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
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 Organization
Beamformer Functions

Receive beamformation block diagram

Three basic functions:
• Delay generation, dynamic and steering delays
• Apodization
• Summing of all delay signals
Interpolator Block Diagram

Diagram details:

- Coarse Delay Control
  - Input from ADC at 20 to 40 MHz, 8 to 12 bits
- FIFO
  - \( H_o(\omega) \)
  - \( H_o(\omega)e^{-j\omega s/4} \)
  - \( H_o(\omega)e^{-j\omega s/2} \)
- MUX
- Fine Delay Control
  - To apodization and further processing
  - Output with delay accuracy up to 160 MHz
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

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Trends in Ultrasound Beamformation
Kai E Thomenius, Ph.D.
Transmit Vectors and Focal Zones

Image formation using transmits along vectors and focal zones

Multiple transmit focal zones

Transmit vector
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, $\theta$, 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

For beam steering:

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

Transmit Focus
Beam # 0 1 2

Transmit Focus Beam n
Beamformation: the movie

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5.0MHz 1-D linear array – beam focused at 5 cm
Still images from pulsing sequence
5.0MHz 1-D linear array – beam focused at 5 cm
Resolution / Penetration Dilemma

Transmit Energy Determines Penetration

Pulse Amplitude

Mechanical Index Limit

Longer pulse gains penetration but sacrifices resolution

Pulse Length
Coded Excitation

Transmitted Pulse Train

Received Pulse Train

Coded Excitation improves sensitivity without resolution tradeoff

- Sensitivity Increase

Decoder

Encoder
Coded Excitation - Experiment

Improve penetration by 3 cm with same resolution to -50 dB
### 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

\[ f\# = \frac{F}{D} \]

\[ bw = \frac{\lambda F}{D} = \lambda (f\#) \]

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 $V(x)$

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

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

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

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

\[
f(x, u, \omega) = \int V(x, \omega) \exp [jkxu] dS = F\{V(x, \omega)\}
\]
Narrowband far-field analysis

Think of an array as:
- infinite array of point sources
- confined by a \( \text{rect} \)-function

Apply spatial Fourier relation

Beam pattern is an infinite train of sinc-functions

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

\[
f(u) = F\{p(x)\} = F\{\text{rect}[L]\} \ast F\left\{\sum_{n=-\infty}^{n=\infty} \delta(x - nd)\right\}
\]

\[
f(u) = \sum_{m=-\infty}^{m=\infty} \text{sinc}\left[\left(\frac{\pi L}{\lambda}\right)\left(u - m \frac{\lambda}{d}\right)\right]\]
Narrowband far-field analysis

Illustration:
• 32 element array
• 3 MHz
• pitch $d = 0.4$ mm
• $\lambda = 0.51$ mm
• $L = N \cdot d = 13$ mm

NOTE: plot wrt to $u$!
Center beam is our main lobe.

Beamwidth:
• $\lambda / L$ u-units
Narrowband far-field analysis

Adjacent beams:
- grating lobes

Separation:
- $\lambda / d$ u-units

Beam steering:
- apply $\tau_s$ phase tilt

Danger!
- Grating lobes move w. main

Visible region:
- $\pm 0.707$ u-units or $\pm 45$ 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
  - $d \leq \frac{\lambda}{2}$

Other points:

- wideband case
- sparse arrays
Apodization

Same array:
- 32 element array
- 3 MHz
- pitch $d = 0.4$ mm
- $\lambda = 0.51$ mm
- $L = N \cdot d = 13$ mm

With & w/o Hanning weighting.
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

Under reasonable assumptions:
- SNR = 6b - 1.24 dB at the 4σ level
- The 4σ rule is probably violated.
- Hence greater SNR’s

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

$$\sigma_e^2 = \frac{\Delta^2}{12} = \frac{2^{-2b}}{12}$$
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
  • \( u(x,y,z) = \nabla \phi(x,y,z) \)

Such functions readily available.

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

This has led to the concept of spatial impulse response.

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

\[
\phi(\vec{r}, t) = \nu_n(t) \ast \int_S \delta \left( t - t_2 - \frac{\vec{r}_1 - \vec{r}_2}{c} \right) \frac{dS}{2 \pi |\vec{r}_1 - \vec{r}_2|}
\]

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

Closed form expressions exist.

Think of field response to $\delta$-function stimulus.

Pressure at any field point directly related.

Particle velocity at any field point related.

Differentiable transducer velocities can be used.

Field II is an excellent tool for analyzing ultrasound beams.

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

\[ p(\vec{r}, t) = -\rho_0 \frac{\partial \phi(\vec{r}, t)}{\partial t} = -\rho_0 \frac{\partial v_n(t)}{\partial t} \ast h(\vec{r}_1, t) \]
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 with velocity distribution at array.

We take the 2D FFT of it.

This amounts to splitting the source to plane waves.

\[ A_o(f_x, f_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} U(x, y, 0) \exp[-j2\pi(f_x x + f_y y)] df_x df_y \]

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

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

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

\[
\nabla^2 U + k^2 U = 0
\]

\[
A \left( \frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; z \right) = A_o \left( \frac{\alpha}{\lambda}, \frac{\beta}{\lambda} \right) \exp \left( j\frac{2\pi}{\lambda} \sqrt{1 - \alpha^2 - \beta^2} z \right)
\]
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.
Angular Spectrum, Operator splitting

Evolution type partial differential equation

\[ \frac{\partial u}{\partial z} = L_{total}[u] \]

\[ = L_{diff}[u] + L_{attn}[u] + L_{nonl}[u] \]

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

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

\( L_{total} \) 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 \( L_{nonl} \).
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:

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

![Graph showing BI-RADS codes and fundamental/harmonics cases](image)
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

Elevation
- 1D
- 1.25D
- 1.5D
- 1.75D
- 2D

Aperture
- Fixed
- Discrete
- Dynamic
- Dynamic
- Dynamic

Focus
- Static
- Static
- Dynamic, Symmetric
- Dynamic, No Symmetry
- 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

2D image

3D image

- 100 elements, electronical delay

- 50x50 -- 100x100 elements

sound beam

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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:
  • $60^\circ \times 60^\circ \times 12$ cm pyramid volume
  • $1^\circ$ beam spacing $\Rightarrow$ 3600 beams
  • $12$ cm x 2 / 1540 m/s = 160 $\mu$sec 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

- Transducer
- Fluid-Filled Housing
- Belt Drive
- Stepper Motor
- Cable Drive
- Cable

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
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
Migration of Beamformation to Handle

2D Transducer Array
(vs. human hair)

Modular Beamformer in Probe Handle
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, pulser, 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**
  - 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.

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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

"Active aperture"
128 elements
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

channel signal

Average phase difference over range gates...

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

Arrival time error \( \tau_{ij} = (2\pi f)^{-1} \text{Phase}\{C_{ij}\} \)
Time Delay Estimation

Arrival time error $\tau_i = (2\pi f)^{-1} \text{Phase}\left\{ \overline{C_i} \right\}$

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

GE LOGIQ 700 MR
Ultrasound Imager

Multirow Transducer

Interface Boards

Channel Data
Beamsum Data
640 MB/s

Time delay
Corrections
10.5 MB/s

Mercury
Multiprocessor
Computer

56 PowerPC
Processors
Liver with **Model Aberration**

**Uncorrected**  **Corrected**

**Arrival Time Error Estimates**

*Iteration 1*

*Iteration 2*

*Iteration 3*

*Iteration 4*

*Net Correction*

*Aberration*
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


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