in medical ultrasound", 1985 IEEE Ultrasonics Symposium Proceedings, IEEE 85CH 2209-5, pp. 793-799 (1985).

J.T. Ylitalo and H. Ermert, ``Ultrasound synthetic aperture imaging: monostatic approach", IEEE Trans. Ultrason., Ferroelectr.,Freq., Control, vol. 41, pp. 333-339, (1994)