Ultrasound Imaging System Performance Assessment

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Abstract

Development of an ultrasound imaging system includes various performance assessment and verification stages. At these stages, a combination of water tank and phantom measurements and extensive clinical evaluations are used to make sure that all the performance objectives are met.

Assessing the performance of an ultrasound system requires understanding the relationships between the characteristics of the system, such as the point spread function, and the system's clinical performance. Also required are quantifiable measures for system performance.

Among the measured and clinically evaluated performance criteria are detail resolution, contrast resolution and sensitivity. These performance criteria will be defined in terms of the system characteristics and measures that can be used to define them. Water tank and phantom measurements used to assess system performance will also be described.

Outline

- Fundamental performance measures
- Imaging system block diagram
- Imaging system as a linear filter
- Spatial impulse response (Point Spread Function)
- Detail Resolution
- Temporal Resolution
- Sensitivity/Penetration
- Contrast Resolution (Anechoic Objects)
- Contrast Resolution (Soft Tissue)
- Appendix for List of Phantoms

Fundamental Performance Measures

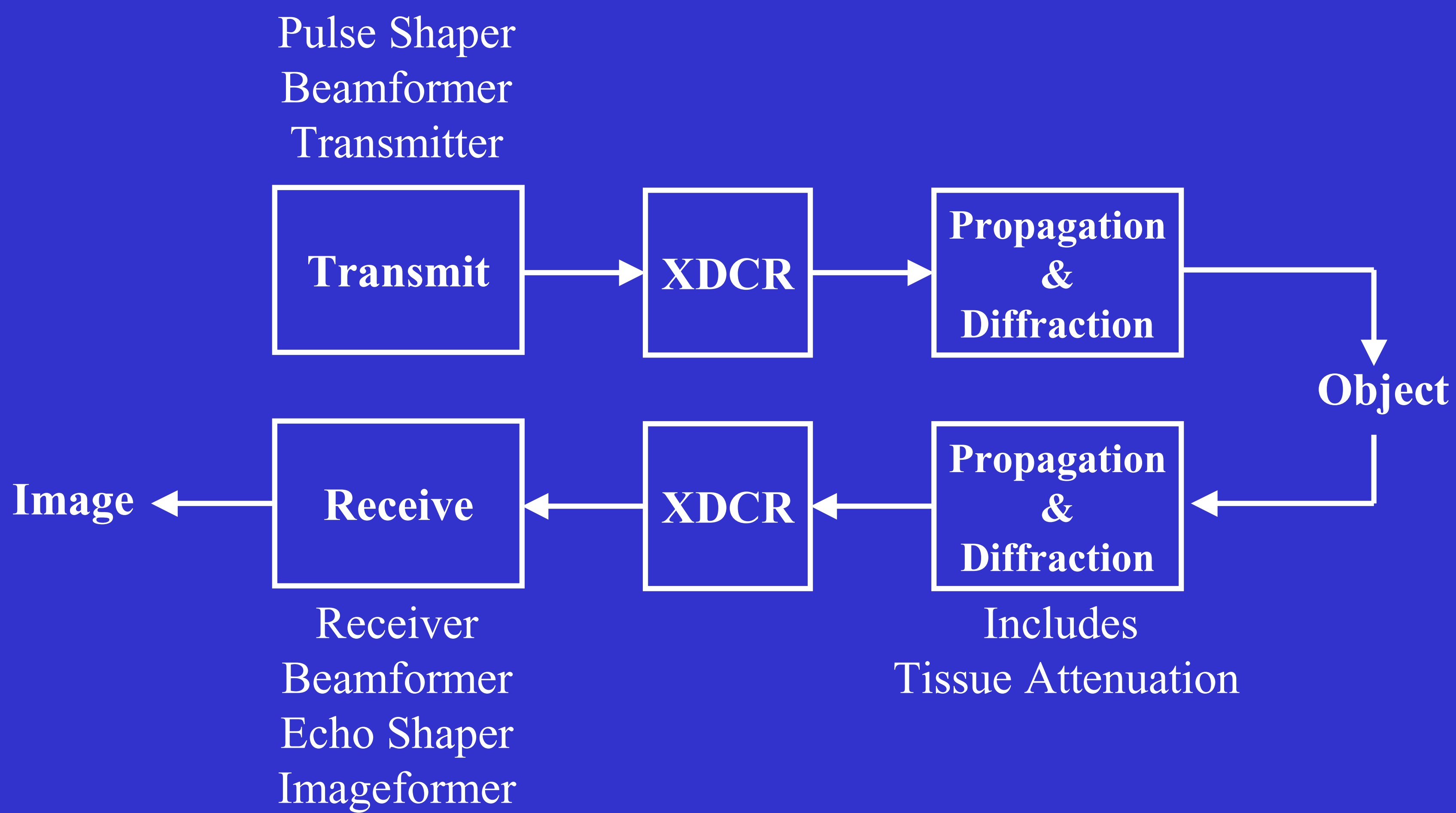
The following performance measures directly determine the information content of images.

- Detail resolution
- Contrast resolution (Soft Tissue, Anechoic Objects)
- Temporal resolution
- Sensitivity
- Dynamic Range

All of these measures are quantifiable through measurements.

All but dynamic range will be discussed here.

Imaging System Block Diagram



Imaging System as a Linear Filter

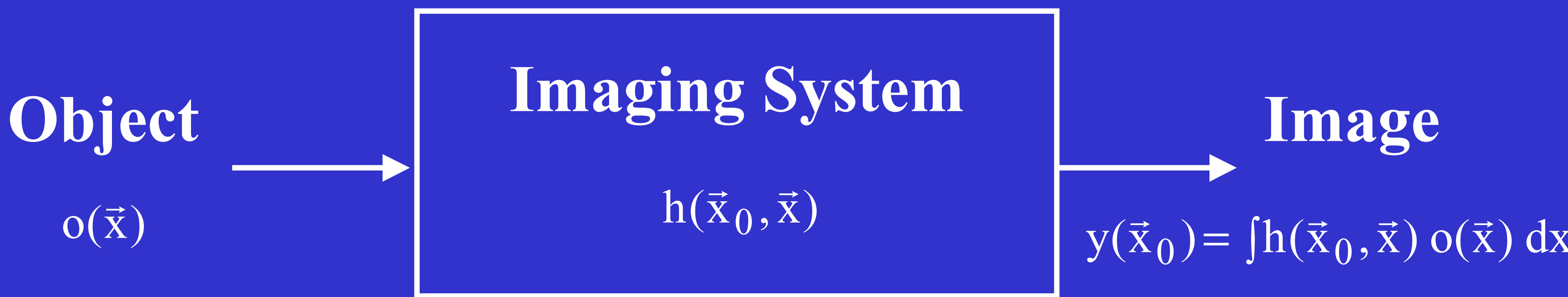
The imaging system block diagram can further be reduced to a single filter block.

The input of the filter is the object's acoustic impedance variations in space and time. Therefore it has four dimensions. The spatial bandwidth of the input is very wide, while the temporal bandwidth varies depending on the object's motion and the user's hand motion.

The filter, also four-dimensional, is a linear band-pass filter. Since the filter is linear, it can be defined by its impulse response. The spatial impulse response is also referred to as the Point Spread Function (PSF). It varies slowly with angle and depth. But it remains shift-invariant for small spatial displacements. The filter also adds thermal and quantization noise to the signal, and generates speckle, an acoustic noise.

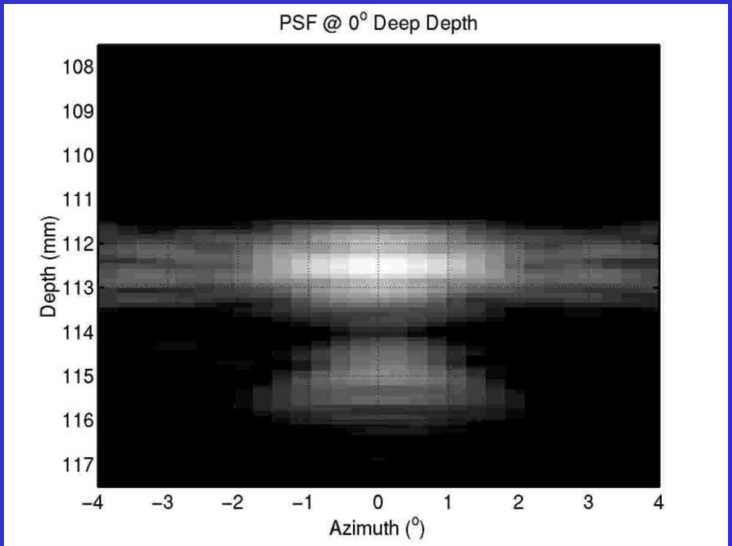
The output is a two-, three- or four-dimensional filtered transformation of the input.

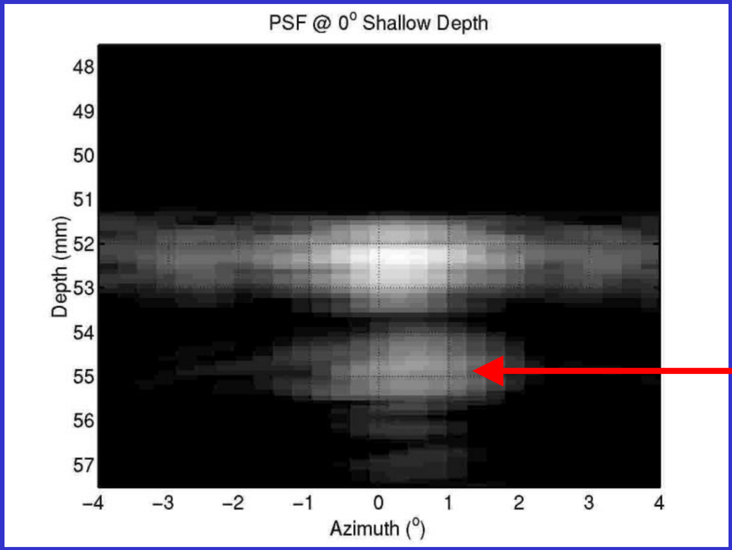
Imaging System as a Linear Filter



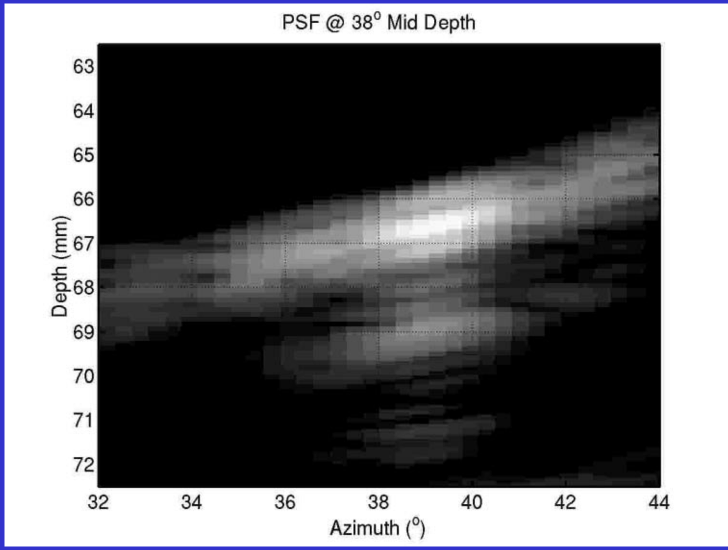
- $h(x_0, x)$ is the spatial impulse response (Point Spread Function)
- Valid for harmonic (nonlinear) tissue imaging as well, as this relies on *linear* scattering of a signal generated by *nonlinear* propagation.

Point Spread Function





Measured Using a Tissue Mimicking High Dynamic Range Phantom



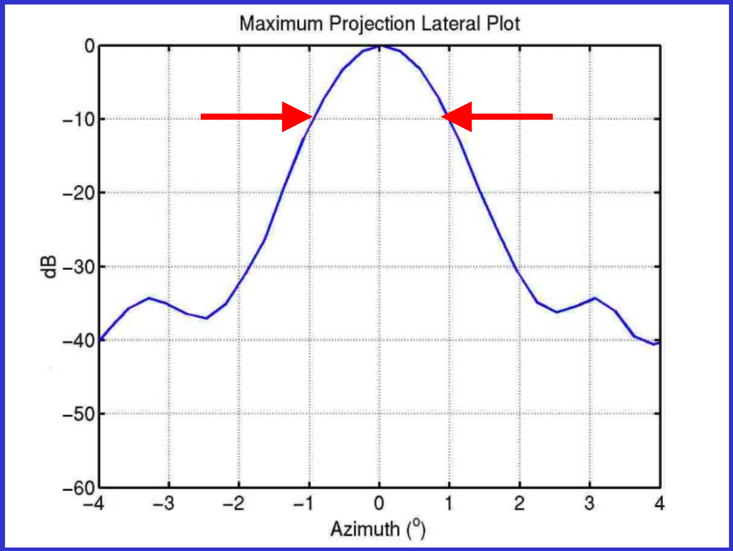
Phantom Membrane Reverb

Detail Resolution

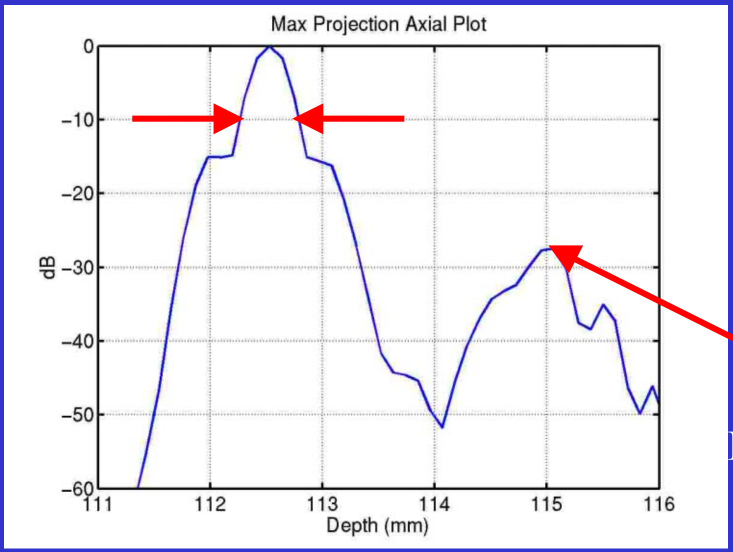
Detail resolution is a measure of the minimum spacing of distinguishable point targets.

It is determined by the main lobe width of the PSF, e.g., 10 dB lateral beam width and 10 dB axial pulse length.

Lateral Plot



Axial Plot



Phantom Membrane Reverb

Temporal Resolution

Temporal resolution refers to the ability of the ultrasound system to visualize moving objects. It is a measure of the fastest detectable object motion.

Temporal resolution is quantified by the temporal bandwidth and determined by:

- Frame rate (acquired frames only, interpolated frames do not count),
- Bandwidth of temporal filters:
  - Persistence,
  - Compounding if it involves averaging multiple frames.

Sensitivity
SNR

Sensitivity refers to the ability to visualize weakly echogenic objects. It is measure of the minimum detectable echogenicity.

Sensitivity is quantified by either the Signal to Noise Ratio or penetration. SNR is the ratio of the reference target peak signal to the rms electronic noise level. Electronic noise includes both thermal and quantization noise.

$$\mathrm{SNR} = 20\log_{10}\left(\frac{\max_{\vec{x}}\left\{\left|s(\vec{x})\right|\right\}}{\sigma_{noise}}\right)$$

A pin target can be used as the reference target. Alternatively a tissue mimicking phantom can be used, in which case the SNR is defined as the ratio of the rms signal to the rms noise level. Note that in the log detected domain the rms level is given simply by the mean.

Sensitivity

SNR Measurement

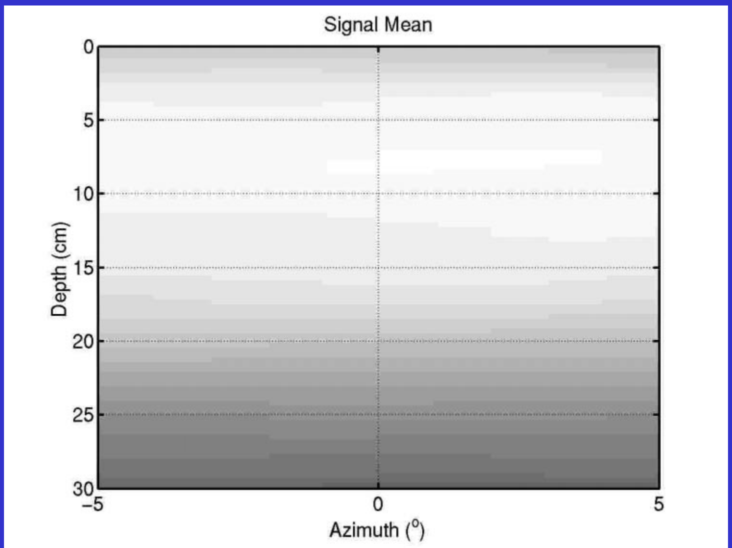
Here is one way of measuring SNR as a function of depth (and angle).

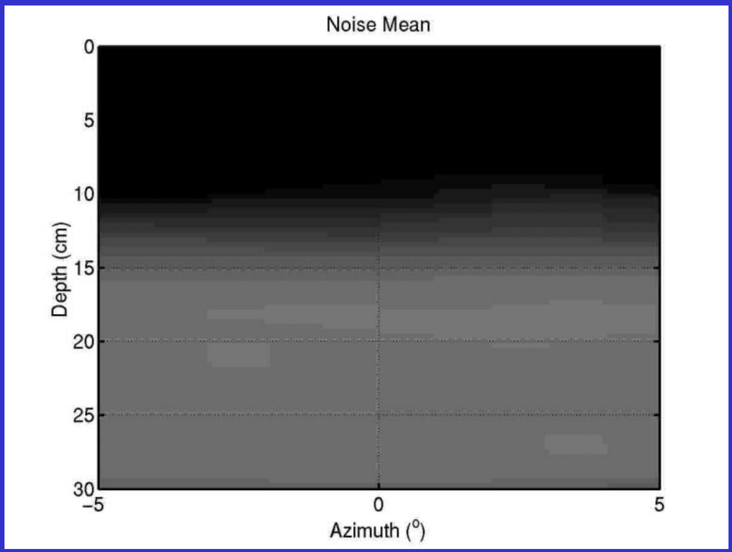
- Capture a tissue mimicking phantom image.
- Turn off the transmitters and capture a noise image.
- Amplitude detect, log compress and low-pass filter both frames to generate a signal mean and a noise mean image.
- Take the difference between the signal mean and noise mean images and plot the difference as a function of depth.

The signal and noise images in the next slide were captured prior to amplitude detection. However, amplitude detected, log detected, or scan converted data can also be used as long as nonlinear filtering or mapping stages, if any, are compensated for.

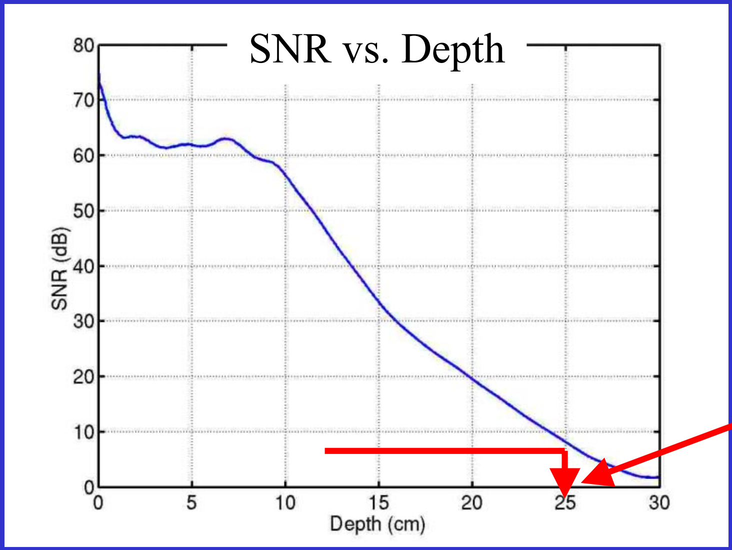
Sensitivity

SNR Measurement





Signal Mean
(Tissue mimicking phantom
Low-pass filtered)



Noise Mean
(Transmitters turned off
Low-pass filtered)

Penetration Depth
(SNR falls below 6 dB)

Sensitivity
Penetration

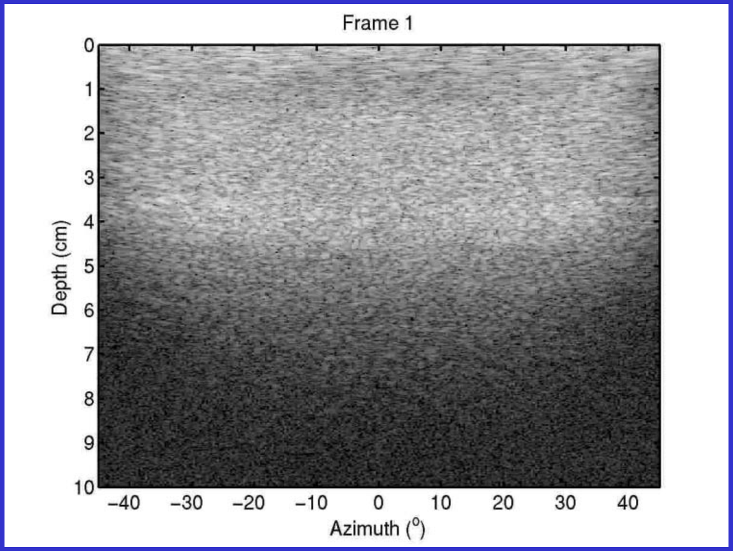
Penetration is another way of quantifying sensitivity. It can be determined from SNR measurements as shown in the previous slide, e.g., the depth at which SNR falls below 6 dB.

Alternatively, it can be estimated directly from the frame-to-frame correlation when imaging a stationary object. In this method, two images of an object are captured and cross correlated. The depth at which the correlation coefficient falls below 0.5 is defined as the penetration depth.

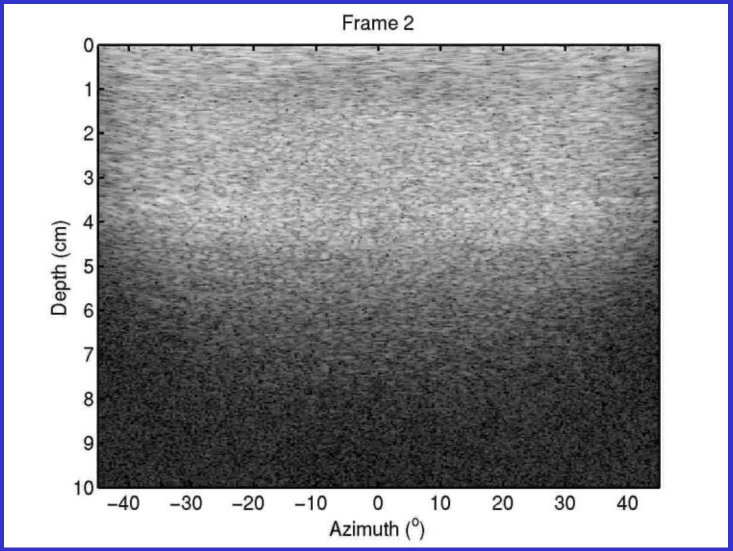
The next slide shows two images of a tissue mimicking phantom captured prior to detection using a high frequency Vector™ transducer. The solid and dashed curves in the bottom figure show the correlation coefficient for the center and edge lines, respectively.

Sensitivity

Penetration Measurement

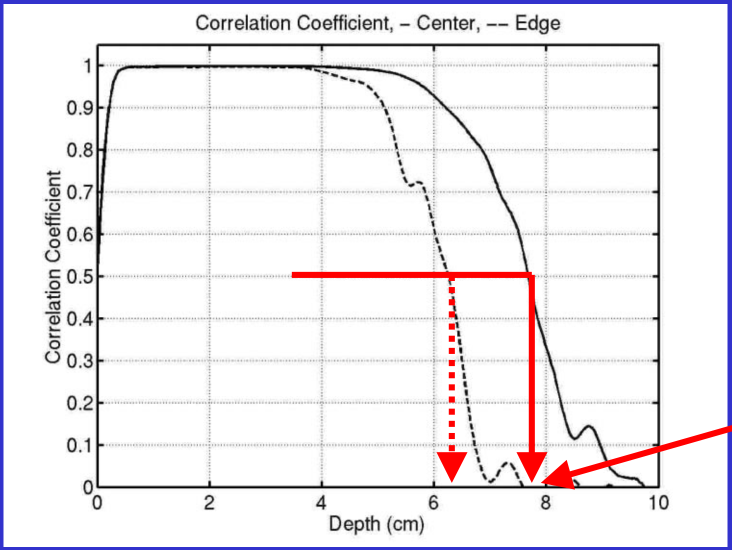


Frame 1



Frame 2

Correlation Coefficient



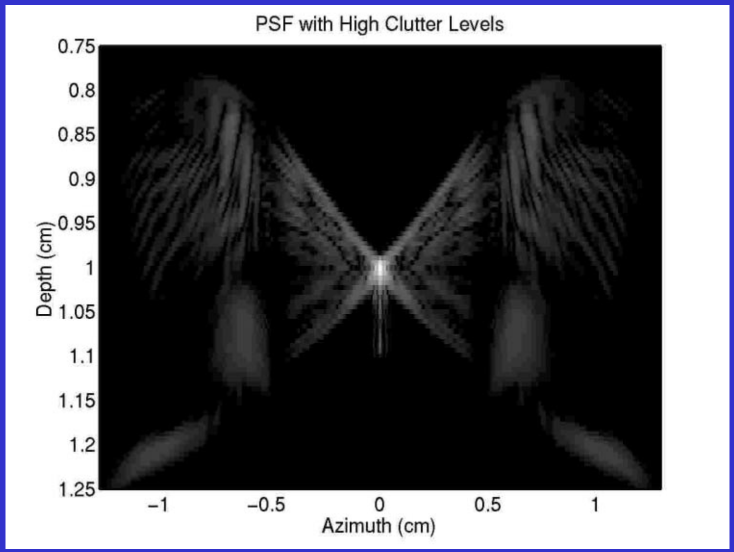
Penetration Depth

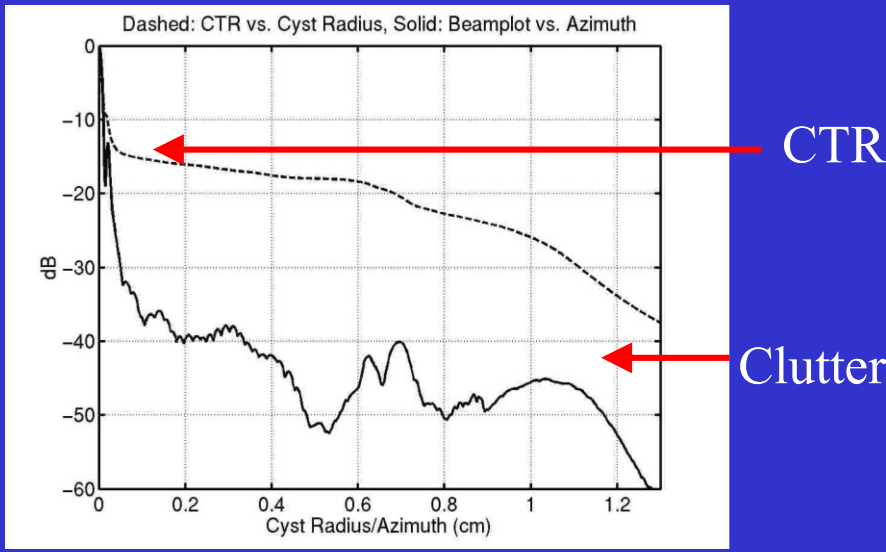
Contrast Resolution (Anechoic Objects)

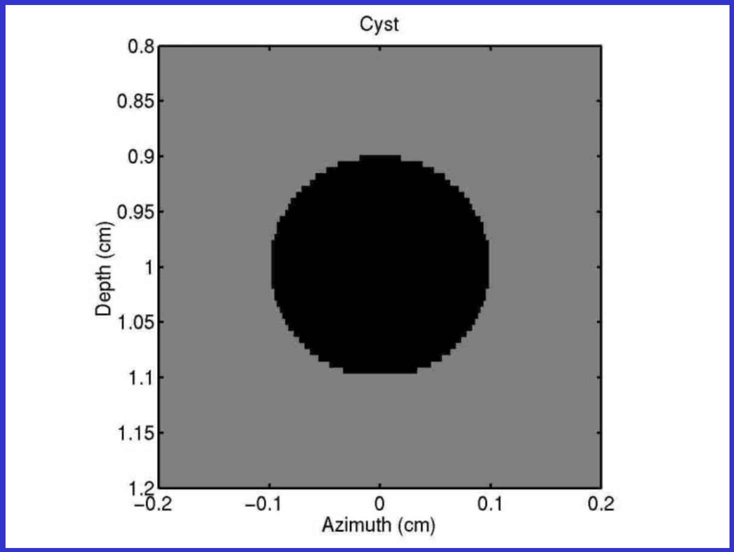
The term contrast resolution sometimes refers to the ability to detect anechoic or weakly echogenic objects in the presence of strong off-axis objects. Acoustic clutter from off-axis objects fill-in images of anechoic objects such as cysts, or weakly echogenic objects such as blood vessels, and reduces their detectability.

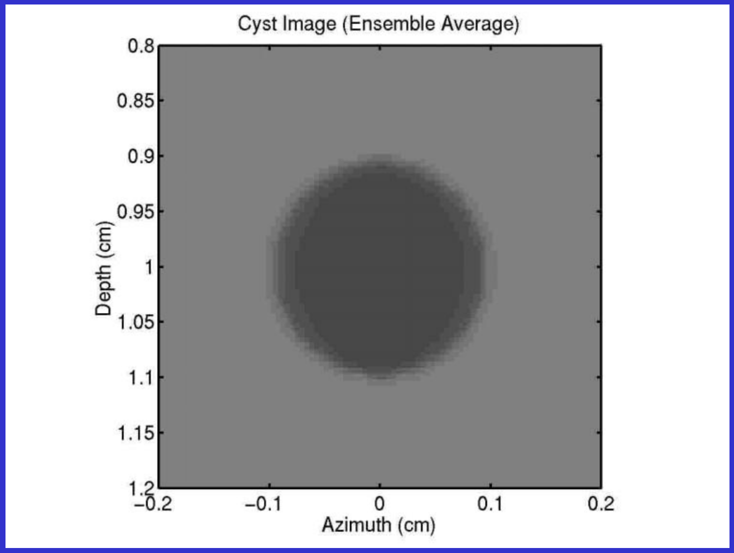
Sources of acoustic clutter are the side lobes, quantization clutter and grating lobes. Tissue aberration is also a significant contributor to acoustic clutter and therefore it is a major source of contrast resolution loss.

Contrast Resolution (Anechoic Objects)









Contrast Resolution (Anechoic Objects)

Clutter Energy to Total Energy Ratio

Contrast resolution of anechoic objects can be quantified by the Clutter Energy to Total Energy Ratio (CTR).

Assume a cyst *R* in a speckle-generating infinite homogeneous medium, and a PSF that is concentric with *R*. CTR is the ratio of the PSF energy outside of *R* to the total PSF energy. This is also the difference between the average brightness levels of the cyst's center and the background.

$$\mathrm{CTR}(\vec{x}_0) = 10\,\log_{10}\left(\frac{\int_{\vec{x}\notin\Re} \left|h(\vec{x}_0,\vec{x})\right|^2 dx}{\int \left|h(\vec{x}_0,\vec{x})\right|^2 dx}\right)$$

R is typically a $5\lambda_0$ diameter sphere (circle for the 2-D case) centered at x_0. CTR is a monotonically decreasing function of the radius of the sphere.

Contrast Resolution (Soft Tissue)

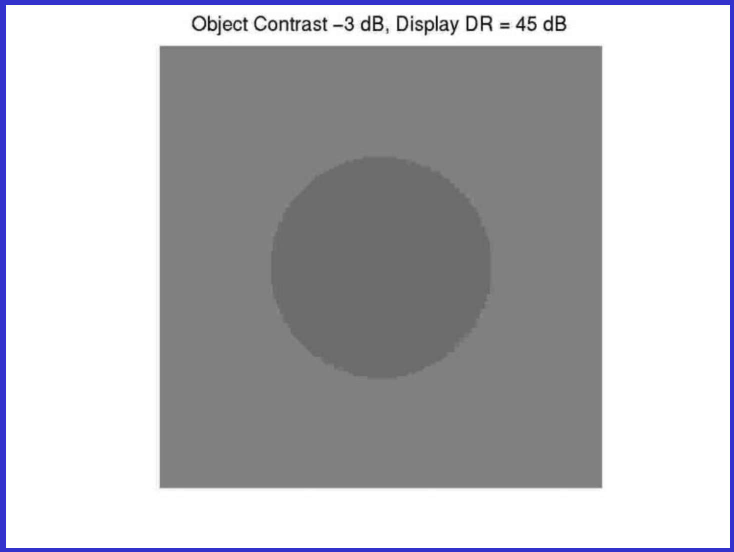
Most commonly, contrast resolution refers to the ability to distinguish echogenicity differences between neighboring soft tissue regions. For example:

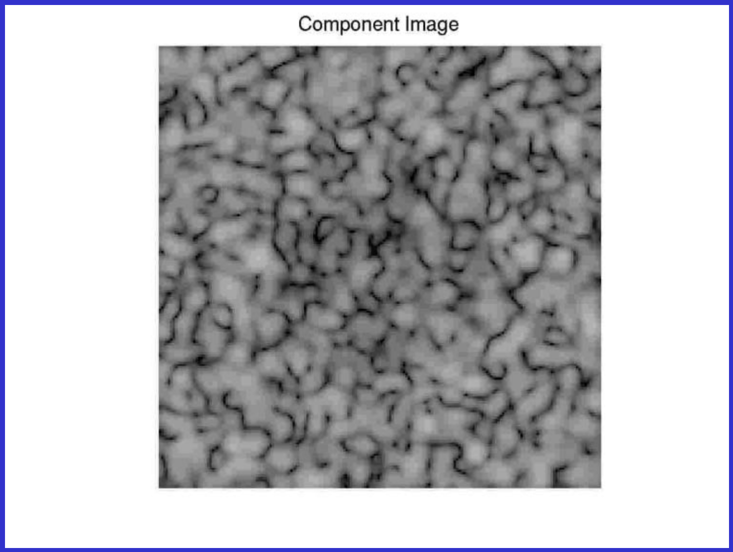
- a hyper-echoic or hypo-echoic lesion in normal soft tissue, e.g., liver parenchyma.
- different types of tissue side by side, e.g., liver/kidney, liver/bowel, etc.

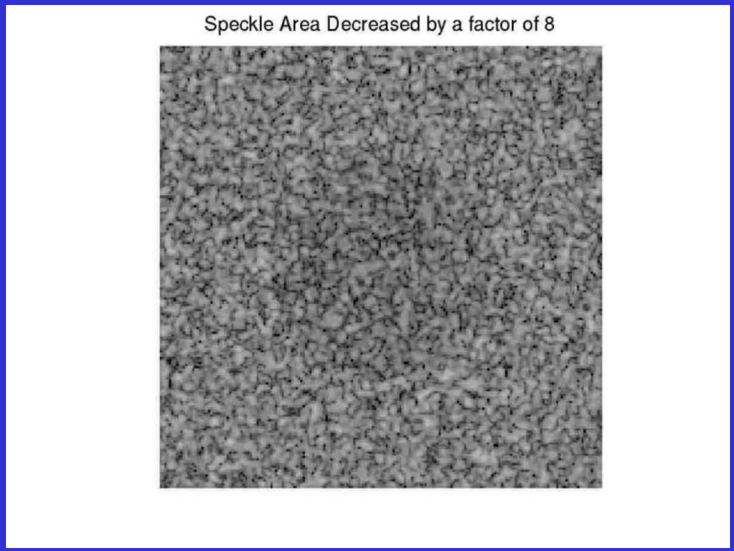
Ultrasound images contain speckle which makes detecting subtle echogenicity variations difficult. Tissue contrast resolution may therefore be improved either by reducing speckle variance or by reducing speckle size.

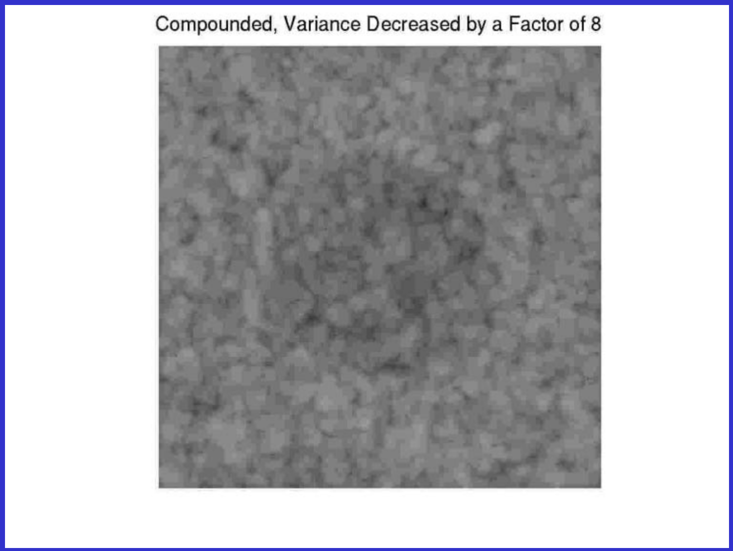
Contrast Resolution (Soft Tissue)

Examples









Contrast Resolution (Soft Tissue)

Object and System Dependencies

Object Contrast (Information)

The mean brightness difference between the lesion and background is determined by the echogenicity (backscattering) difference. Except for the imaging frequency, it is independent of the system parameters.

Speckle Variance (Additive Acoustic Noise)

In the log domain, the standard deviation of the fully developed speckle is fixed, i.e., independent of the object structure. It is 5.57 dB if the image is unalised, uncompounded and not filtered post detection.

Speckle (Independent Sample) Size

The average size of the fully-developed speckle is determined by the lateral and axial bandwidth of the system point spread function. It is independent of the object.

Contrast Resolution (Soft Tissue)

Contrast to (Acoustic) Noise Ratio

Tissue contrast resolution is commonly quantified by CNR. It expresses simply the fact that detectability increases with increasing object contrast and decreasing acoustic noise (speckle variance).

$$\mathrm{CNR} = \frac{\langle L_{\mathrm{lesion}} \rangle - \langle L_{\mathrm{background}} \rangle}{\sqrt{\sigma^2_{\mathrm{lesion}} + \sigma^2_{\mathrm{background}}}}$$

where <L> and σ^2 are the mean and variance of the log image.

- Ignores speckle size.
- Object dependent.

Contrast Resolution (Soft Tissue)
Information Density

Information Density is a detectability measure for soft tissue echogenicity differences (i.e., object contrast) by an ideal (i.e., machine) observer.

$$\text{Information Density} = \frac{\text{CNR}^2}{\text{S}} \qquad (\text{units} \quad \text{mm}^{-2} \text{ or mm}^{-3})$$

where S is the average speckle size,

$$\text{S} = \int_{+\infty}^{-\infty} \gamma_{LL}(\xi)\ d\xi \qquad (\text{mm}^2 \text{ or mm}^3)$$

where γ is the peak normalized autocovariance function.

- Incorporates speckle size.
- Object dependent.

Contrast Resolution (Soft Tissue)

Normalized Information Density

In the case of fully developed speckle, variance of the log image is independent of object echogenicity. In this case, we can replace the (object-dependent) Information Density with a Normalized Information Density, which is purely system dependent. The Normalized Information Density reflects the ability of a system to distinguish 1 dB brightness differences in the presence of fully-developed speckle:

$$\mathrm{NID} = \frac{1}{2\, S\, \sigma^2_{speckle}} \qquad (\text{units} \quad \mathrm{mm}^{-2} \text{ or } \mathrm{mm}^{-3})$$

- Incorporates speckle size.
- Object independent.

Contrast Resolution (Soft Tissue)

Discussion

COMPOUNDING

Spatial and frequency compounding reduce the speckle variance but increase the speckle size. However, in many cases (e.g., because of aberrations or system limitations), compounded images can make better use of the available spatial or temporal spectrum than can non-compounded images. In these cases the increase in speckle size is smaller than the decrease in speckle variance, and ID can be increased.

POST-DETECTION FILTERS

Video filters reduce/increase the speckle variance at the same rate that they increase/reduce the speckle size. No net effect on ID.

CONCLUSIONS

- Fundamental performance measures for an ultrasound imaging system are detail resolution, contrast resolution, temporal resolution, and sensitivity.
- All performance measures are quantifiable through measurements.
- Ultrasound imaging systems can be modeled as four-dimensional (spatio-temporal) linear filters. The point spread function is extremely important for image quality as it determines both detail resolution and contrast resolution.
- Sensitivity (SNR) is an important measure primarily as it effects penetration.
- As compounding and other image processing techniques become more important, information density is becoming an important metric to optimizing and assessing image quality.
- No lab measurement can replace clinical evaluations.

APPENDIX
PHANTOMS

HIGH DYNAMIC RANGE TISSUE MIMICKING PHANTOMS

These custom-made phantoms provide line targets in a liquid with a speed of sound and attenuation coefficient matching those of tissue. Since the liquid has very low scattering, these phantoms are used for measuring the psf down to -50 dB levels and more.

APPENDIX
PHANTOMS

WATER TANK

Water tanks, typically with regulated 37ºC water temperature, are widely used for various engineering tests. A line target, point target or a hydrophone can be scanned in all three dimensions for psf measurements. Transmit-only and receive-only as well as round-trip psf measurements can be made.

Tanks filled with the same fluid that is in the high dynamic range tissue mimicking phantoms can also be used when tissue attenuation effects need to be included.

APPENDIX
PHANTOMS

TISSUE MIMICKING PHANTOM

These commercially available phantoms provide line targets, anechoic cysts, hypo-echoic and hyper-echoic cylindrical or triangular targets of various sizes suspended in a medium with tissue mimicking speed of sound, attenuation and backscattering coefficients. They are used for detail resolution (lateral, axial), brightness uniformity, resolution uniformity and distance accuracy measurements, and qualitative assessment of contrast resolution and shift-invariance. Tissue mimicking phantoms with extra depth and no targets can be used for SNR and penetration measurements. They can also be used for lateral and axial bandwidth (resolution) measurements using the power spectrum of speckle.

APPENDIX
PHANTOMS

SPHERICAL LESION PHANTOM

These phantoms provide anechoic spherical targets of various diameters suspended in a medium with tissue mimicking speed of sound, attenuation and backscattering coefficients. They can be used to assess contrast resolution through CTR measurements. Note that the difference (in log domain) between the mean brightness of the center of the cysts and the mean brightness of the background is equal to CTR for that target geometry.

APPENDIX
PHANTOMS

ABERRATION PHANTOM

These phantoms mimic tissue aberration. They provide speed of sound and attenuation inhomogeneities with various standard deviations and correlation lengths. They can be used to test the system's sensitivity to aberration.

APPENDIX
FUNDAMENTAL PERFORMANCE MEASURES

Detail Resolution: A measure of the minimum spacing of distinguishable point targets.

Contrast Resolution (Tissue): A measure of the minimum echogenicity difference of distinguishable neighboring soft tissue regions.

Contrast Resolution (Anechoic Objects): A measure of detectability of anechoic objects in the presence of strong off-axis objects.

Sensitivity: A measure of the minimum detectable echogenicity.

Temporal Resolution: A measure of the fastest detectable object motion relative to the transducer.

Dynamic Range: A measure of the maximum echogenicity difference of targets simultaneously detectable.