Ultrasound Bioinstrumentation

Topic 2 (lecture 3)

Beamforming

CAIRO UNIVERSITY

Angular Spectrum

- 2D Fourier transform of aperture

$$A(f_X, f_Y; 0) = \iint_{-\infty}^{\infty} U(x, y, 0) \exp[-j2\pi(f_X x + f_Y y)]\, dx\, dy.$$

- A

$$U(x, y, 0) = \iint_{-\infty}^{\infty} A(f_X, f_Y; 0) \exp[j2\pi(f_X x + f_Y y)]\, df_X\, df_Y.$$

$$A\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; 0\right) = \iint_{-\infty}^{\infty} U(x, y, 0) \exp\left[-j2\pi\left(\frac{\alpha}{\lambda}x + \frac{\beta}{\lambda}y\right)\right] dx\, dy$$

Propagation of Angular Spectrum

$$A\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; z\right) = A\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; 0\right)\exp(-\mu z)$$

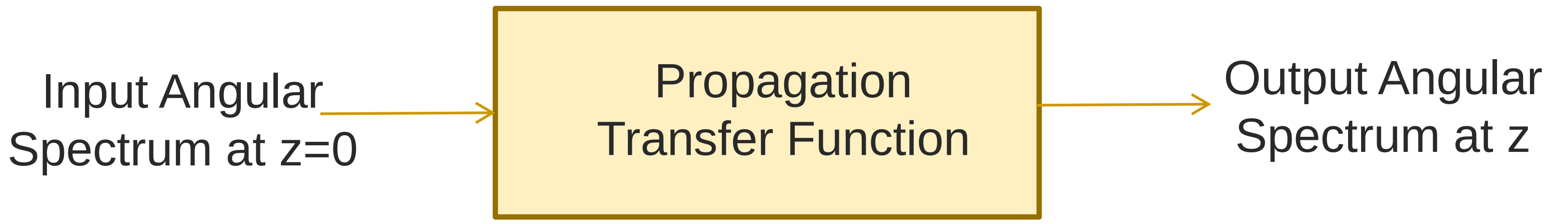
$$\mu = \frac{2\pi}{\lambda}\sqrt{\alpha^2 + \beta^2 - 1}.$$

Propagation as a Linear Spatial Filter

- Free space propagation transfer function

$$H(f_X, f_Y) = \begin{cases} \exp\left[j2\pi \frac{z}{\lambda} \sqrt{1 - (\lambda f_X)^2 - (\lambda f_Y)^2} \right] & \sqrt{f_X^2 + f_Y^2} < \frac{1}{\lambda} \\ 0 & \text{otherwise.} \end{cases}$$

$$\alpha = \lambda f_X \quad \beta = \lambda f_Y$$



Fresnel Approximation

- Paraxial (near field) approximation

$$\sqrt{1-(\lambda f_X)^2-(\lambda f_Y)^2} \approx 1-\frac{(\lambda f_X)^2}{2}-\frac{(\lambda f_Y)^2}{2},$$

$$H(f_X, f_Y) = e^{jkz} \exp\left[-j\pi\lambda z\left(f_X^2+f_Y^2\right)\right].$$

$$h(x, y) = \frac{e^{jkz}}{j\lambda z} \exp\left[\frac{jk}{2z}\left(x^2+y^2\right)\right].$$

Fraunhofer Approximation

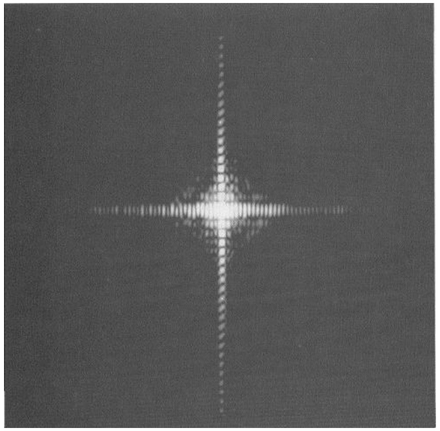
- Far field approximation

$$z \gg \frac{k(\xi^2 + \eta^2)_{\max}}{2}$$

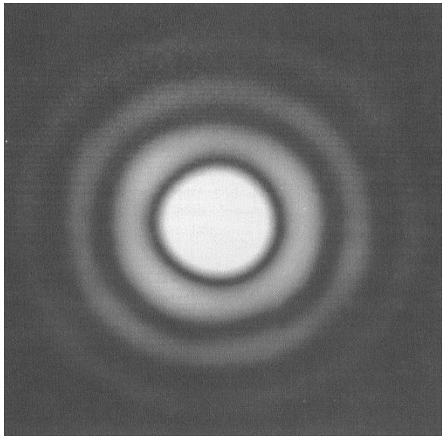
$$U(x, y) = \frac{e^{jkz} e^{j\frac{k}{2z}(x^2+y^2)}}{j\lambda z} \iint_{-\infty}^{\infty} U(\xi, \eta) \exp\left[-j\frac{2\pi}{\lambda z}(x\xi + y\eta)\right] d\xi \, d\eta.$$

Examples

- Rectangular aperture



- Circular aperture



Examples

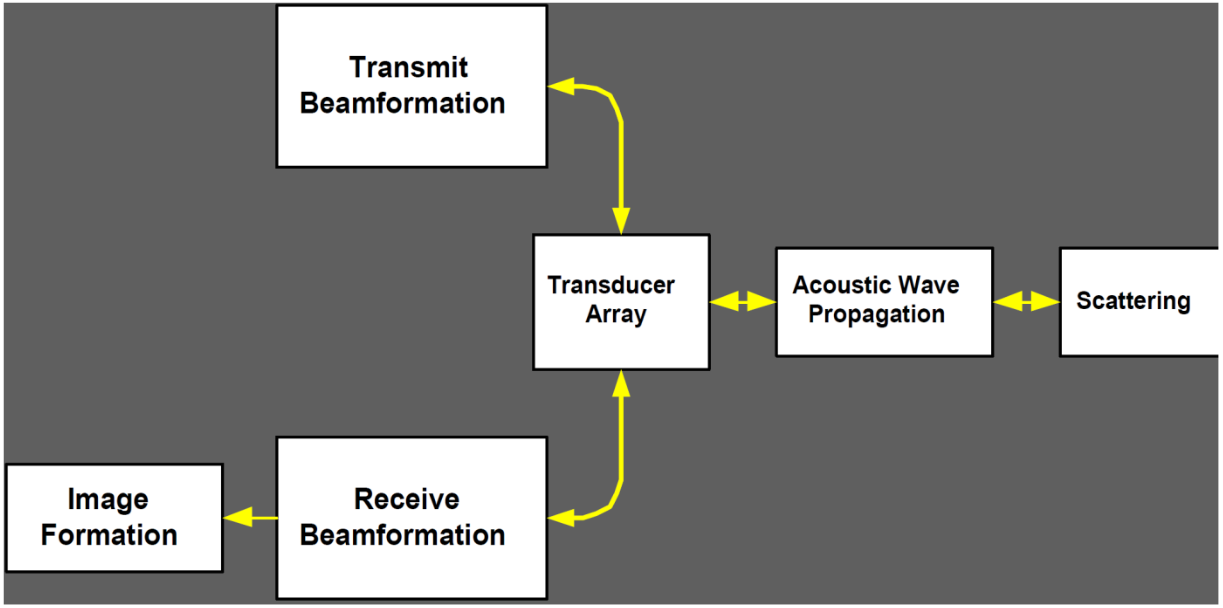
- Array transducer
  - Separable
  - Solve two 1D problems

Field Calculation in Ultrasound

- Narrowband far-field analysis
  - Totally unrealistic model
  - Amazingly useful results
  - will be used to introduce key points
- Wideband analysis
  - Calculate at multiple wavelengths
  - Weighted sum based on frequency spectrum of pulse
- Research field calculation software
  - Field II (free)
  - PiezoFlex (commercial)

Beamformer: Role in an Imager

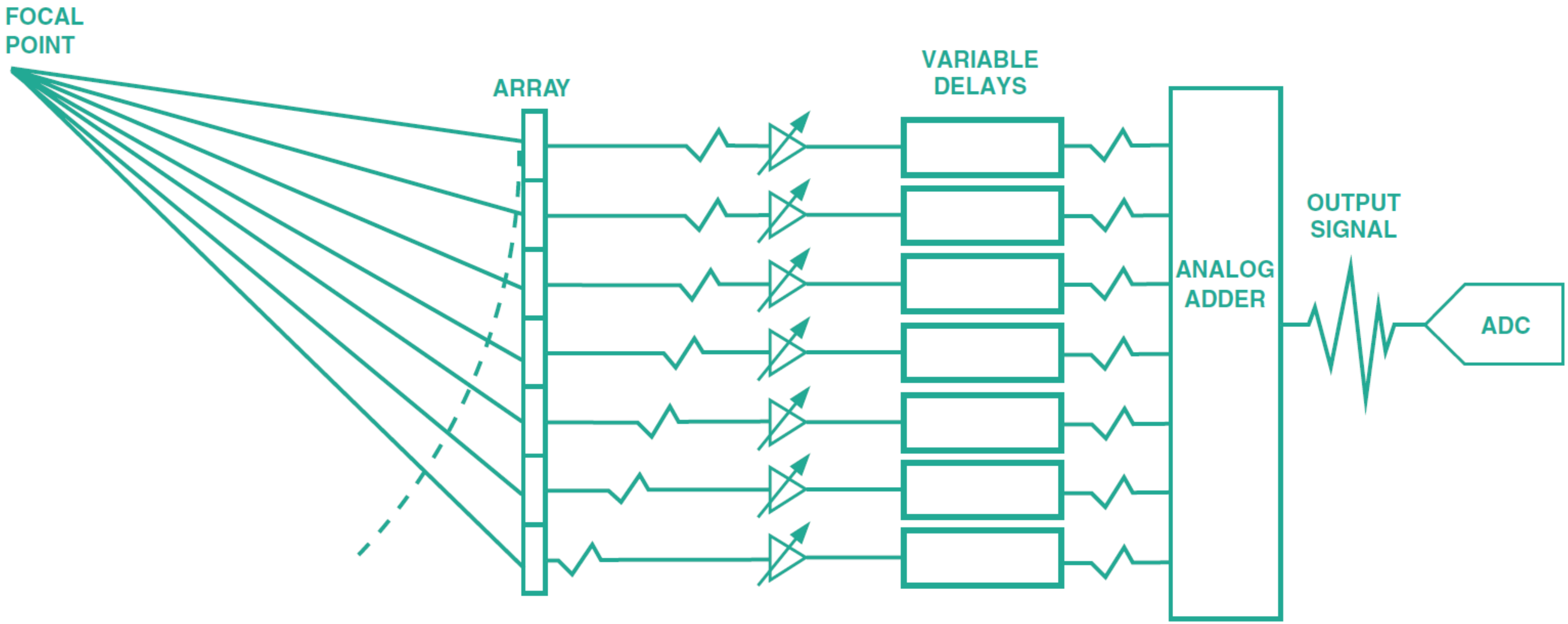
- Perhaps the most important building block.
  - Soul of the machine?
- Probably the most expensive building block.
  - 30 -50% of parts & labor of a scanner



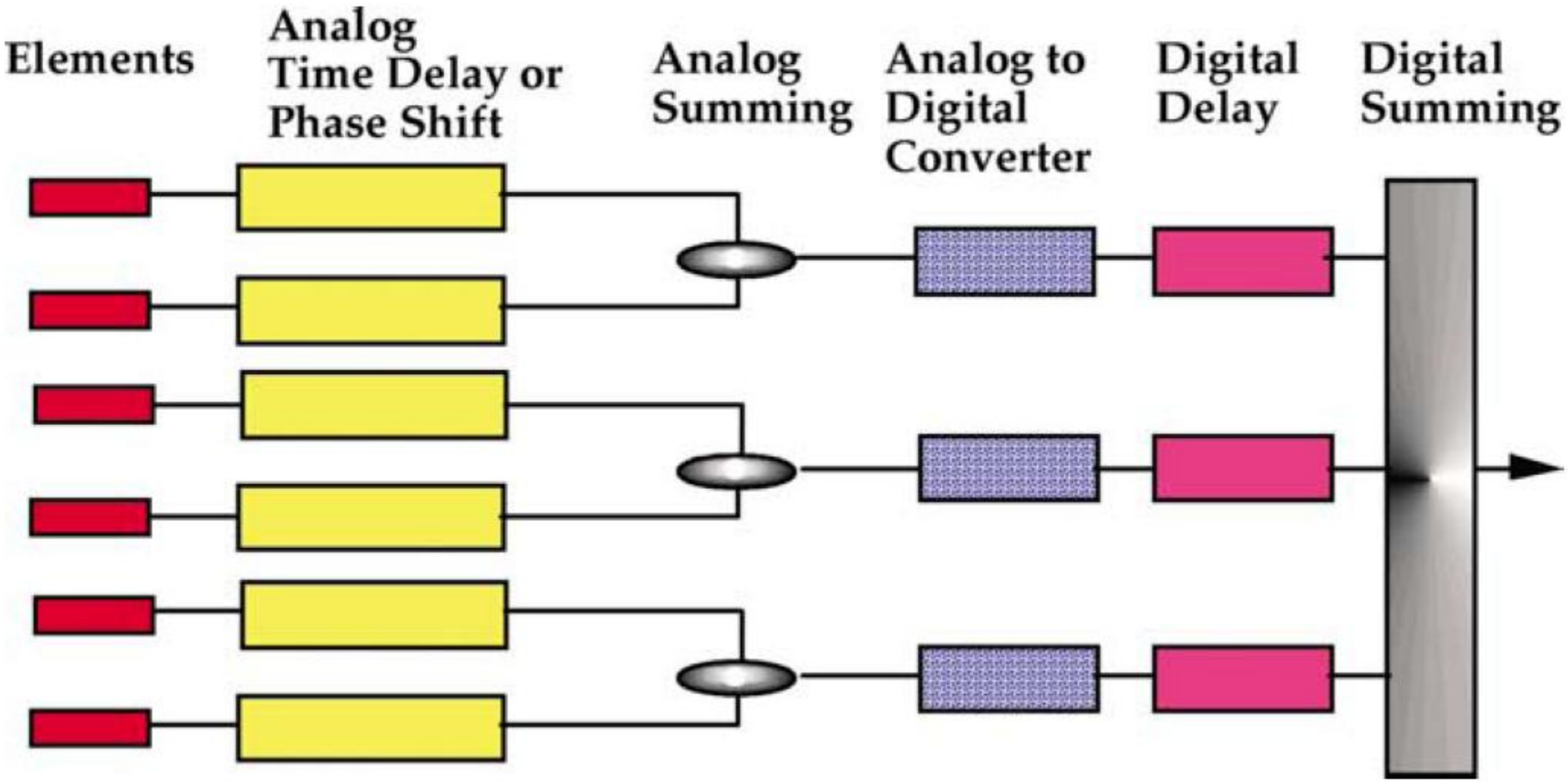
Beamformer History

- Before the mid-70s
  - Single element scanners, no beamformer necessary
- 1975 -1980
  - Array based systems
  - Analog beamformation
  - Typically 32 channels
- Mid 1980s
  - High channel count systems (High = 128)
- Early 90s
  - Digital beamformation

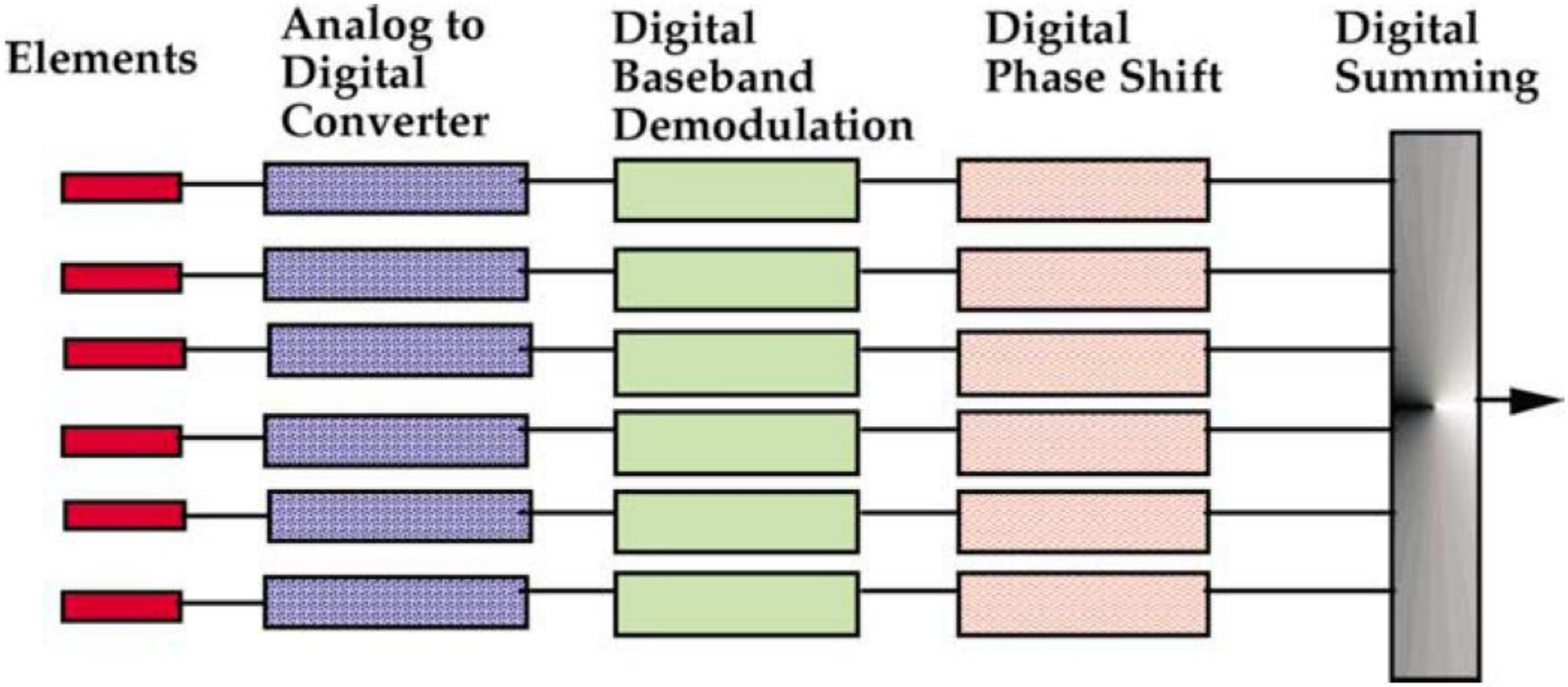
Analog Beamformer



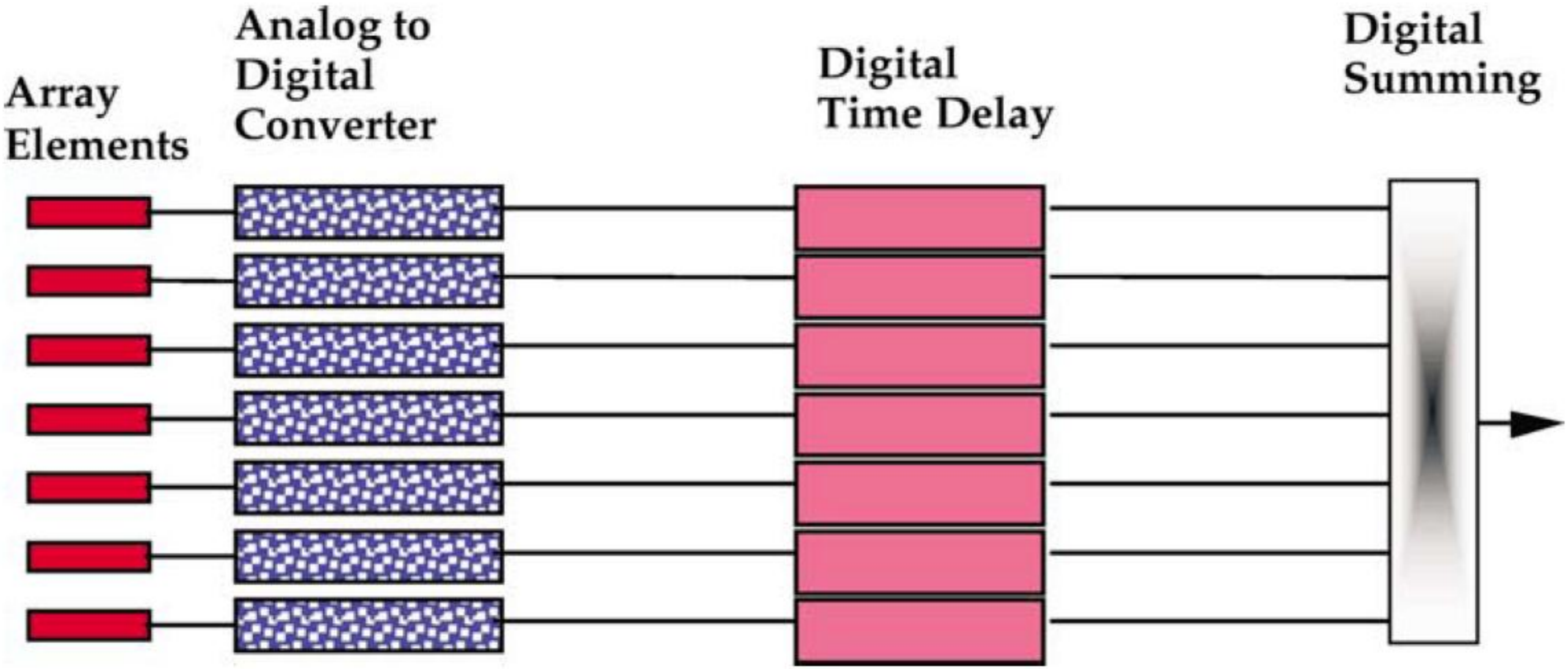
Hybrid Analog/Digital Beamformer



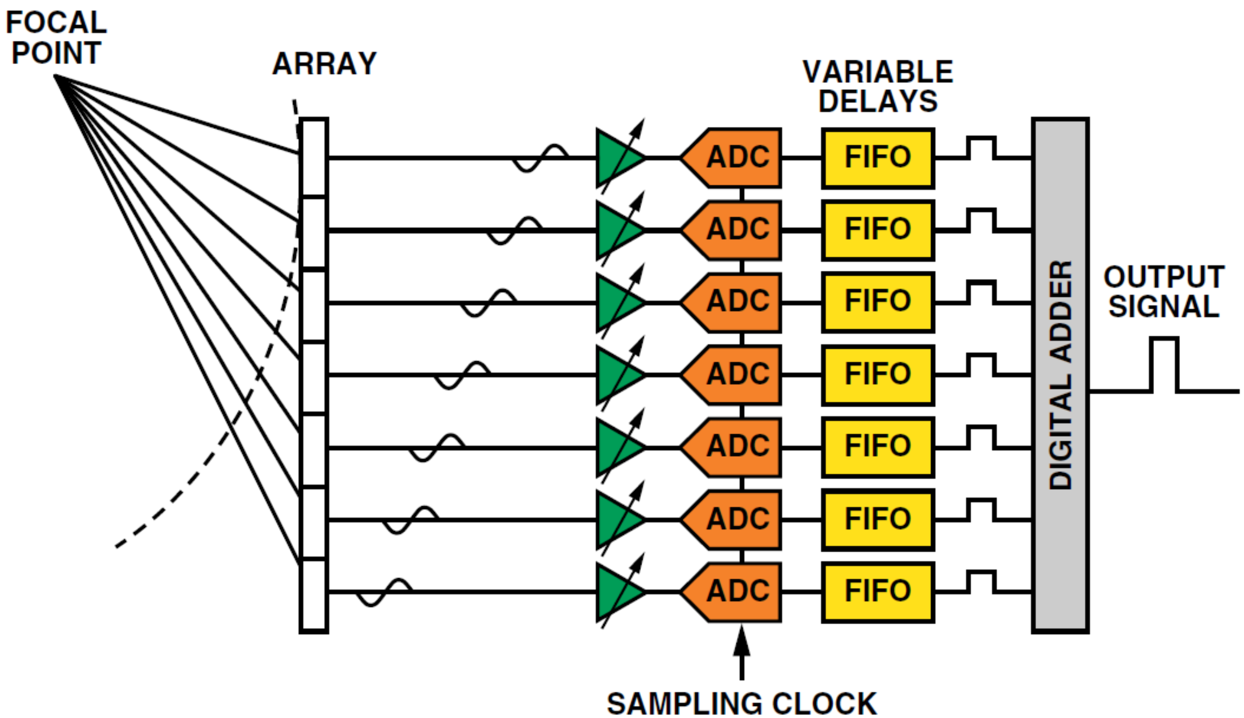
Digital Beamformer with Phase Shift

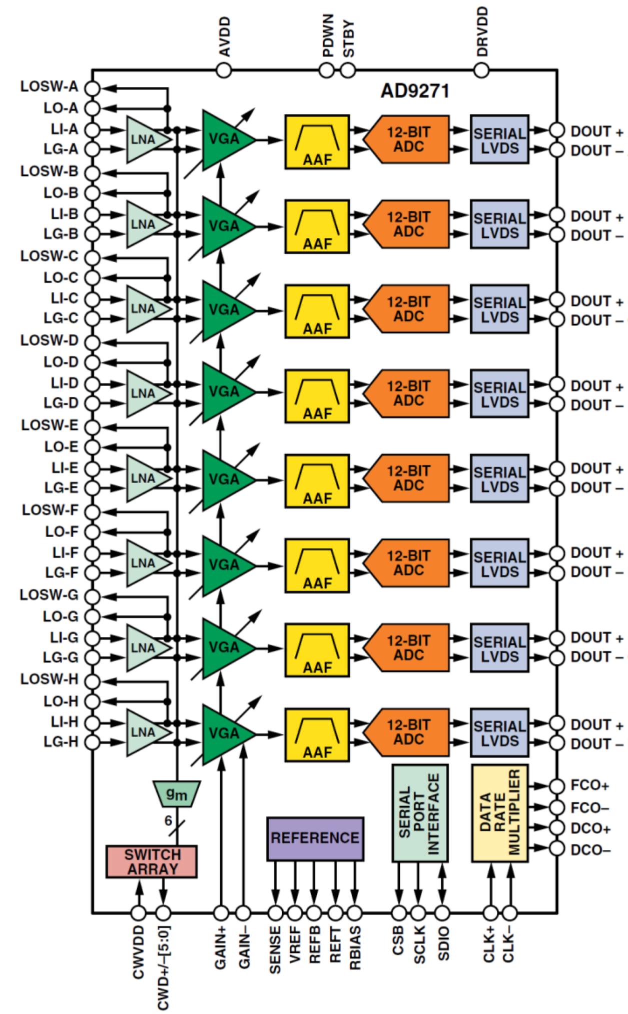


True Digital Beamformer



Digital Beamformer Hardware

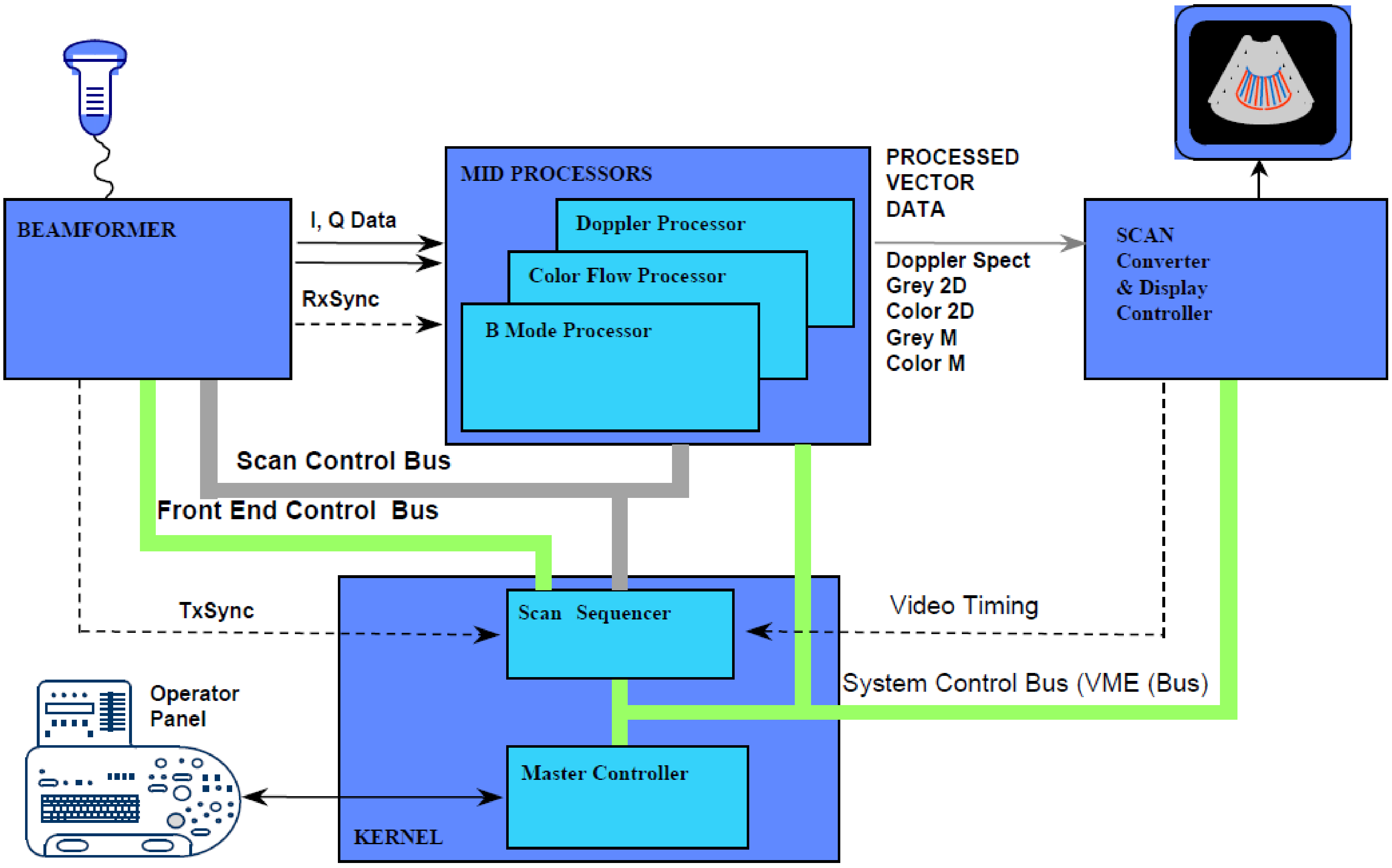




Acoustic Wave Propagation

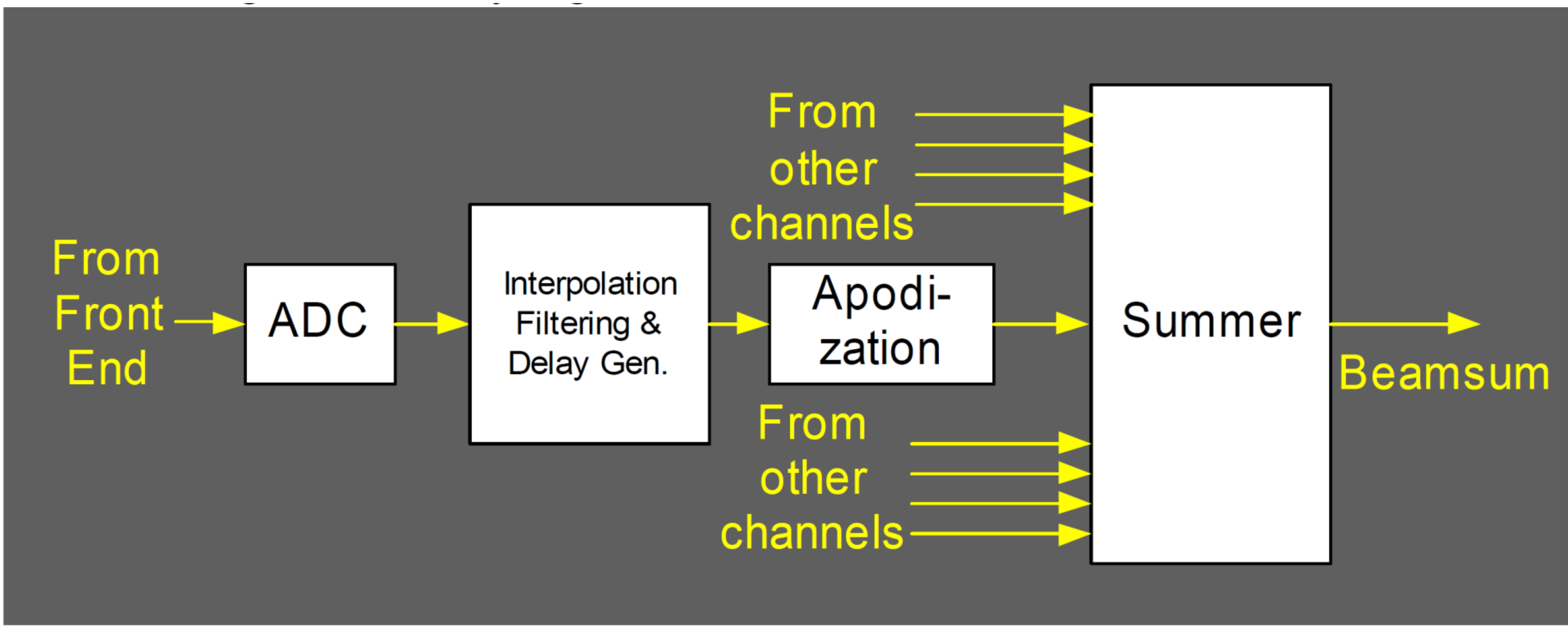
- Transmit voltages are typically in order of 100 V.
- These create pressures of appr. several 100 KPa.
- Typical tissue attenuation: 0.5 dB/(cm MHz)
  - Example: 10 cm penetration @ 5 MHz –25 dB one-way
- Backscatter from tissues -< 10% of incident pressure
- Transducer conversion efficiency –50 –75%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

Typical System Organization

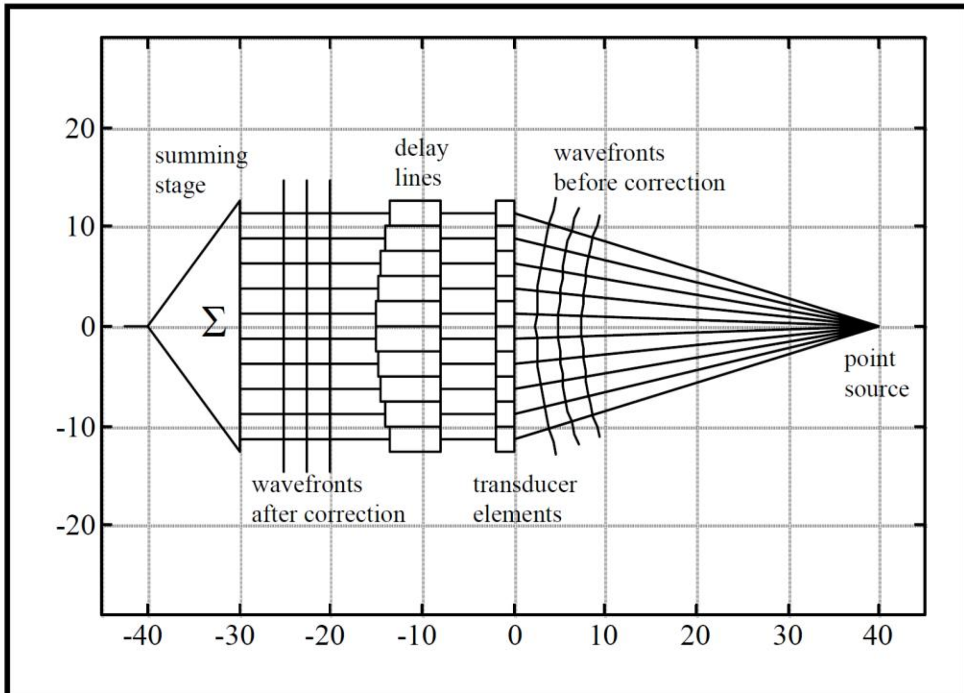


Receive Beamformer Functions

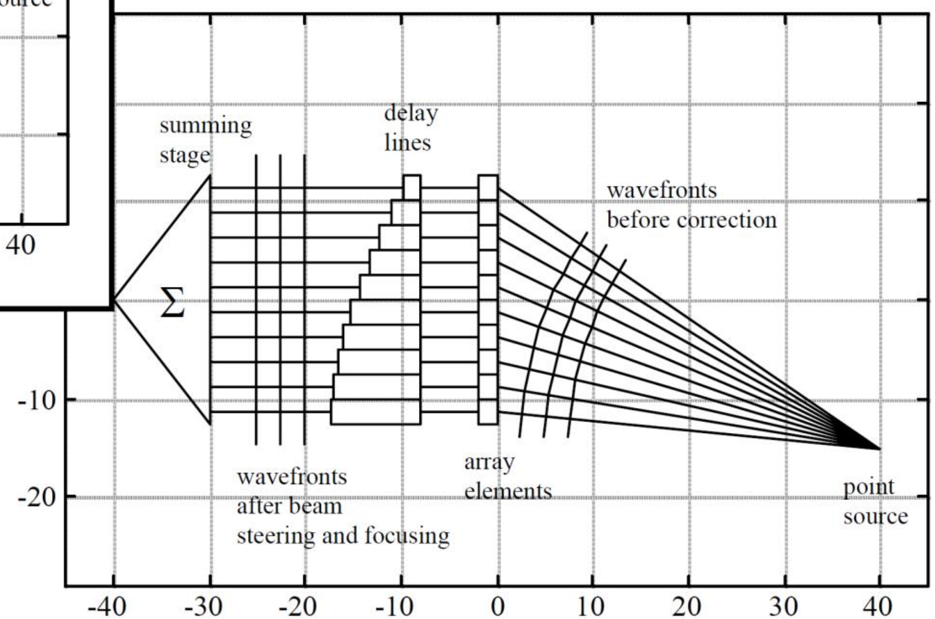
- Delay generation, dynamic and steering delays
- Apodization
- Summing of all delayed signals



Focusing and Steering Delays

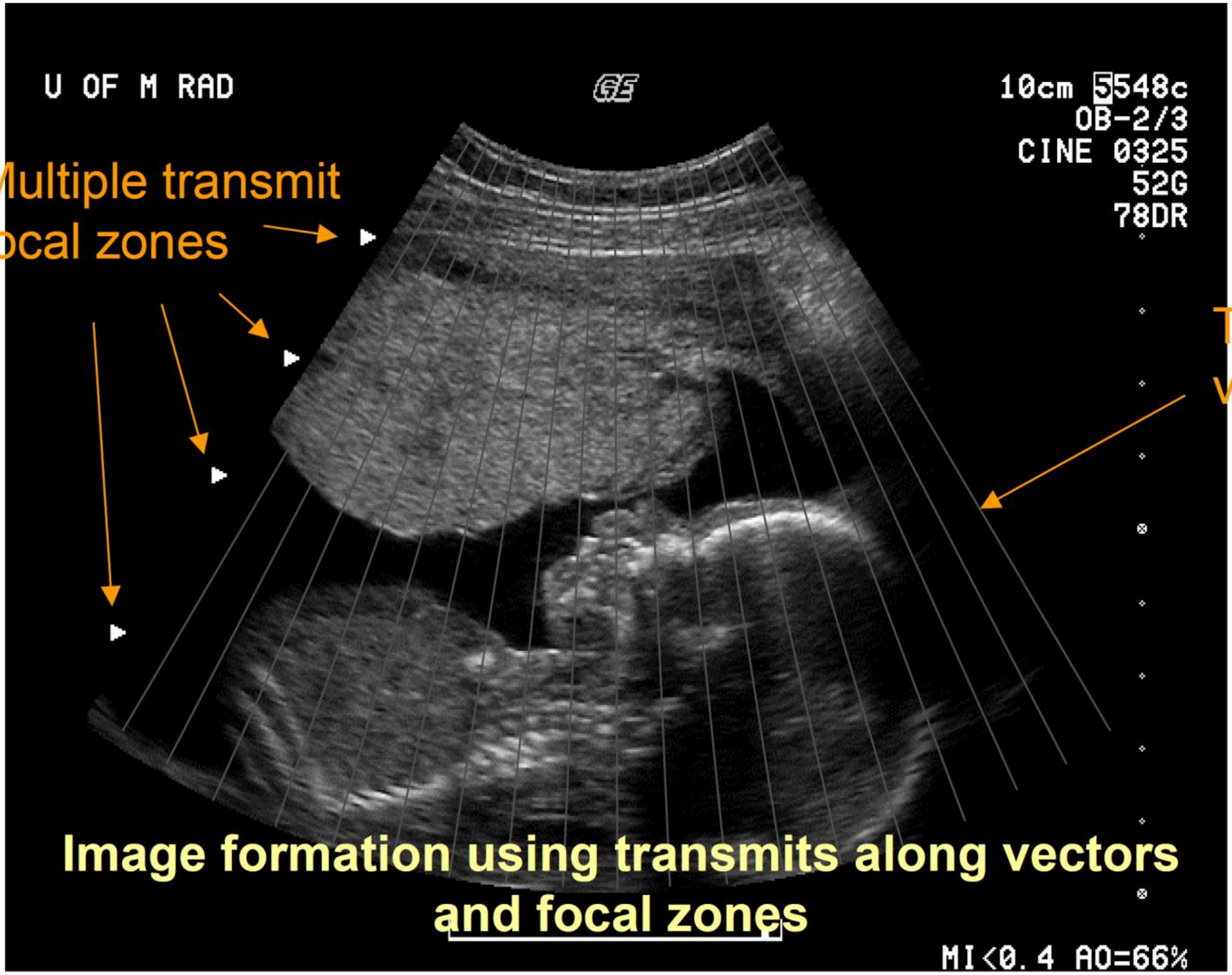


- Basic focusing type beamformation
- Symmetrical delays about phase center.



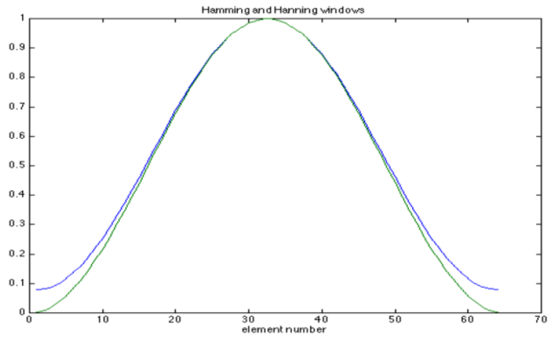
- Beam steering w. linear phased arrays.
- Asymmetrical delays, long delay lines

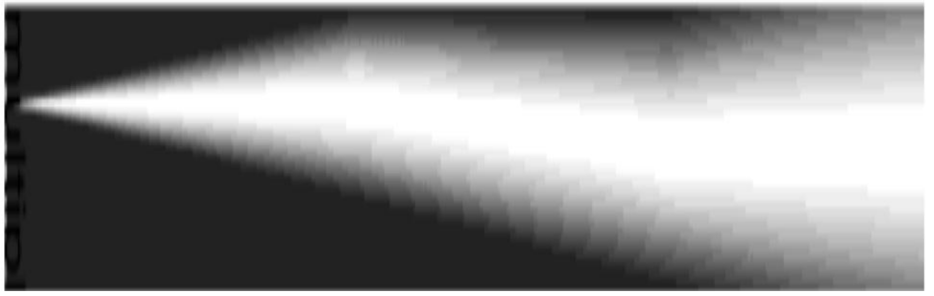
Transmit Vectors and Focal Zones



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.



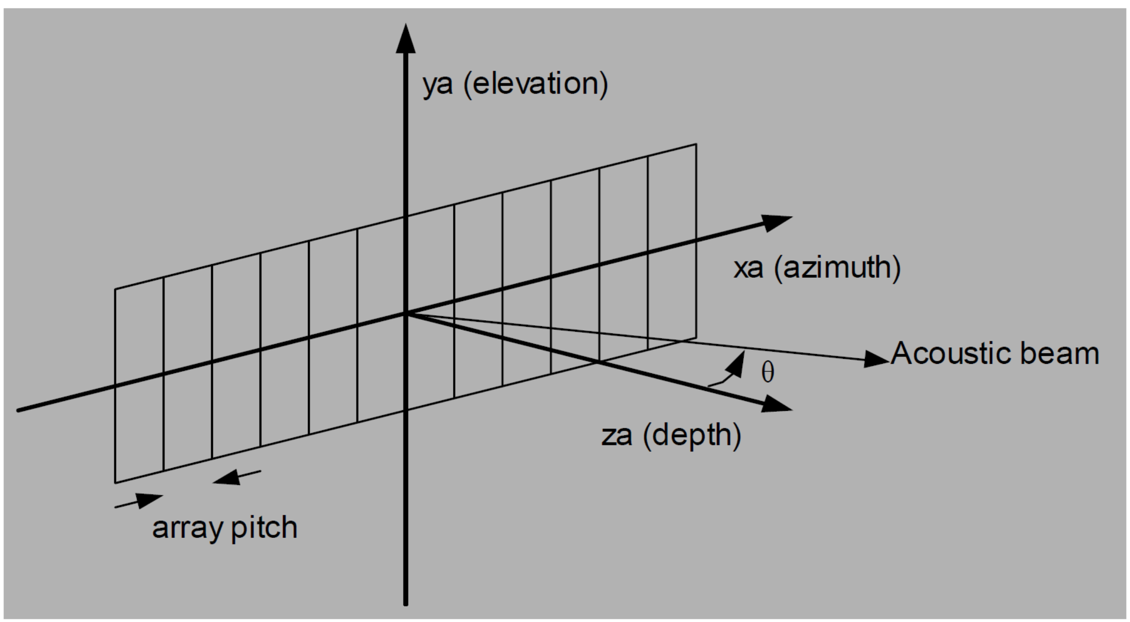


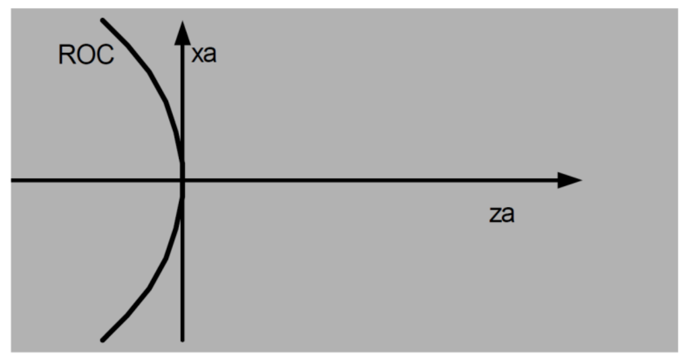
Types of Arrays and Beamformers

- Linear array beamformer
  - Generation of focusing delays
  - Beam steering by element selection
- Curvilinear array beamformer
  - Generation of focusing delays
  - Beam steering by element selection
- Phased array beamformer
  - Generation of focusing delays
  - Beam steering by phasing

Array Geometries

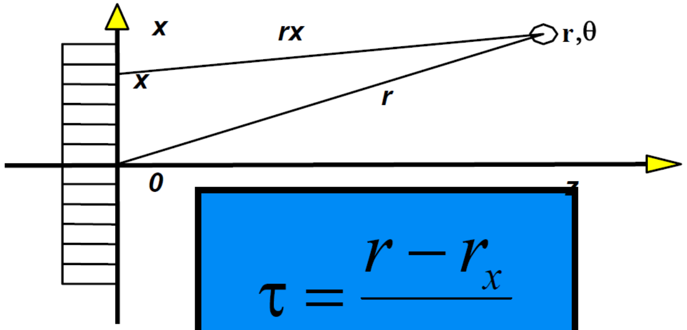
- Definition of azimuth, elevation
- Scanning angle shown, θ, in negative scan direction.
- Similar definitions for a curved array





Delay Calculation from 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

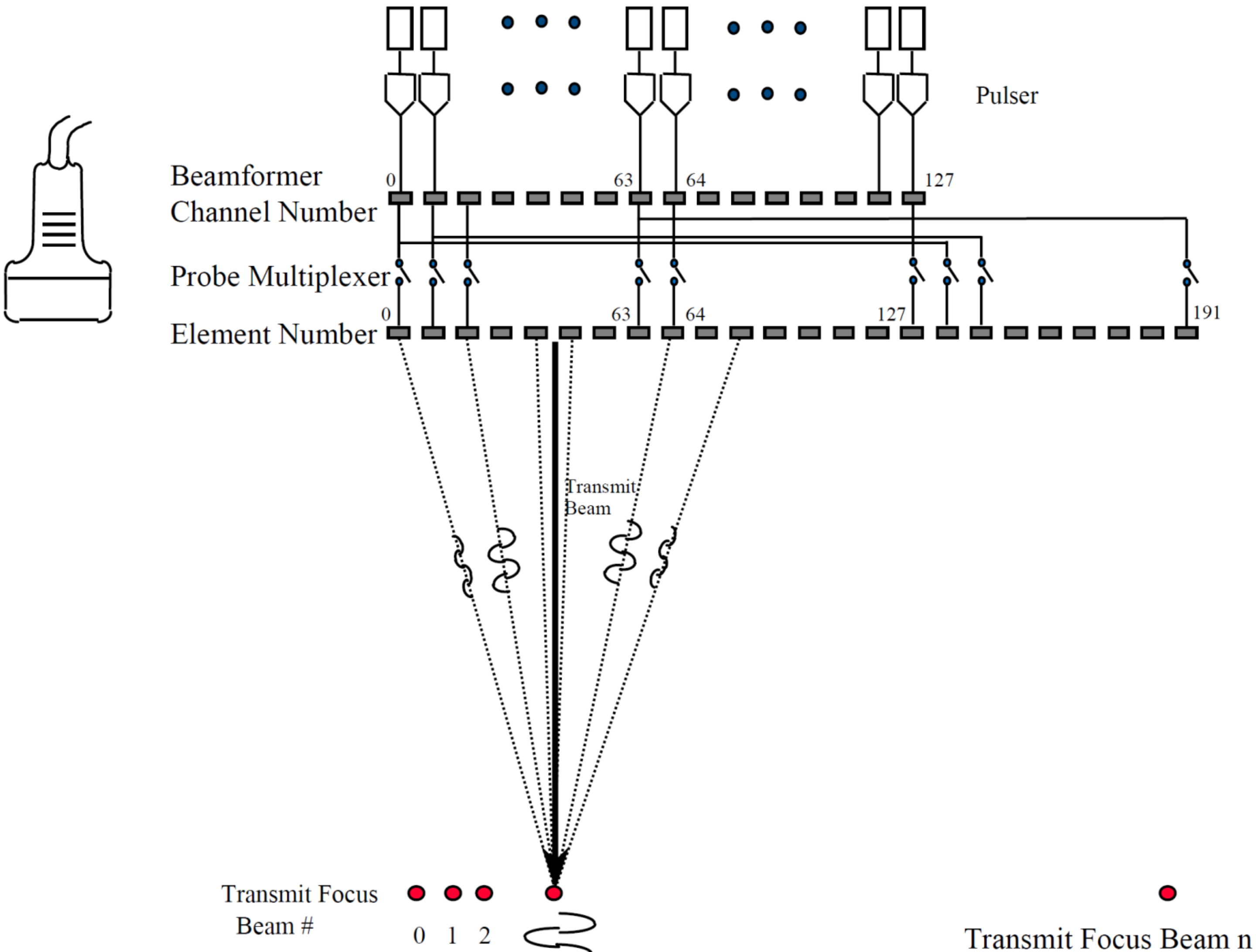


$$\tau = \frac{r - r_x}{c}$$

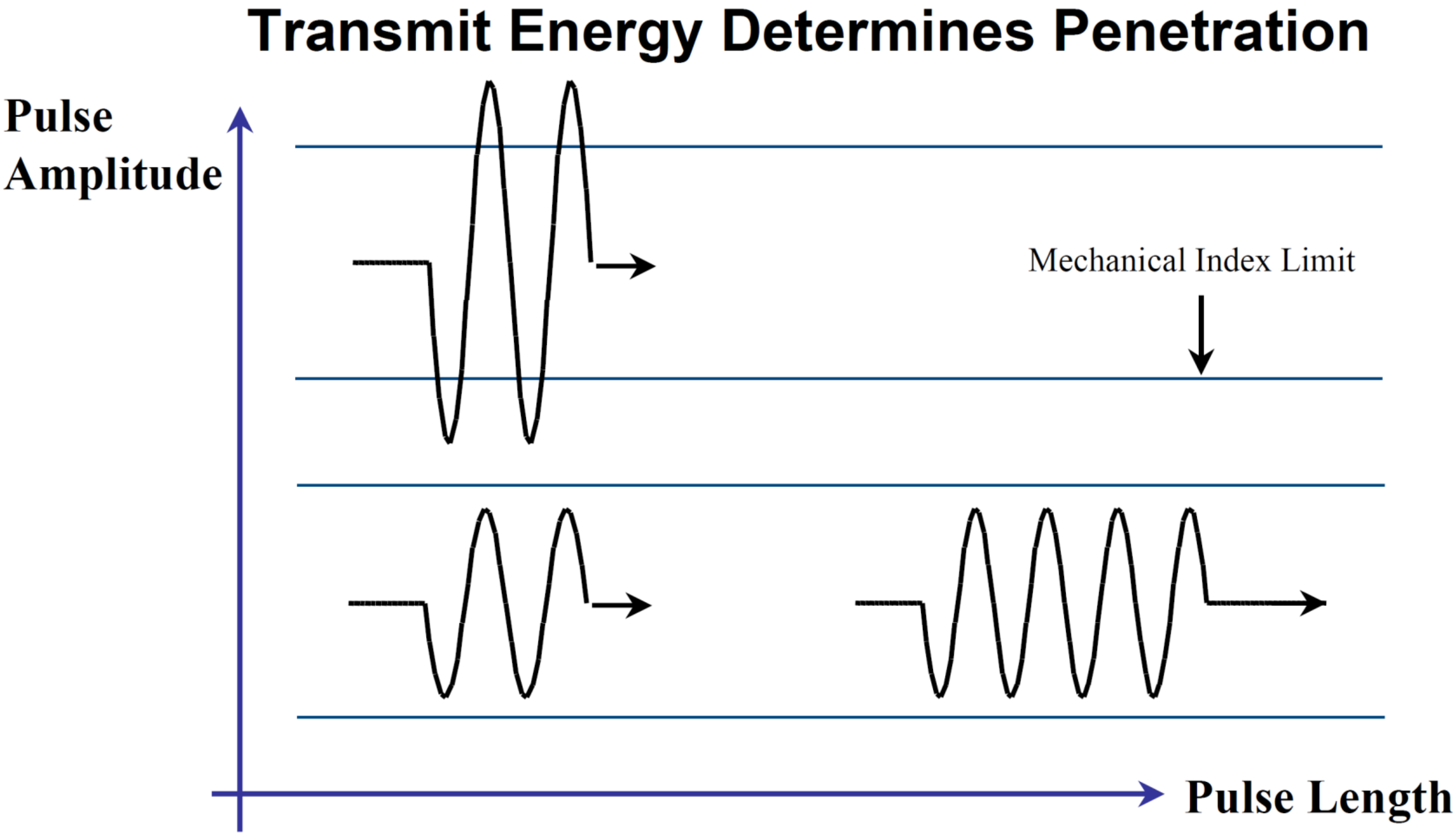
$$\tau = \frac{1}{c}\left[\sqrt{x^2 - 2rx\sin(\theta) + r^2} - r\right]$$

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

Transmit Beamforming

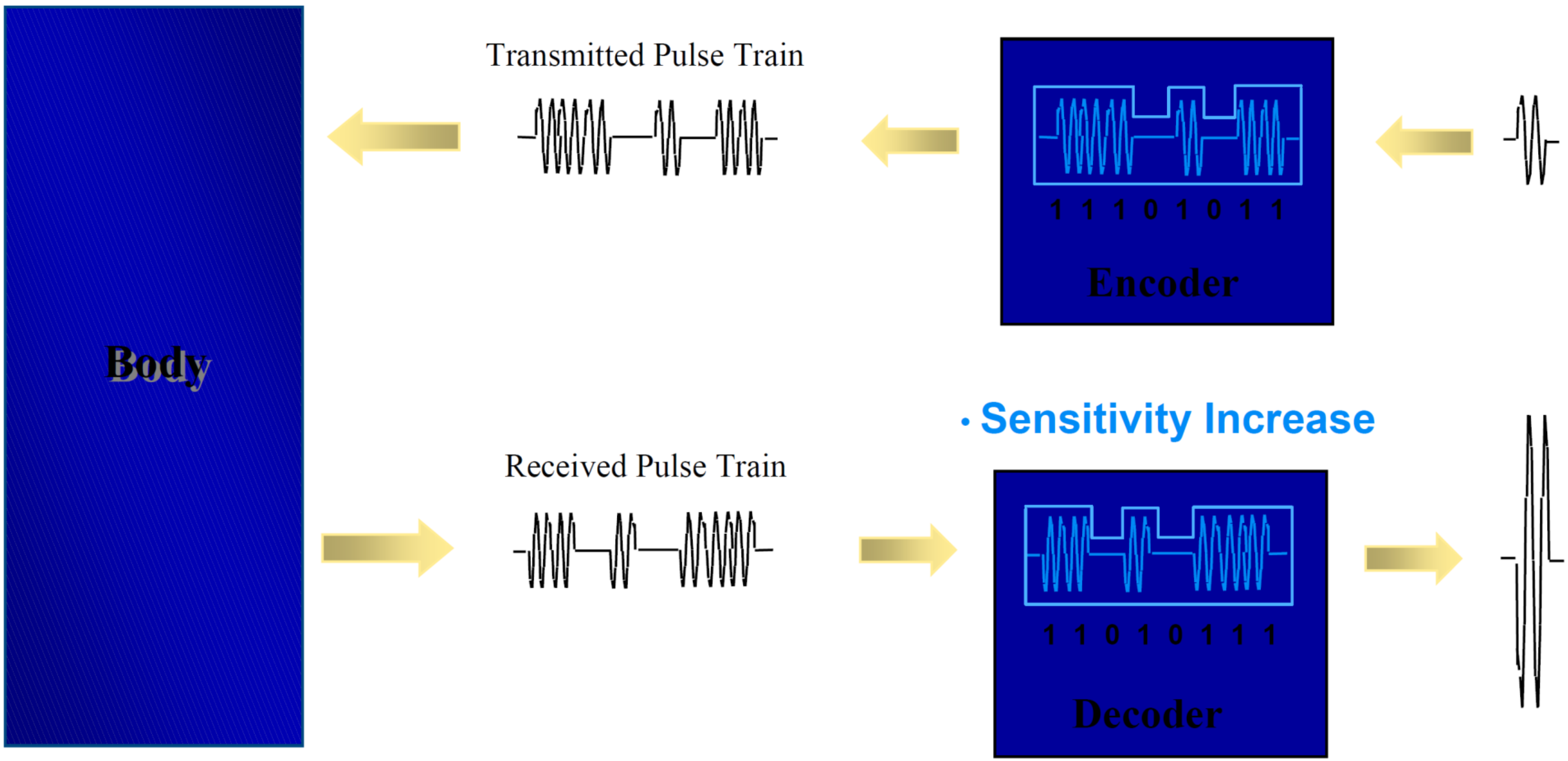


Resolution / Penetration Dilemma



Longer pulse gains penetration but sacrifices resolution

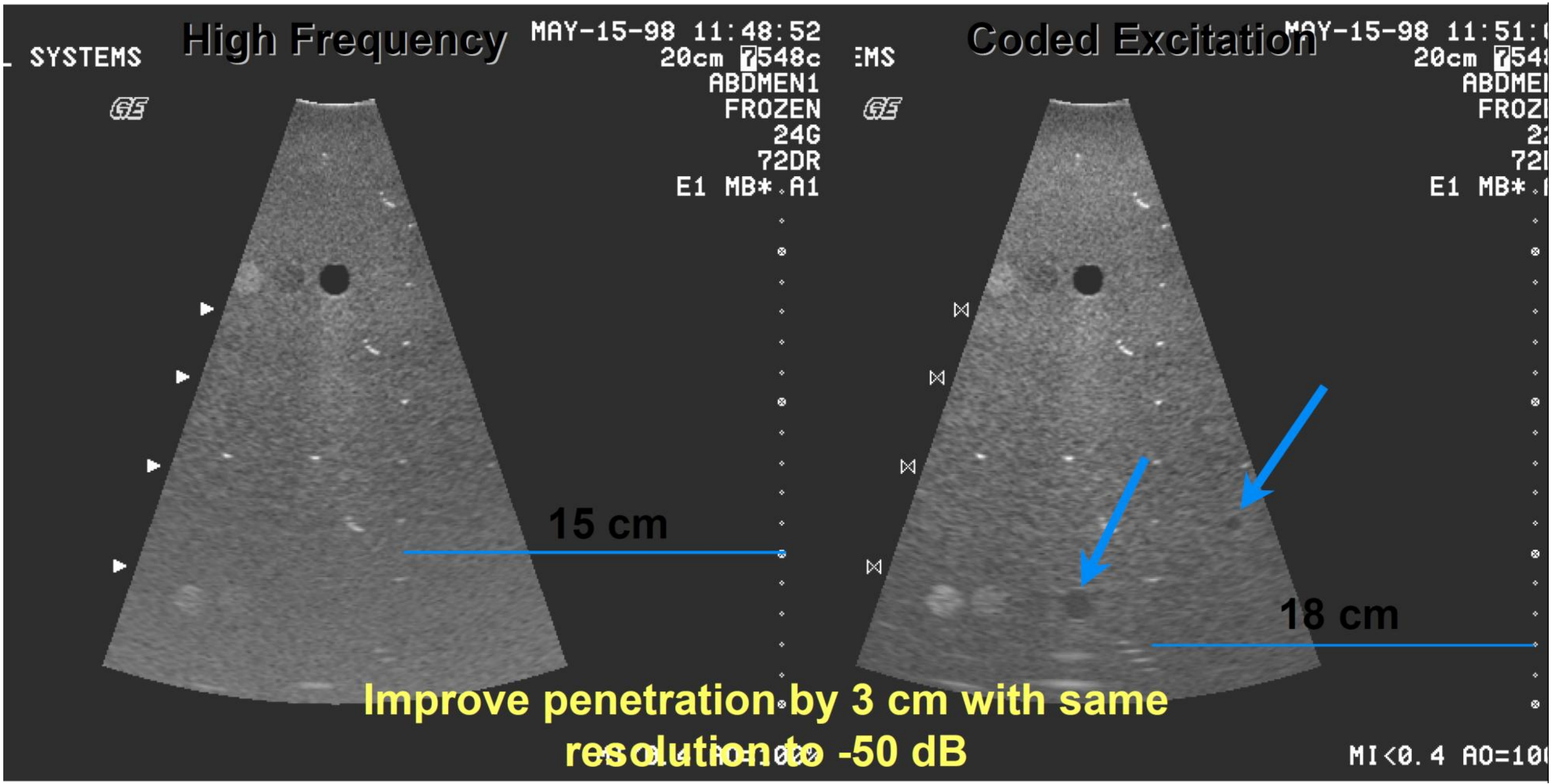
Coded Excitation



- Sensitivity Increase

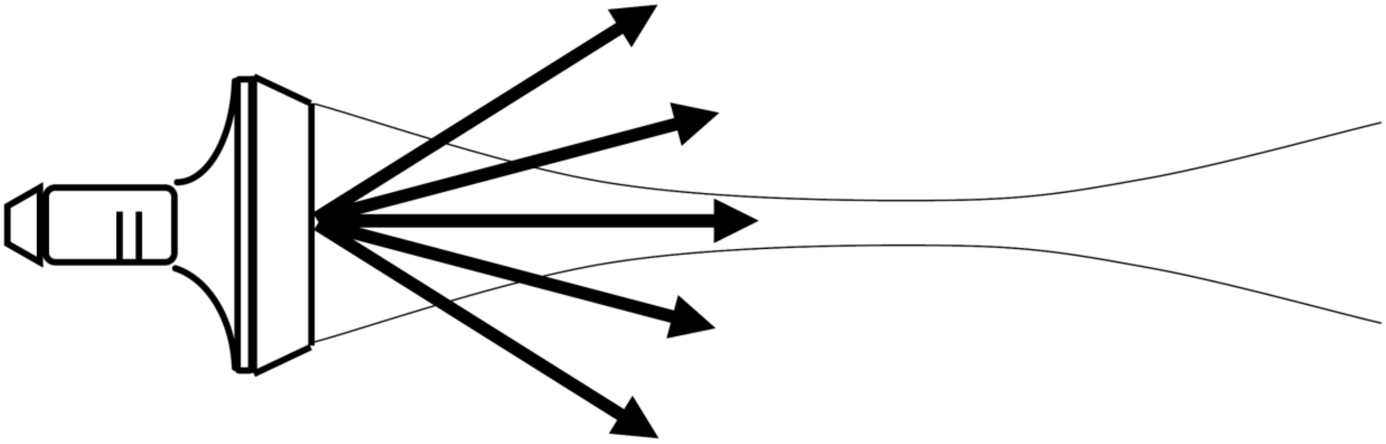
Coded Excitation improves sensitivity without resolution tradeoff

Coded Excitation: Example



Beam Compounding

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

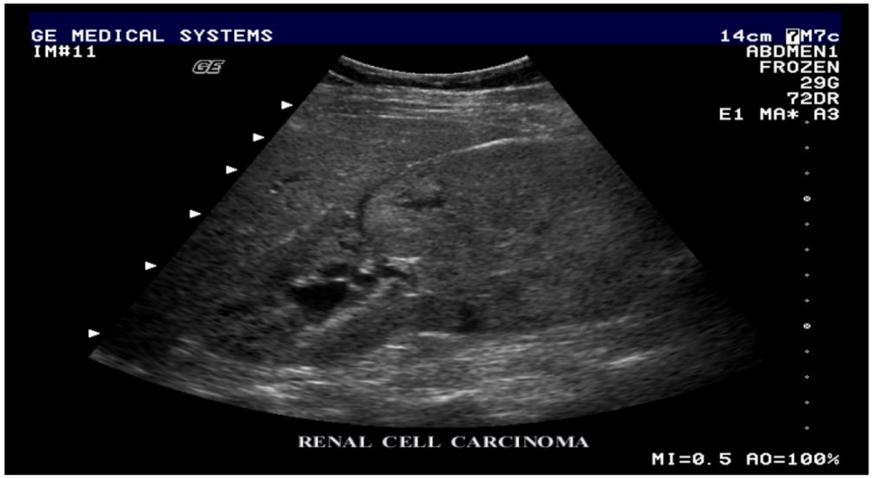


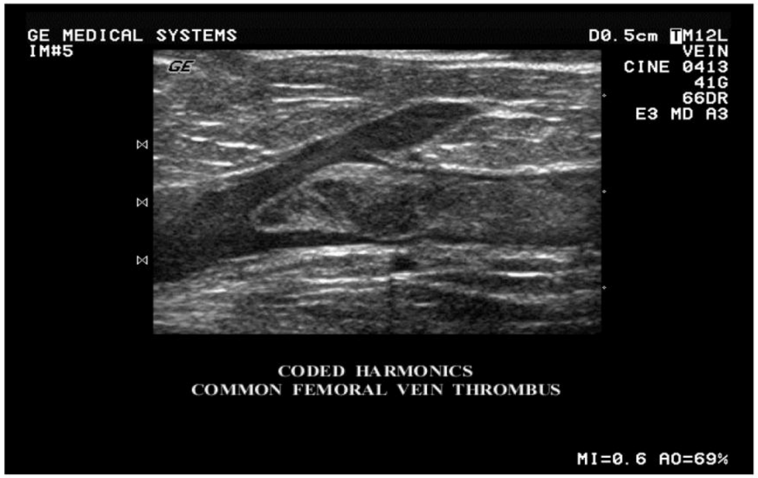
Targets of Ultrasound Imaging

- 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

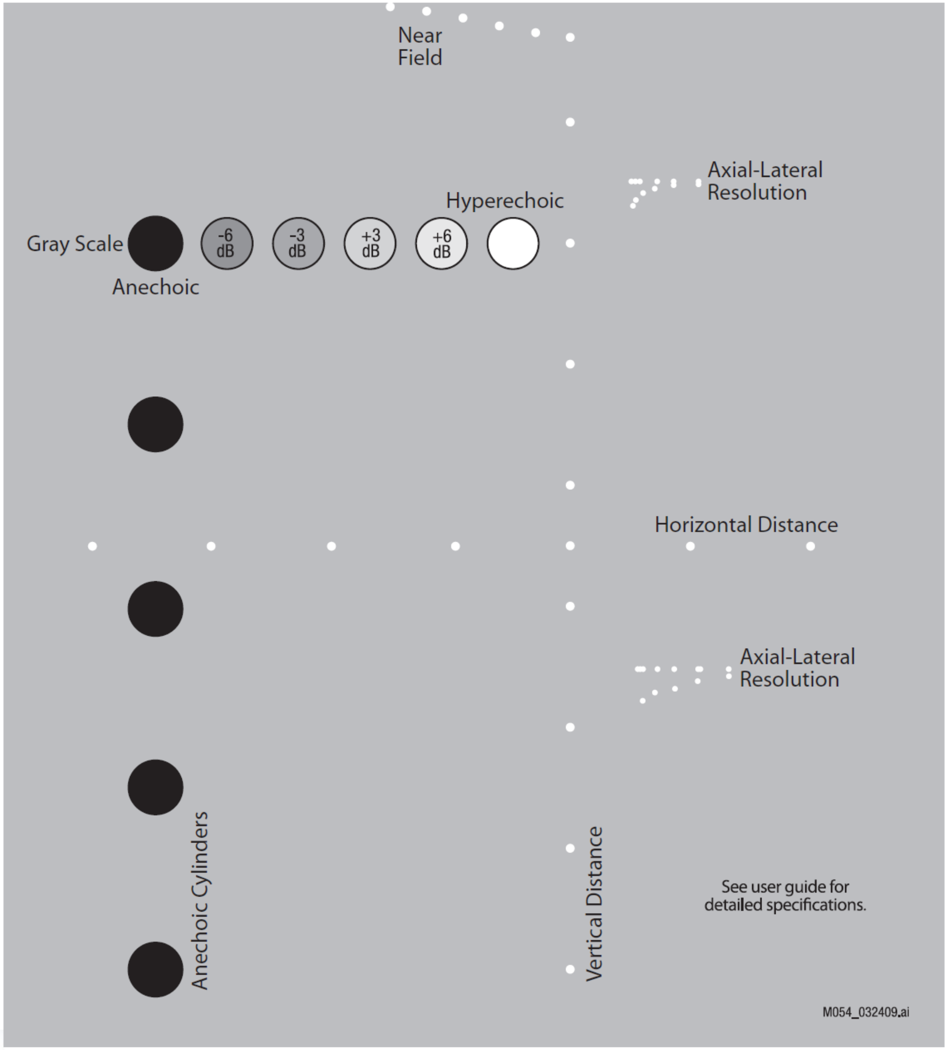
Quality Measures

- Image uniformity
  - large depth of penetration
  - reasonably uniform tissue texture
- Ability to bring out subtle changes.
  - minimal beam distortion
  - minimal reverberant noise





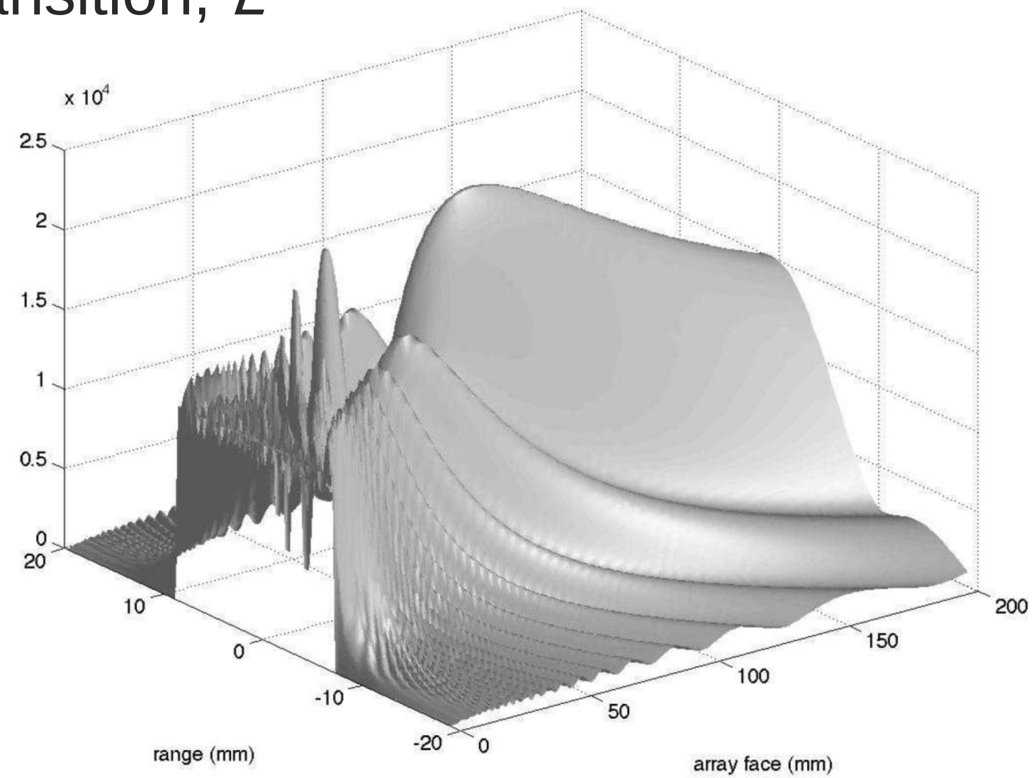
Quality Control Phantoms



Anatomy of an Ultrasound Beam

- Near field or Fresnel zone
- Far field or Fraunhofer zone
- Near-to-far field transition, *L*

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

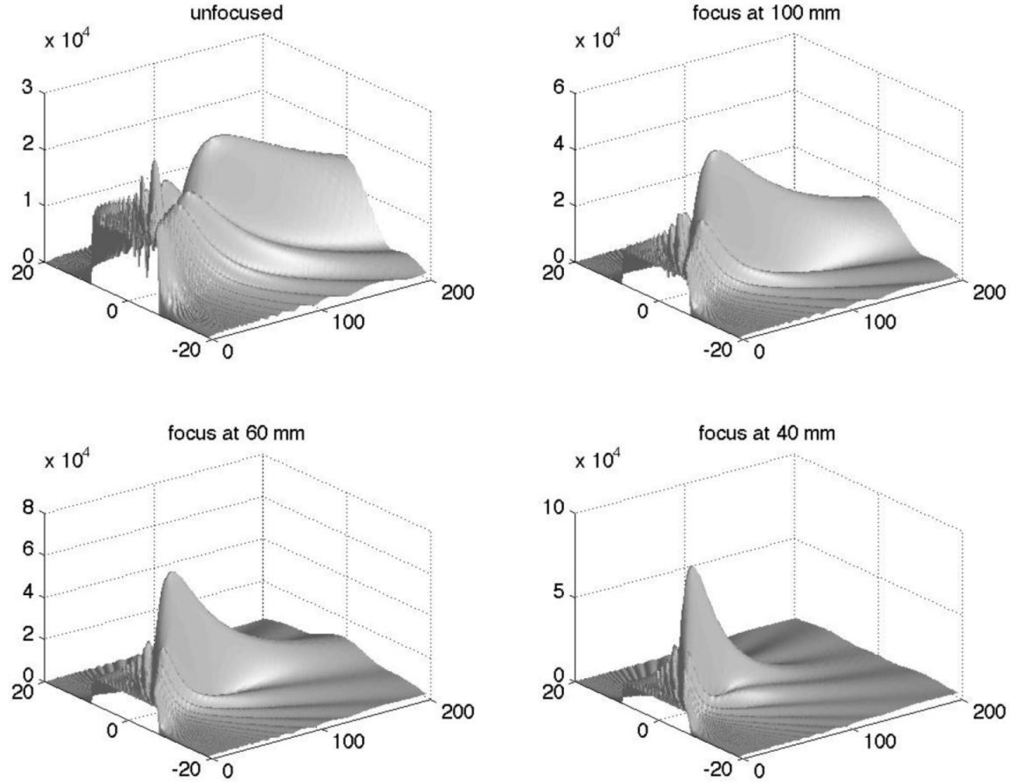


Anatomy of an Ultrasound Beam

- Spatial resolution, beamwidth
- Depth of field (DOF)
- F-number

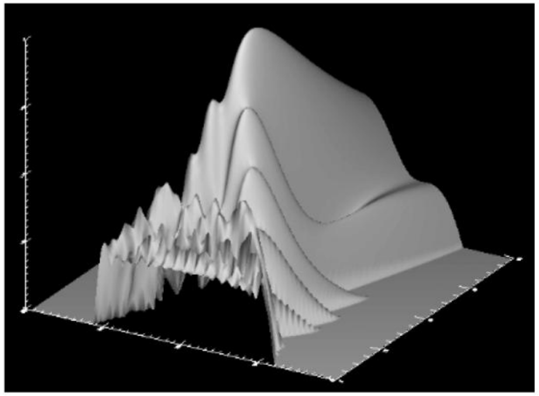
$$f\# = \frac{F}{D}$$

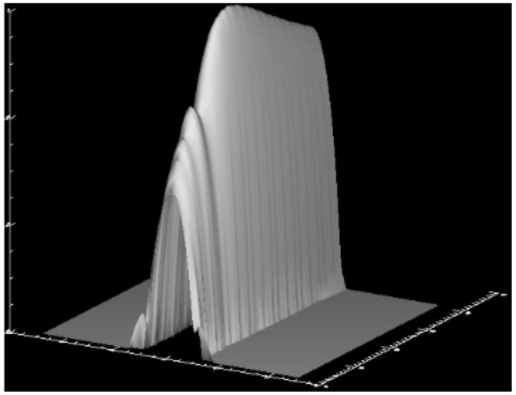
$$bw = \frac{\lambda F}{D} = \lambda (f\#)$$



Beamformer Optimization

- Beam shape is improved by several processing steps:
  - Transmit apodization
  - Multiple transmit focal locations
  - Dynamic focusing
  - Dynamic receive apodization
  - Post-beamsum processing
- Example
  - Upper frame: fixed transmit focus
  - Lower frame: the above steps.



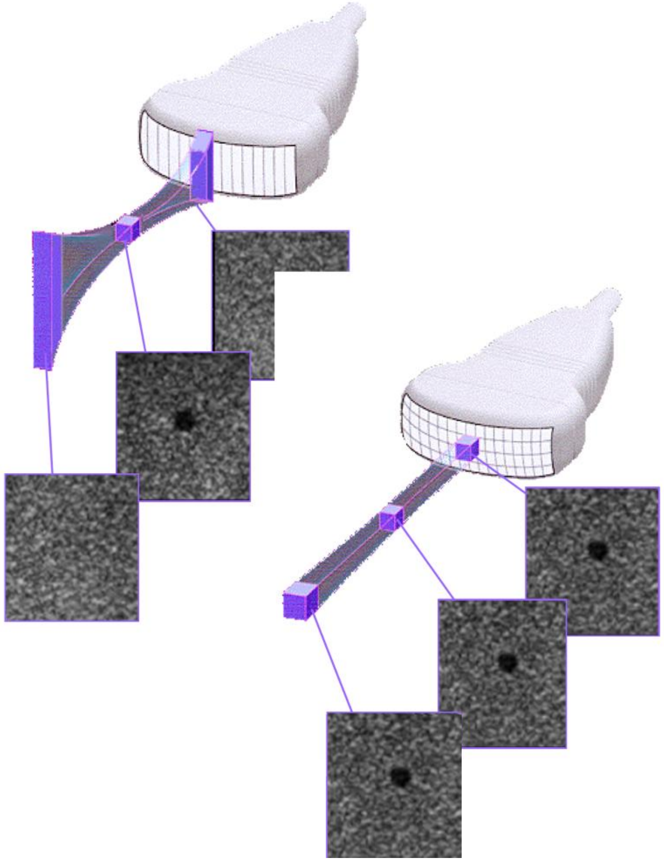


Channel Count Issues

- 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

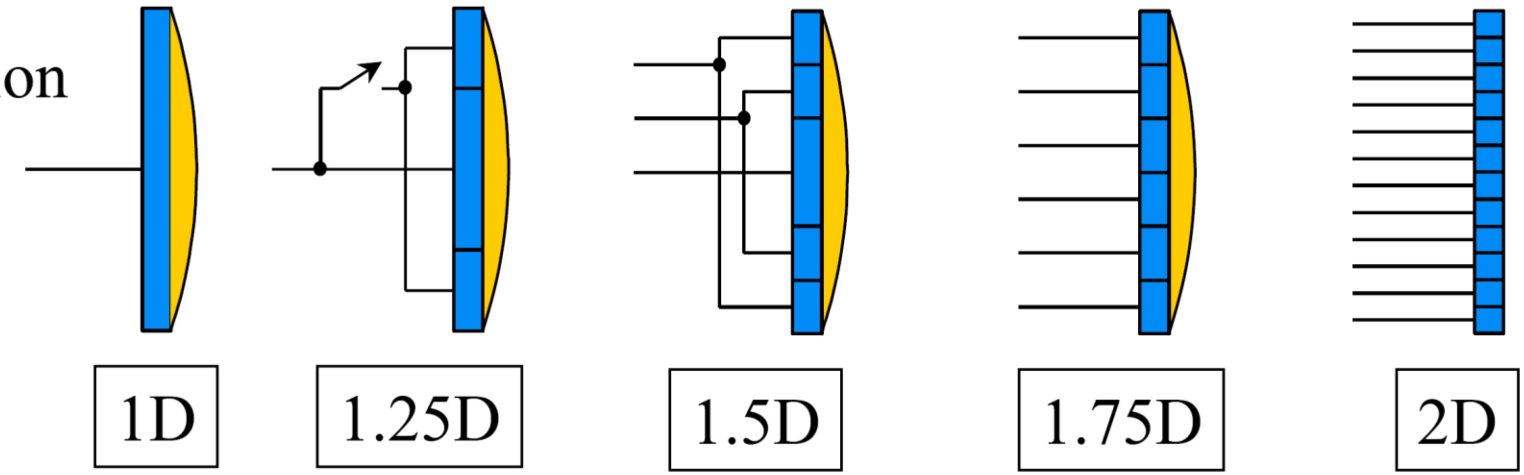
Elevation Beamforming

- Limited performance available with 1D designs
  - Poor beamformation away from elevation focus.
  - 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



Array Taxonomy

Elevation



Aperture	Fixed	Discrete	Dynamic	Dynamic	Dynamic
Focus	Static	Static	Dynamic, Symmetric	Dynamic, No Symmetry	Dynamic, Steerable

Value of Elevation Focusing

Phantom with 2 mm Spherical Cysts

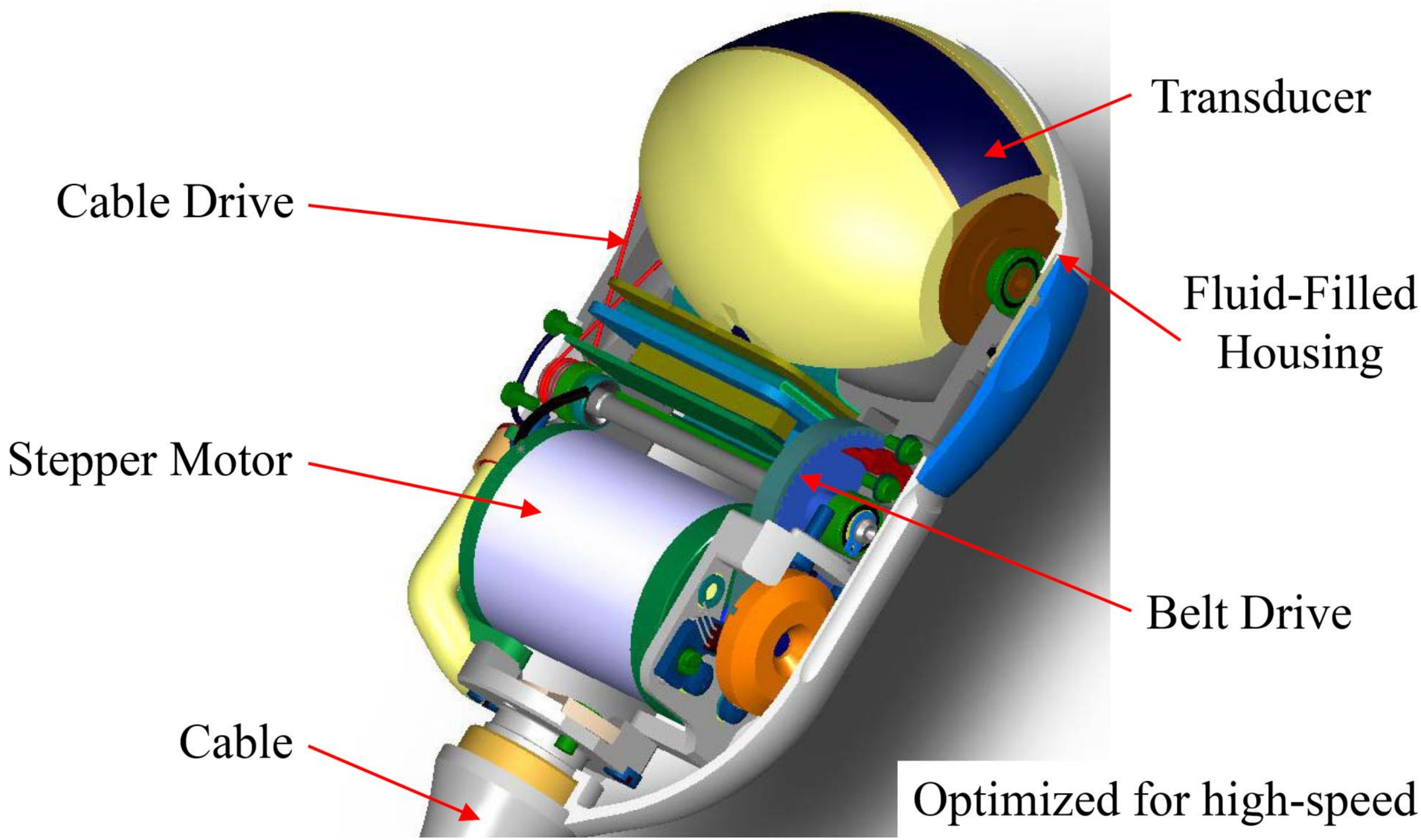
Channel Count Requirements

- Let N = azimuthal channel count desired, e.g. 128.
- 1.25D
  - no increase over N.
- 1.5D
  - assume 5 rows (3 independent), 3N channels required
- 1.75D
  - with 5 rows, 5N channels required
- 2D
  - sparse arrays w. 256 channels currently available, for 4D
- For ergonomic scanning, no. of cables is < 256–512

3D/4D Imaging 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 ⇒3600 beams
  - 12 cm x 2 / 1540 m/s = 160 μsec per beam
  - ⇒1.7 volumes / sec

Mechanical 4D Probes



Concurrent 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

Harmonic Imaging

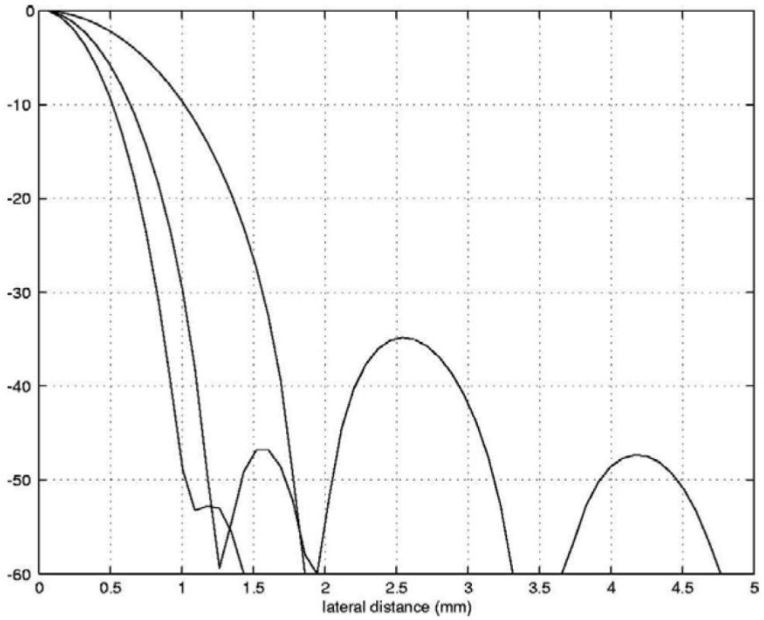
- Perhaps most important innovation of the last 10 yrs
  - Now default mode in most cardiac scanners
- Discovery due to two major sources:
  - harmonic imaging for contrast agents
  - transducer bandwidth increases
- Arises from pressure dependence of sound speed
  - Compressional wave is faster than rarefactional
- Need to understand via simulations.

Harmonic Imaging: Beamforming

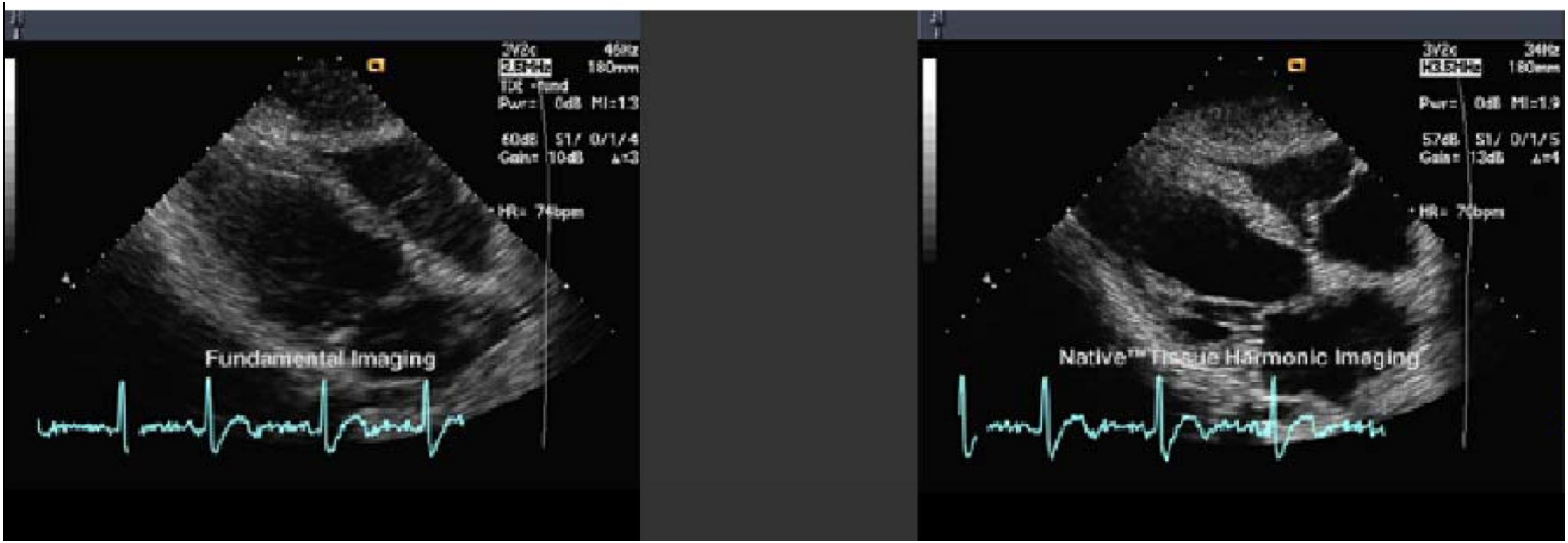
- During propagation, harmonics are formed.
- Rate of generation of 2nd harmonic proportional to p^2
- This is equivalent to having an extra beamformer to narrow the beam shape.
- Beamformer requirements:
  - added transmit flexibility
  - increased filtering capacity
  - Higher receive signal bandwidth

Harmonic Imaging: Advantages

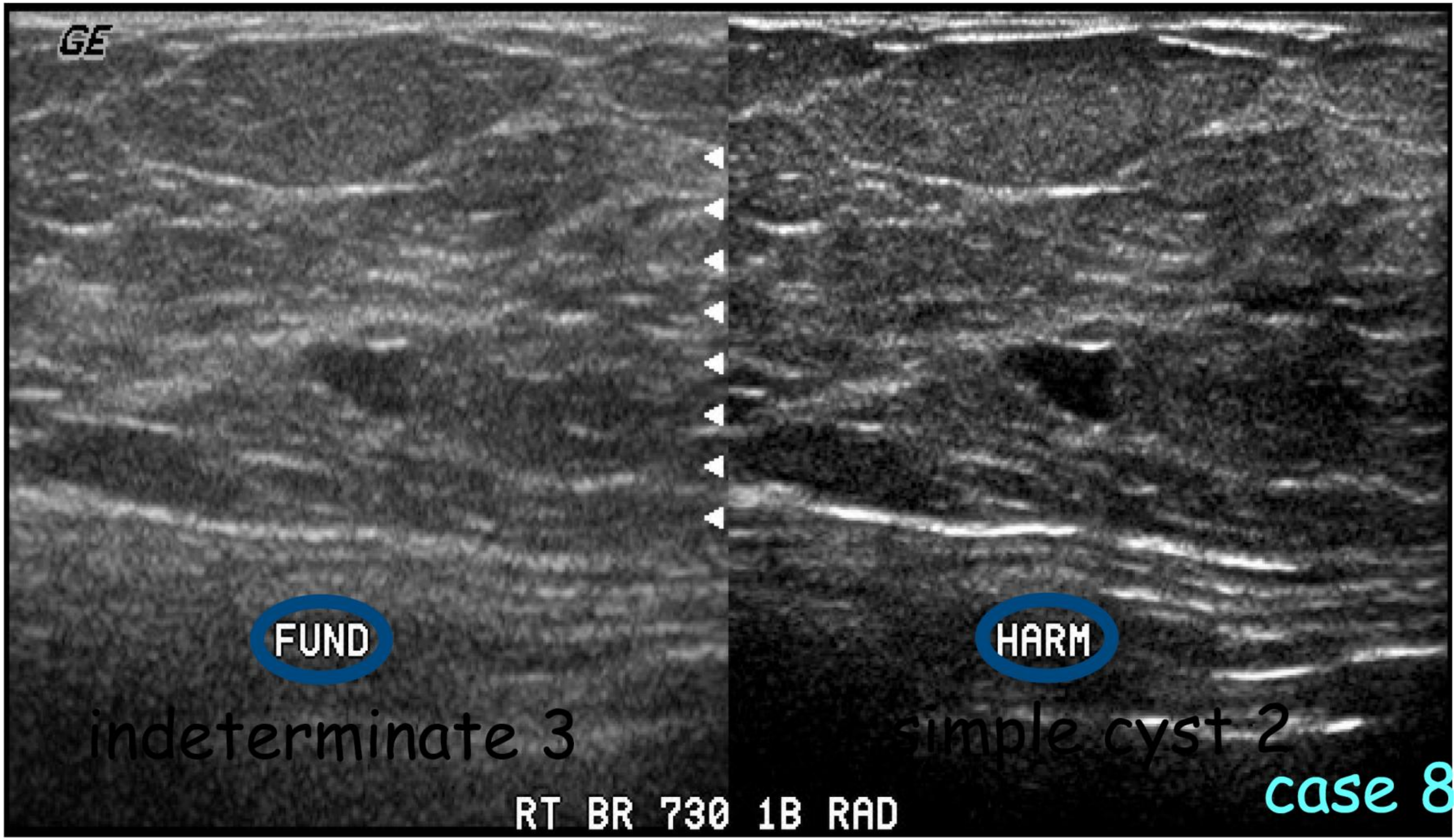
- Harmonics formed at main lobe
  - narrower beams
  - lower sidelobes
- much acoustic noise generation at fundamental
  - refraction from fat layers
  - reverberations near fat/muscle layers
- Optimization of beamformers may be necessary



Harmonic Imaging Example 1

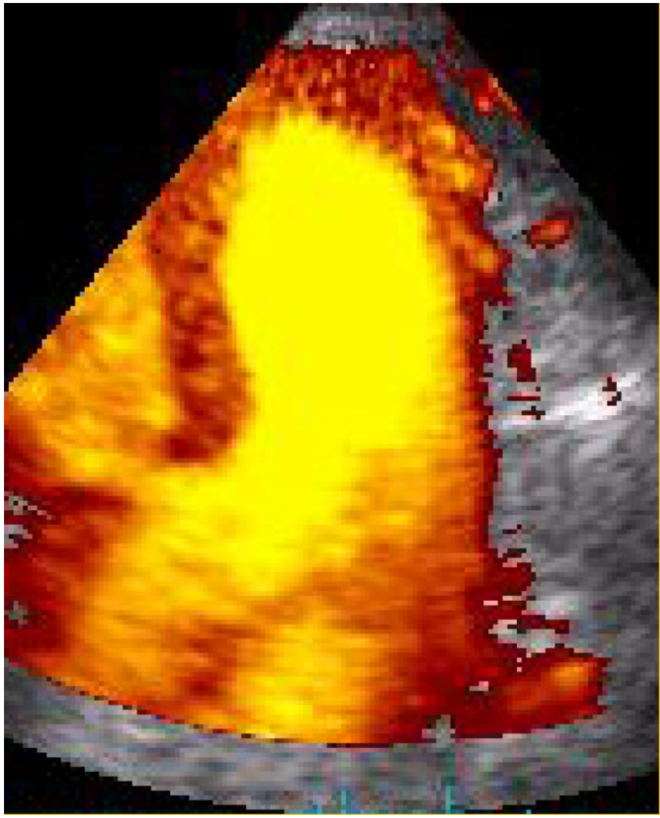


Harmonic Imaging Example 2



Harmonic Imaging with Contrast

- Ultrasound contrast agent
  - 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



Comparison between Tissue and Contrast Harmonic Imaging

Tissue Harmonics

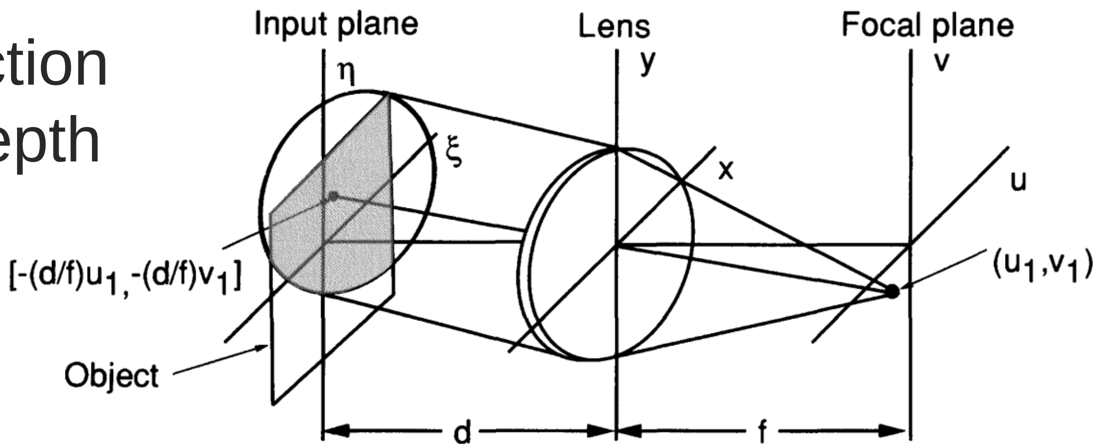
- Goal: best tissue images
- Methods
  - Maximize harmonic energy
  - Higher f-numbers to allow harmonic energy to accumulate
  - Consider non-spherical focusing

Contrast Harmonics

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

Focusing Theory

- Fraunhofer diffraction pattern at focal depth when d=0



$$t_l(x, y) = \exp\left[-j\frac{k}{2f}(x^2 + y^2)\right].$$

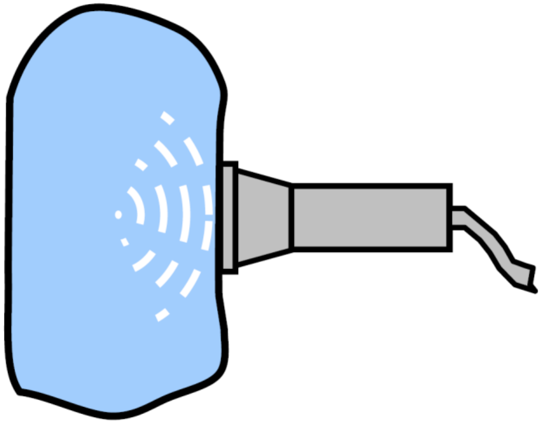
$$U_f(u, v) = \frac{\exp\left[j\frac{k}{2f}(u^2 + v^2)\right]}{j\lambda f}\iint_{-\infty}^{\infty} U_l(x, y)\exp\left[-j\frac{2\pi}{\lambda f}(xu + yv)\right]dx\,dy.$$

Focusing Implementation

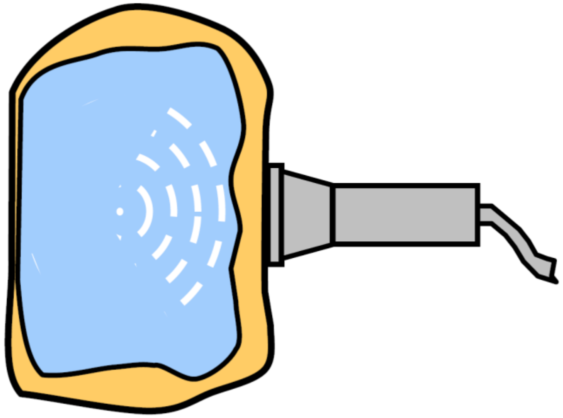
- Reciprocity theorem
  - Beamform at Transmit = beamform at Receive
  - Overall beamform = Trans beamform x Rec beamform
- Static focusing
  - Static focal point
  - Used in transmission
- Dynamic focusing
  - Multiple focal points
  - Used in reception
  - Ideally, focused in all points

Phase Aberration

- Present ultrasound imaging
  - People are bags of water !
  - Crude approximation



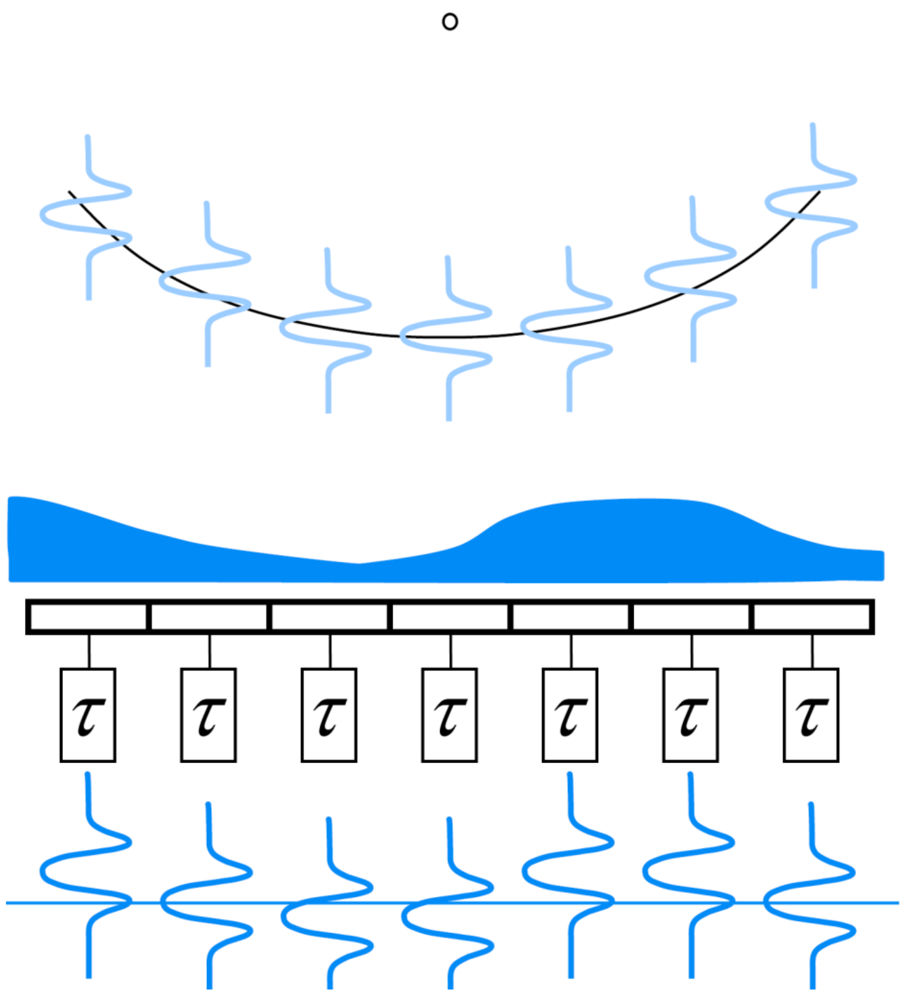
- Practical Imaging
  - Fat and muscle degrade quality
  - Time-delay Errors from the abdominal wall are *10-50 Times Larger than beamformer delay quanta!*
  -



Phase Aberration

- All beamformers use an assumption of constant speed of sound (1540 m/s in all ultrasound systems)
  - This assumption is not valid.
- In soft tissues, we have these speeds:
  - fat 1440 m/s
  - liver1510
  - kidney1560
  - muscle1570 (skeletal)
  - Tumors1620
- This variation limits further spatial & contrast resolution improvements.

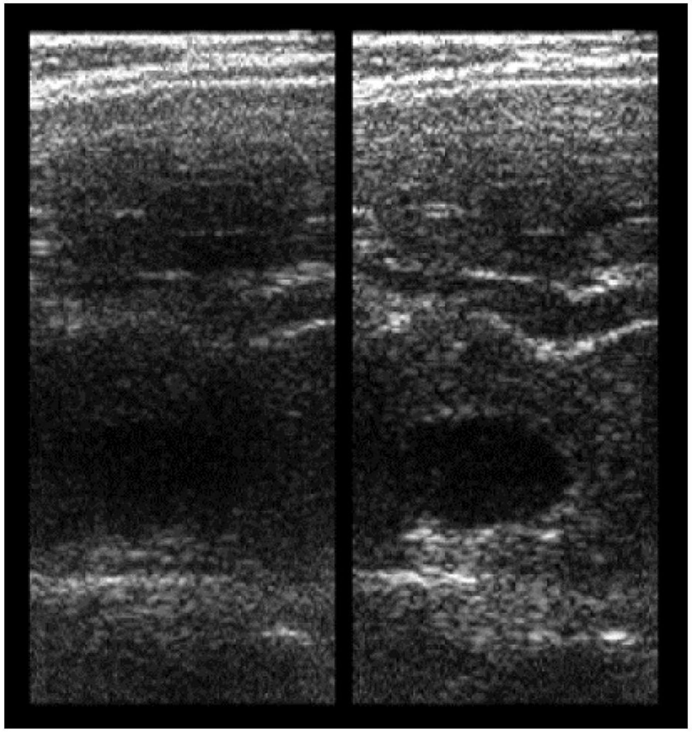
Phase Aberration



Phase Aberration Solutions

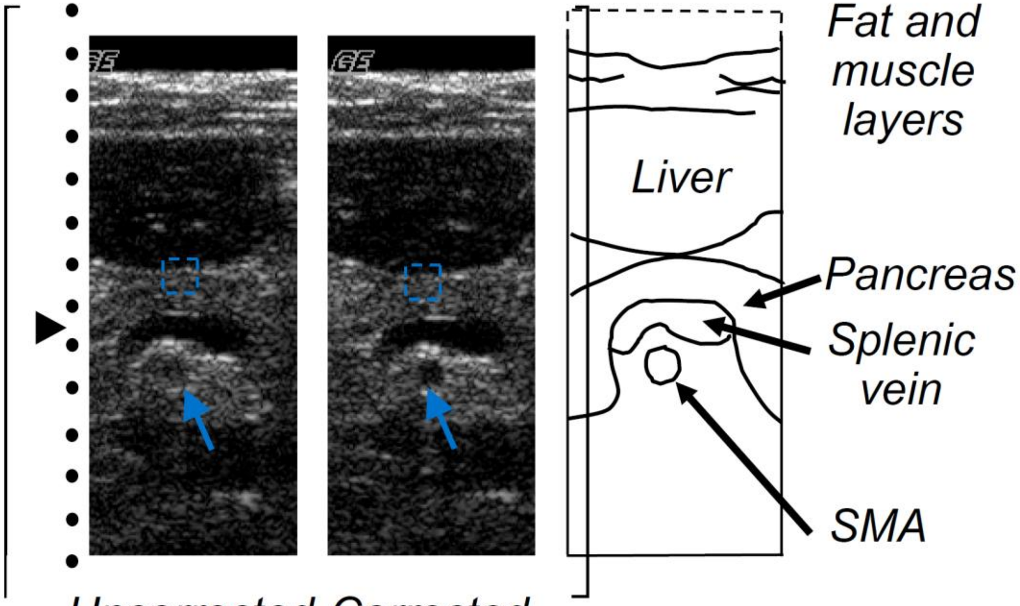
- Phase screen models
  - all aberrating sources near skin line
  - deaberration can occur via time shifting of the echoes
  - amount of shift determined by correlations.
- Distributed aberrators
  - aberrating sources away from skin (as well as near it). Interference among refracted beams occurs.
 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

Phase Aberration Correction Results



Uncorrected   Corrected

Pancreas and
Superior Mesenteric Artery



Uncorrected Corrected

SMA 4.4 dB darker, pancreas 1.4 dB brighter

Remaining Beamformer Issues

- Expanding aperture receive beamforming
- Synthetic aperture beamforming
- Digital beamforming
  - Hilbert transformation
  - Fractional period delay filters
  - Sampling issues

Problem Assignments

- At the end of second lecture on Beamforming, there will be a problem assignment for you. Problems include programming tasks on Matlab or “mini-projects”.