Ultrasound Bioinstrumentation

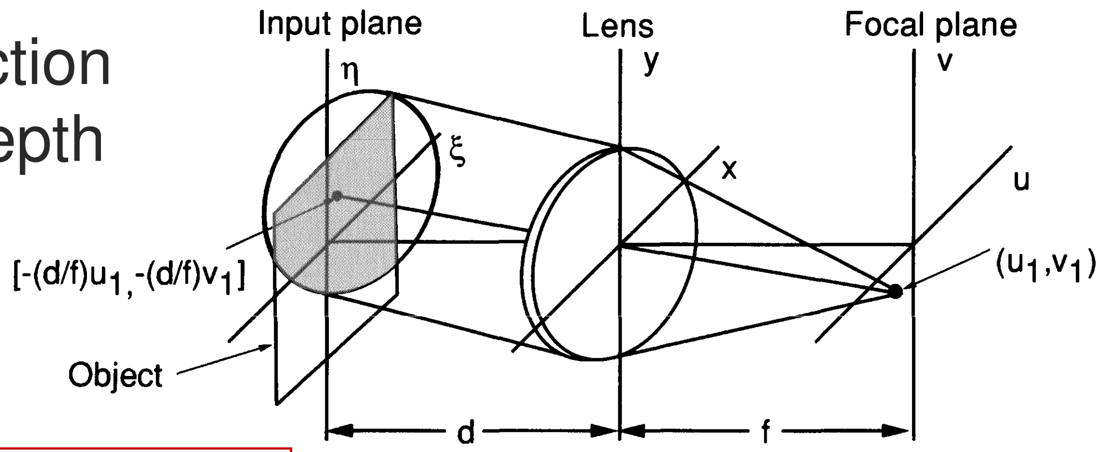
Topic 2 (lecture 3)

Phase Aberration Correction

CAIRO UNIVERSITY

Focusing Theory

- Fraunhofer diffraction pattern at focal depth when d=0



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

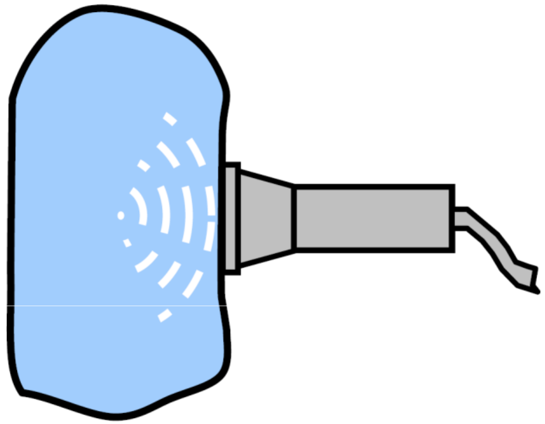
$$U_f(u, v) = \frac{\exp\left[j\frac{k}{2f}(u^2 + v^2)\right]}{j\lambda f} \iint_{-\infty}^{\infty} U_l(x, y) \exp\left[-j\frac{2\pi}{\lambda f}(xu + yv)\right] dx\, dy.$$

Focusing Implementation

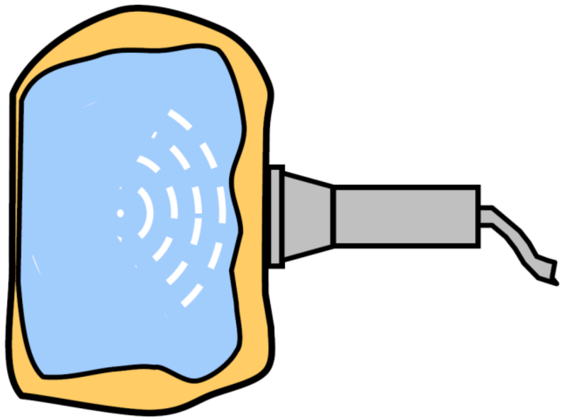
- Reciprocity theorem
  - Beamform at Transmit = beamform at Receive
  - Overall beamform = Trans beamform x Rec beamform
- Static focusing
  - Static focal point
  - Used in transmission
- Dynamic focusing
  - Multiple focal points
  - Used in reception
  - Ideally, focused in all points

Phase Aberration

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



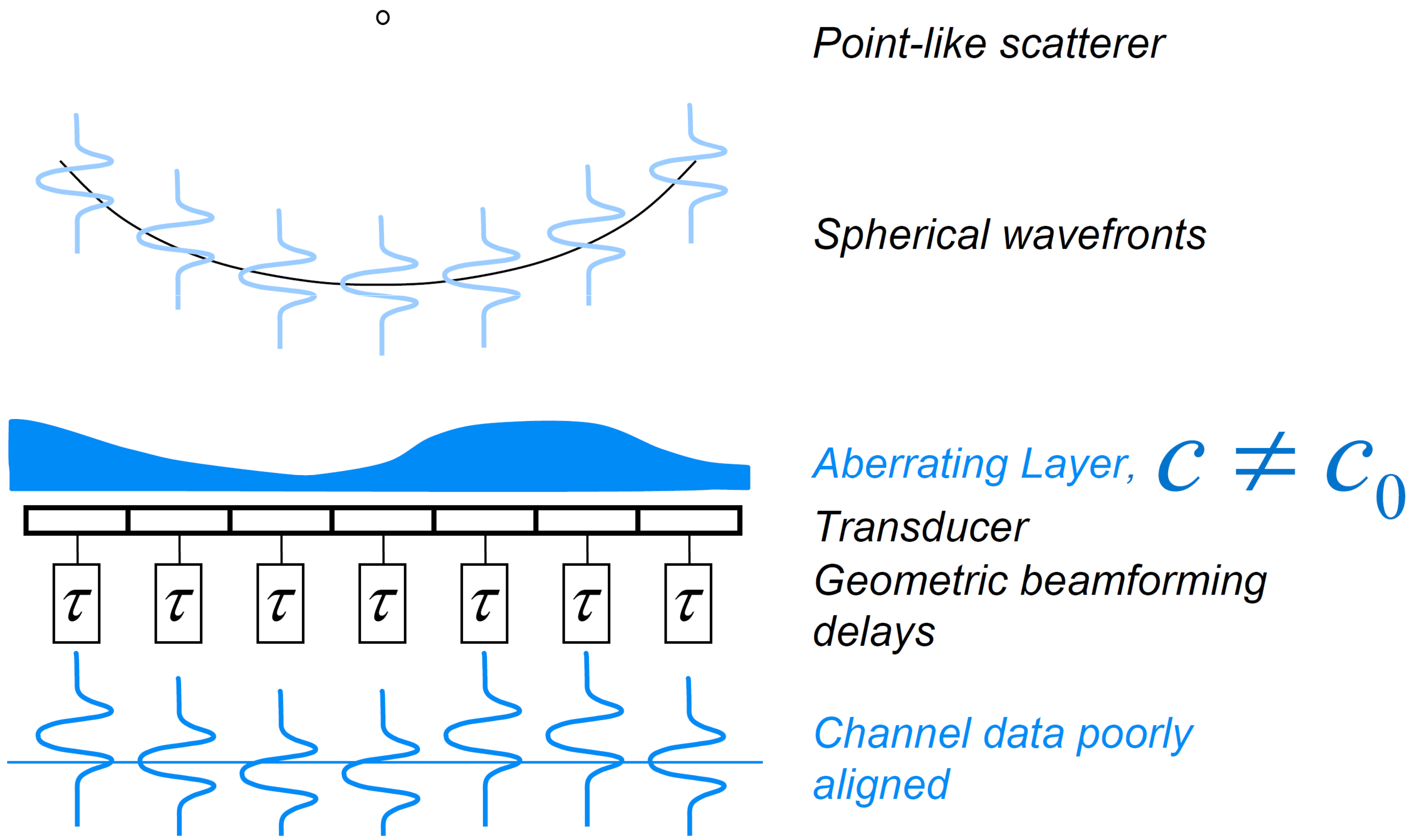
- Practical Imaging
  - Fat and muscle degrade quality
  - Time-delay Errors from the abdominal wall are ***10-50 Times Larger than beamformer delay quanta!***
  -



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



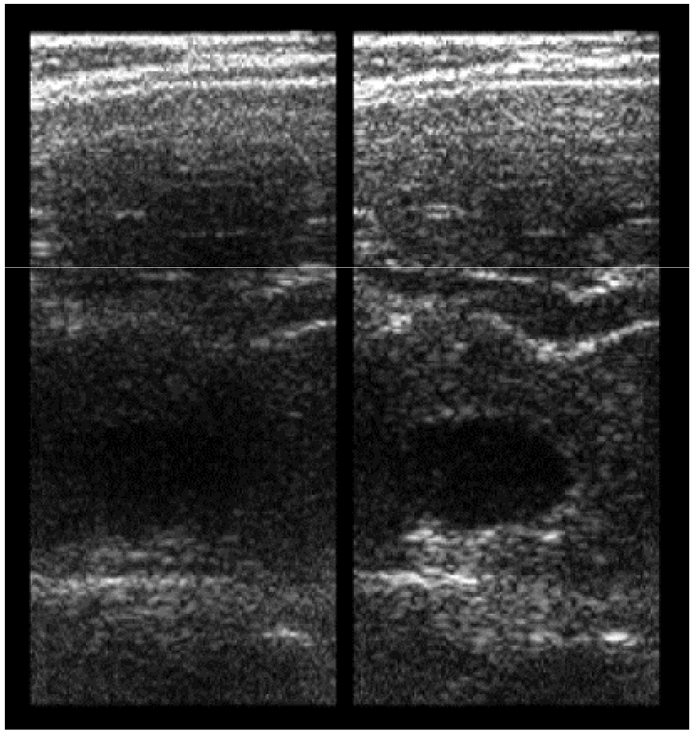
Phase Aberration Solutions

- 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 Techniques

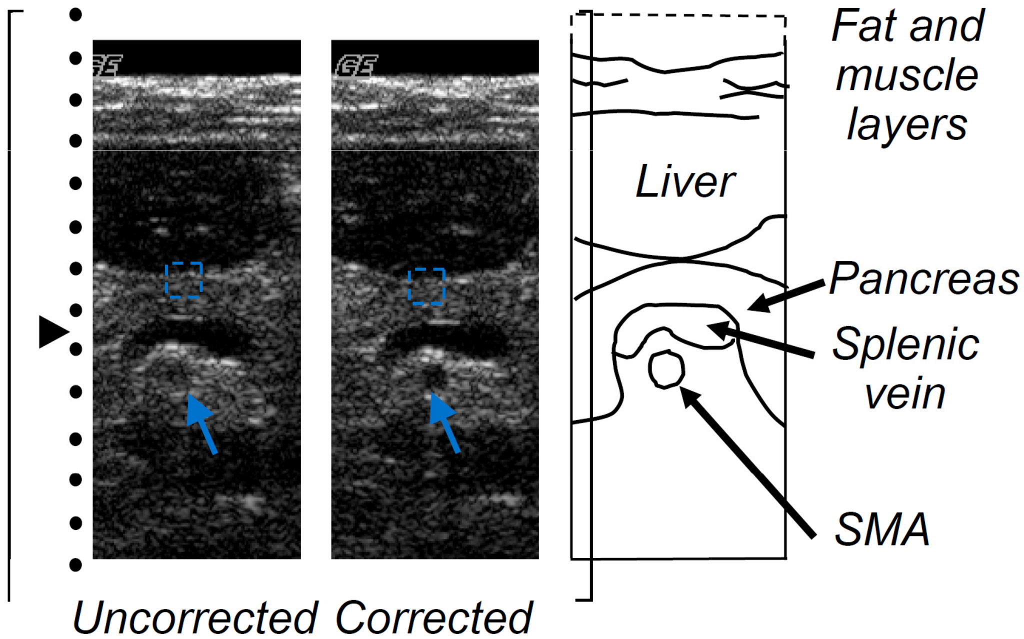
Algorithm	Method of arrival time (phase) difference measurement	Size of reference group Geometric relationship of reference group to the element(s) to be corrected	Technique by which phase correction profile is obtained
Flax and O'Donnell [12]	Cross-correlation peak	One element Nearest azimuthal neighbor	Individual element pair arrival time measurements summed across array
Nock *et al.* [13]	Speckle Brightness	All elements in array Entire array	Each element is aligned relative to summed signal of all elements
Freiburger *et al.* [7]	Local correlation and phase closure	One element Nearest azimuthal and elevational neighbors	Enforcement of local phase closure within 4 element loop using simulated annealing
Rachlin [14]	Detection of difference of linear component in phase spectra of echoes	Element pair symmetric about a common midline with element pair to be corrected Adjacent element pair	Phase profile is estimated from matrix of arrival time measurements
Current Paper	Speckle Brightness	Group of corrected elements Nearest neighbors	See algorithm of Nock *et al.*

Phase Aberration Correction Results



Uncorrected Corrected

Pancreas and
Superior Mesenteric Artery



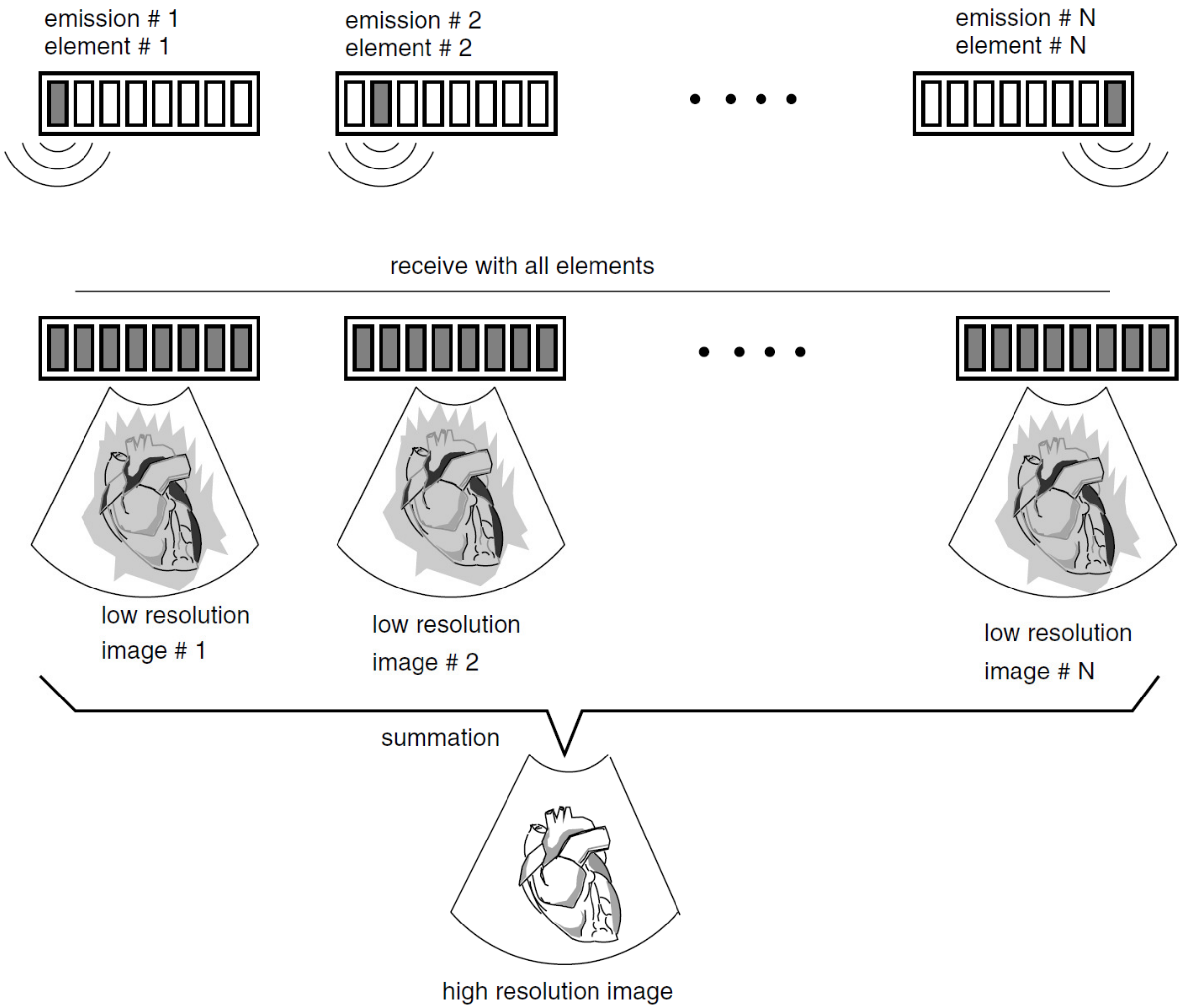
SMA 4.4 dB darker, pancreas 1.4 dB brighter

Synthetic Aperture

- Synthetic-aperture radar (SAR) is a form of radar in which multiple radar images are processed to yield higher resolution images than would be possible by conventional means.
- SAR has seen wide applications
  - remote sensing
  - mapping.

http://en.wikipedia.org/wiki/Synthetic_aperture_radar

Synthetic Aperture in Ultrasound



Jensen et al., Ultrasonics, 2006

Synthetic Aperture in Ultrasound

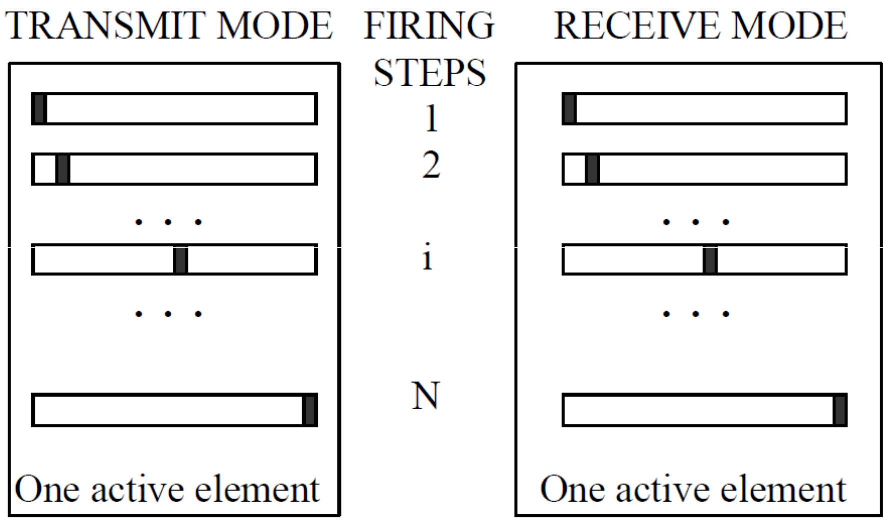


Fig.1: SAFT imaging method

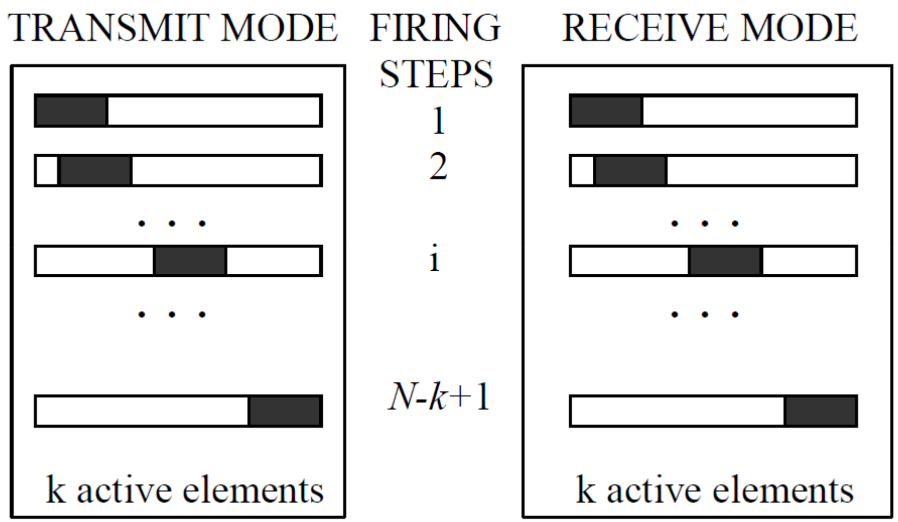


Fig.2: MSAF imaging method

Synthetic Aperture in Ultrasound

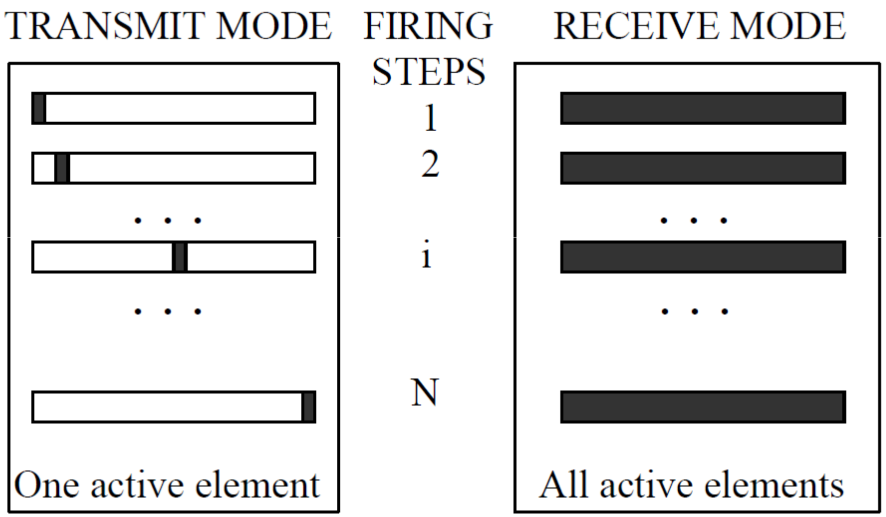


Fig.3: STA imaging method

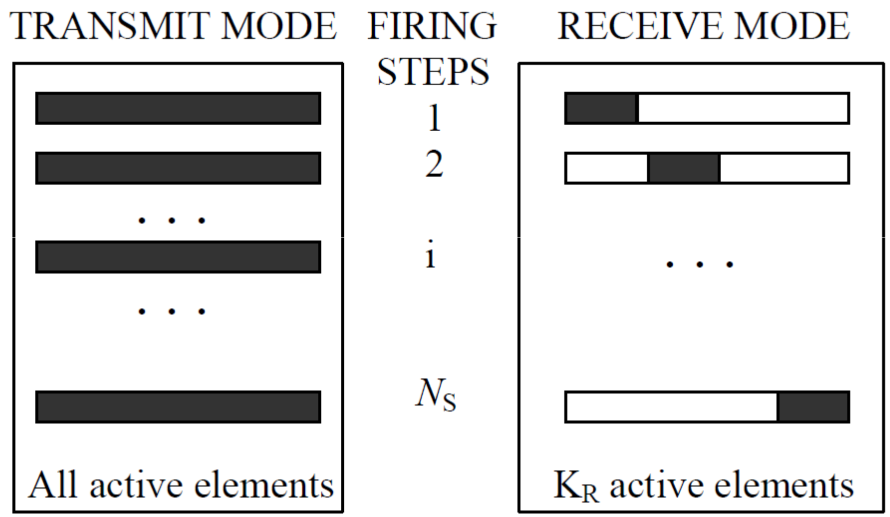


Fig.4: SRA imaging method

Synthetic Aperture in Ultrasound

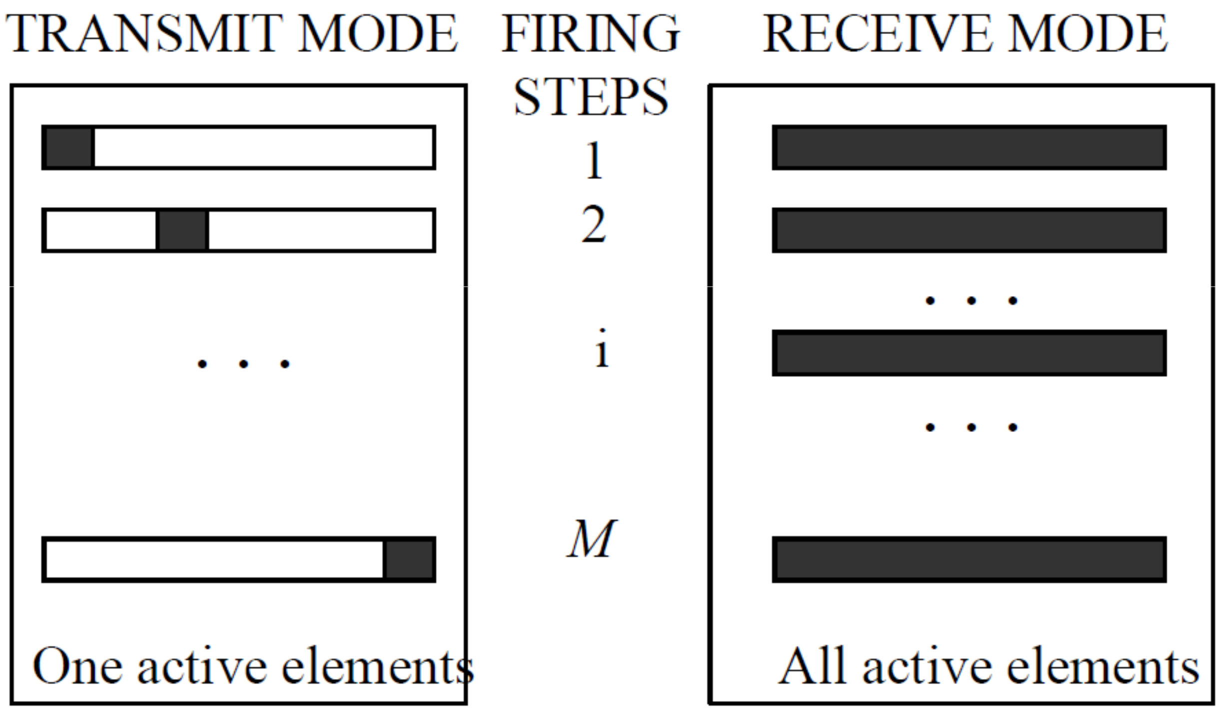
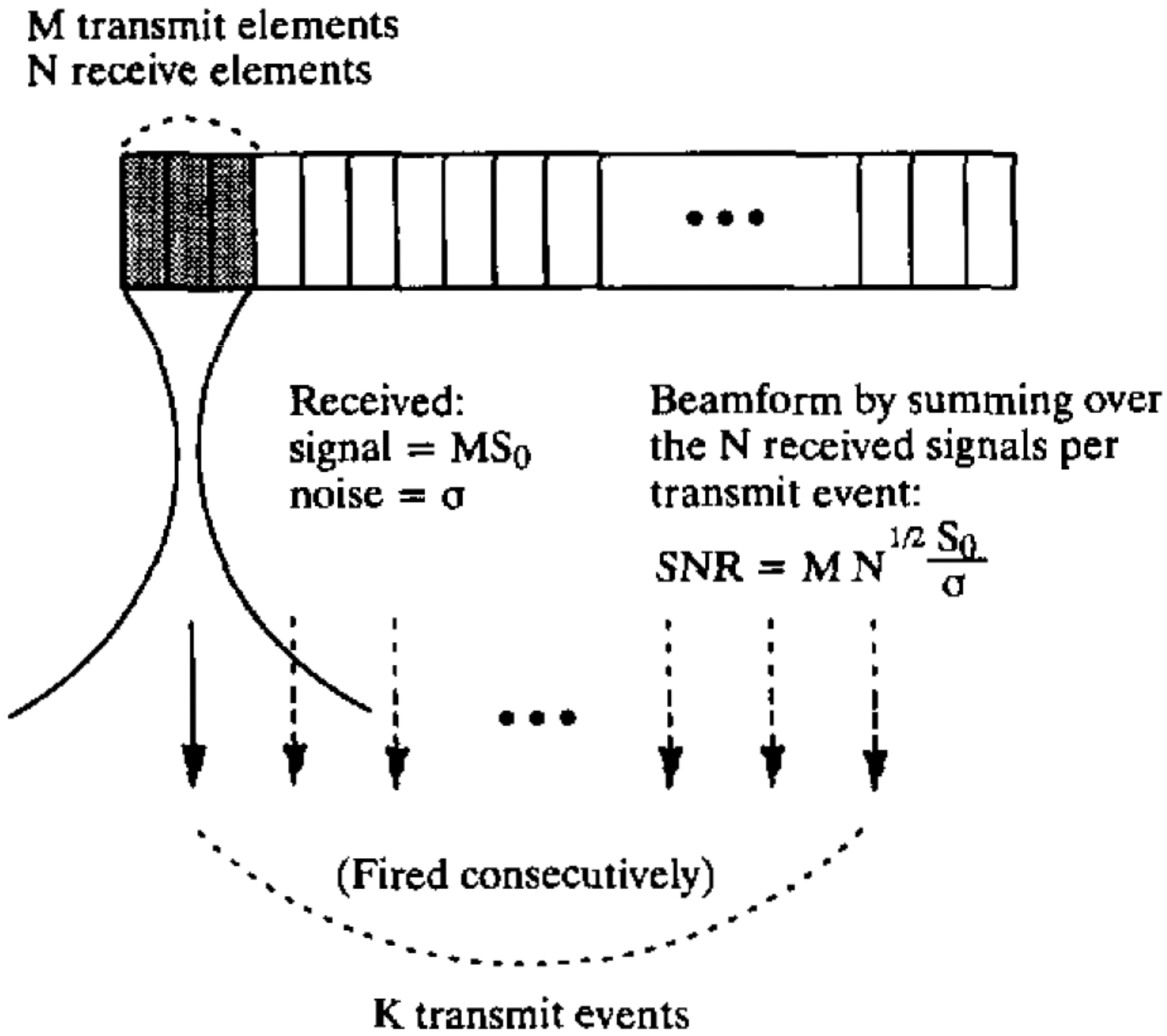


Fig.5: Sparse STA imaging method

Concurrent Multi-Line Acquisition

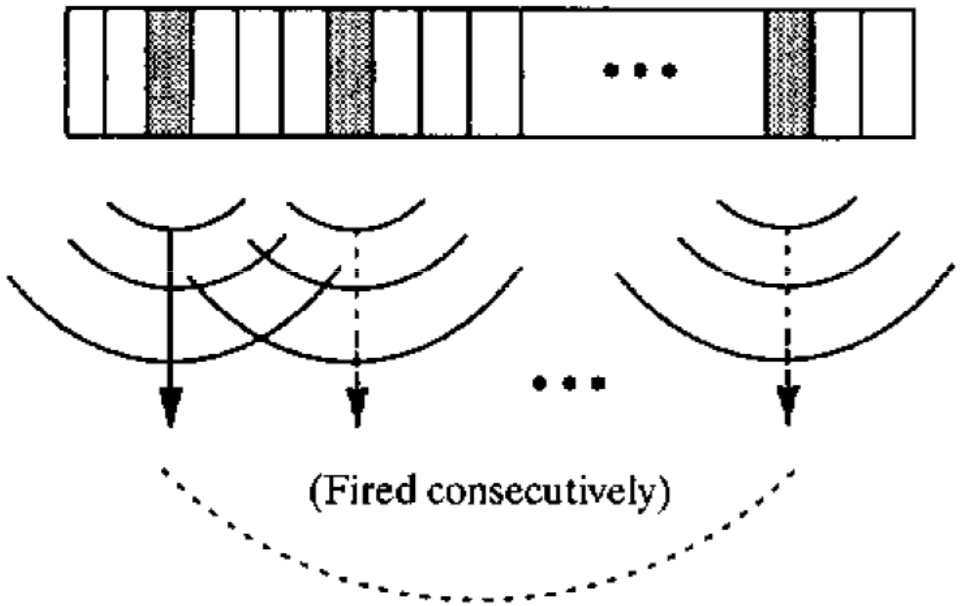
- Transmit beam is broader than receive beam
  - transmit is static focus, usually high f-number for max depth of field
- Create 2 –16 simultaneous receive beams within the transmit beam
- Substantial increase in volume rate!
- Essential for effective 4D imaging

Conventional Focused Transmit



Synthetic Transmit Aperture (STA): No Spatial Encoding

M transmit elements, N receive elements



K=M transmit events,
each using a single transmit element.

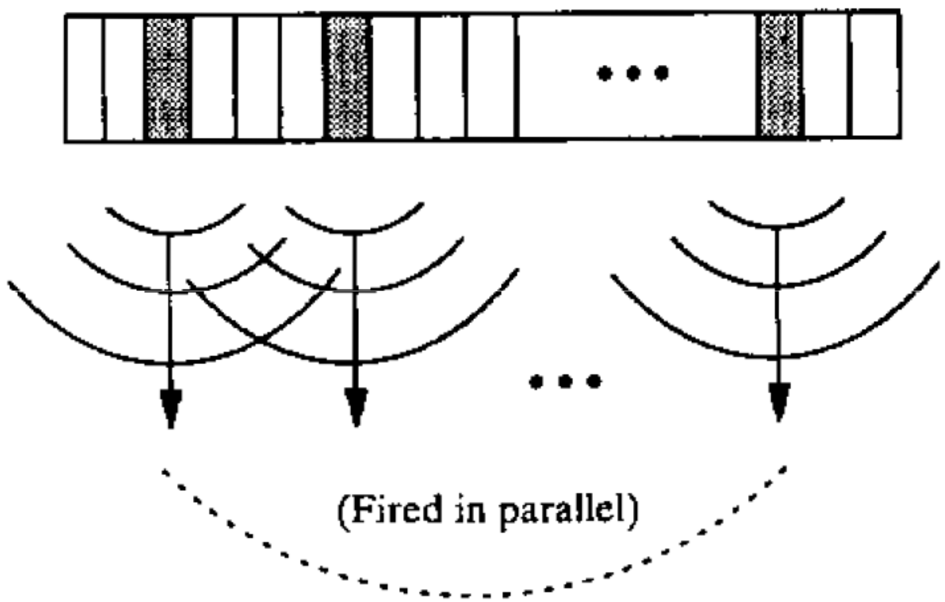
Received:
signal = S_0
noise = σ

Beamform by summing over the MN complete data set:

$$SNR = (MN)^{1/2} \frac{S_0}{\sigma}$$

Synthetic Transmit Aperture (STA): With Spatial Encoding

M transmit elements, N receive elements



K=M transmit events,
each using M encoded elements

Received signal after decoding:

signal = MS_0

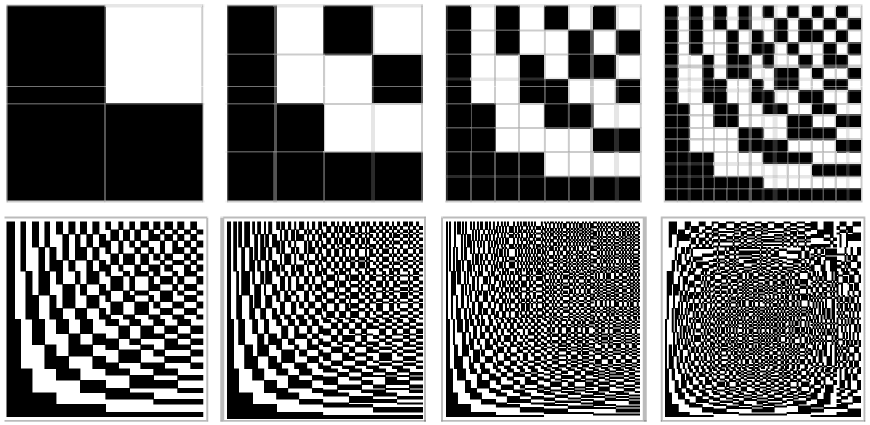
noise = $M^{1/2}\sigma$

Beamform by summing over the MN complete data set after decoding:

$$SNR = MN^{1/2}\frac{S_0}{\sigma}$$

Transmit Encoding / Decoding : Hadamard Matrix

- Hadamard matrix is a square matrix whose entries are either +1 or –1 and whose rows are mutually orthogonal



$$H H^{\mathrm{T}} = n I_n$$

$$H_1 = \begin{bmatrix} 1 \end{bmatrix},$$

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix},$$

$$H_{2^k} = \begin{bmatrix} H_{2^{k-1}} & H_{2^{k-1}} \\ H_{2^{k-1}} & -H_{2^{k-1}} \end{bmatrix} = H_2 \otimes H_{2^{k-1}},$$

http://mathworld.wolfram.com/HadamardMatrix.html - http://en.wikipedia.org/wiki/Hadamard_matrix

Transmit Encoding / Decoding : Hadamard Matrix Example

- 4 Channel Hadamard encoding/decoding
- Received signals from 4 excitations:

Received Mixed Signals

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}$$

Decoded Individual Line Signals

$$\begin{bmatrix} s_1^* \\ s_2^* \\ s_3^* \\ s_4^* \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} 4s_1 \\ 4s_2 \\ 4s_3 \\ 4s_4 \end{bmatrix}$$

Transmit Encoding / Decoding : SNR Advantage

- Independent and identically distributed noise in all received signals (i.i.d.)
- Decoding Process
  - Signals add
  - Noise cancel
  - Averaging effect leading to √N improvement in SNR

$$\begin{bmatrix} s_1^* \\ s_2^* \\ s_3^* \\ s_4^* \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} 4s_1 \\ 4s_2 \\ 4s_3 \\ 4s_4 \end{bmatrix}$$

Problem Assignments

- At the end of this lecture, there will be a problem assignment for you on the web site.
- Problems include programming tasks on Matlab or "mini-projects".
- Problem solutions are due in 3 weeks.