Advanced BME Laboratory (AM5019)
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EXPERIMENT 2:
Axial and lateral resolution estimation in ultrasound simulation.

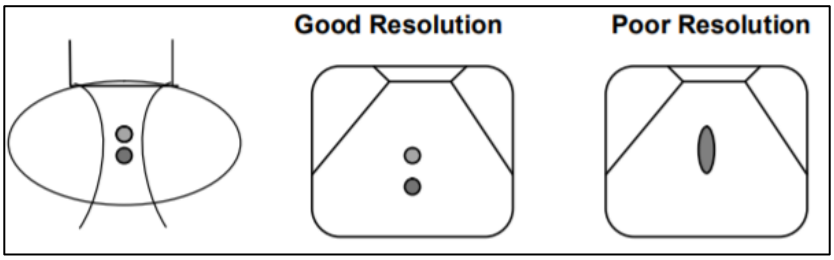
AIM:
Estimate the practical axial and lateral resolution values from a simulation of an ultrasound transducer.

OBJECTIVE:
i. Estimate the practical axial and lateral resolution values from a simulation of an ultrasound transducer for the input data obtained from a target containing two point scatterers embedded in a medium.
ii. Calculate the Axial resolution by varying center frequency and Lateral resolution by varying beamwidth.
iii. Compare the obtained values with the theoretical axial resolution and lateral resolution obtained from the formula and infer on the same.

THEORY:
Resolution of an image can be defined as the minimum distance between two points in the image that can be differentiated. A more precise definition of resolution would be: the ability of a medical imaging system to accurately depict two distinct events in space, time, or frequency as separate and are called spatial, temporal, or spectral resolution, respectively. Given the PSF (Point Spread Function- the output corresponding to a single point source) of a medical imaging system, the resolution can be quantified using a measure called the full width at half maximum (FWHM). This is the (full) width of the PSF at one-half its maximum value. Provided there is no geometric scaling, the FWHM equals the minimum distance that two points must be separated in space in order to appear as separate in the recorded image.

Spatial Resolution:

1. Axial Resolution:

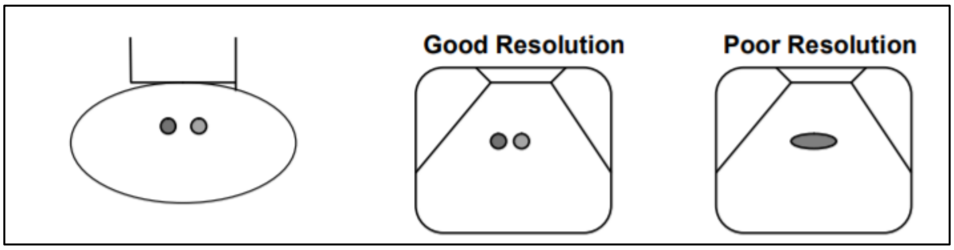


Axial/longitudinal resolution refers to spatial resolution in the direction of beam propagation. It can be described as the instrument's ability to resolve two reflecting boundaries that are closely spaced in the axial (or longitudinal) direction. The theoretical value of axial resolution is given by:

$$AR = \frac{Q\lambda}{4}$$

Q is the quality factor which is given by $Q = \frac{f}{\Delta f}$, where f is the centre frequency of the transducer and Δf is the bandwidth of the transducer. Therefore, a higher frequency and short pulse length will provide a better axial resolution. Transducers of high frequency have thin piezoelectric elements that generate pulses of short wavelength. However, a drawback of high-frequency pulses is that they are attenuated well in soft tissue. This means that they may not be reflected back sufficiently from deep structures, for detection by the transducer.

2. Lateral resolution



Lateral/Transverse resolution is measured in the plane perpendicular to the beam's direction. The spacing in the transverse plane at which the points are resolvable is known as the lateral resolution (LR). The lateral resolution depends on the beam width of the ultrasound wave at that particular depth. The width of the beam and hence lateral resolution varies with distance from the transducer. At the transducer, beam width is approximately equal to the width of the transducer. Then, the beam converges to its narrowest width which is half the width of the transducer, at a perpendicular distance from the transducer called the near-zone length. The region of space subtended by the beam is called the near zone (Fresnel's zone). At a distance greater than the near-zone length i.e., the far zone (Fraunhofer's zone), the beam diverges such that it becomes the width of the transducer, when the distance from the transducer to the reflector is twice the near-zone length. Here, lateral resolution decreases. Lateral resolution is high when near-zone length is long. Near-zone length is given by the following equation- $\frac{D^2}{4\lambda}$, where D is the width of the transducer and λ is the wavelength of the pressure wave. Short wavelength i.e., high frequency of transducer increases the near-zone length. When low-frequency transducers are utilized, lateral resolution deteriorates: in this situation, near-zone length is short which means that structures beyond the near zone are scanned by a divergent beam. When the piezoelectric elements are operated at different times resulting in a narrow-focussed beam, it leads to a creation of a focal region with high lateral resolution. The beam beyond the focal region is divergent and so there is a reduction in lateral resolution of structures deeper than this point.

SOFTWARE USED:

MATLAB programming interface to create virtual ultrasound simulation.

PROCEDURE:

i. Ultrasound simulation images were created considering two point sources. The US image was obtained after convolution between the PSF and TSF followed by an envelope detection and log compression.

ii. To check the effect of frequency on axial resolution, the frequency was varied (3MHz, 5MHz, 7.5MHz) keeping the beam width constant (1mm).

iii. To find the axial resolution, axial profiles were taken and the distance between the peaks was calculated. The minimum distance when the separation between the peaks was greater than or equal to the FWHM ($\frac{1}{\sqrt{2}}(amplitude)$) was estimated as the axial resolution.

iv. To check the effect of beam width on lateral resolution, the beam width was varied (1mm, 5mm, 7mm) keeping the frequency constant (3MHz).

v. To find the lateral resolution, lateral profiles were taken and the distance between the peaks was calculated. The minimum distance when the separation between the peaks was greater than or equal to the FWHM ($\frac{1}{\sqrt{2}}(amplitude)$) was estimated as the lateral resolution.

vi. The values obtained were compared with the theoretical values of axial and lateral resolution.

RESULTS & CALCULATIONS:

Simulation phantom = 40mm x 40 mm
c = 1540 m/s

Axial Resolution:
Beam width fixed at 1mm.
Q = 1/ (fractional_bandwidth) = 1/0.6 = 1.6667
Frequencies: 3MHz, 5MHz, 7.5MHz

Frequency (MHz)	Wavelength (m)	Theoretical Axial Resolution (mm) $\frac{Q\lambda}{4}$	Practical Axial Resolution (mm)
3MHz	**5.1333e-04**	**0.214**	**0.3846**
5MHz	**3.0800e-04**	**0.128**	**0.3078**
7.5MHz	**2.0533e-04**	**0.0855**	**0.2052**

Calculations:

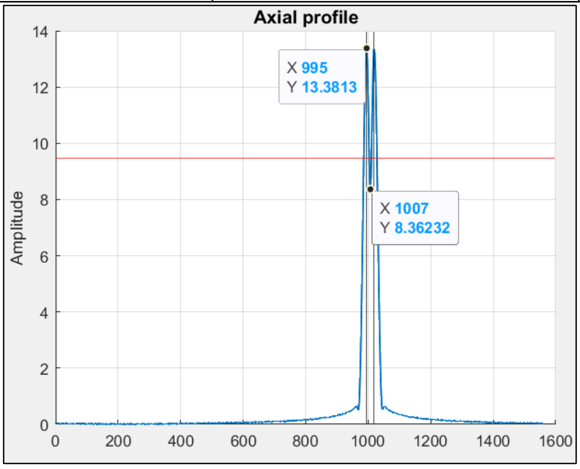
At 3MHz:

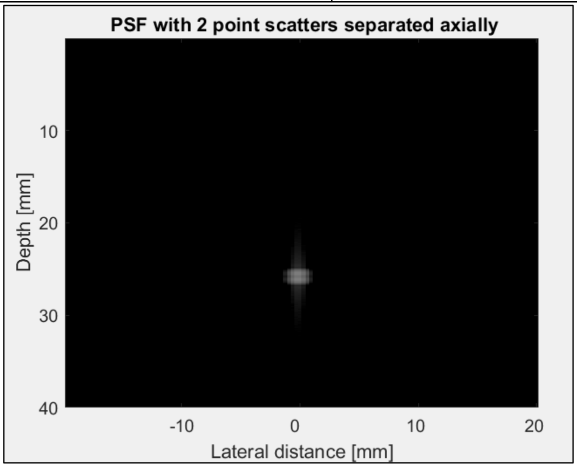
No. of pixels (matrix rows) corresponding to 40mm: 1560

Axial distance in mm corresponding to y pixels = 40/1560*y

15 pixels = 0.3846mm

Distance in pixels	Maxima of axial profile	Max (Axial profile) /√2	Separation
14	13.733	9.7107	11.194
15	13.3813	9.4620	8.3623
16	13.3892	9.4676	5.6247





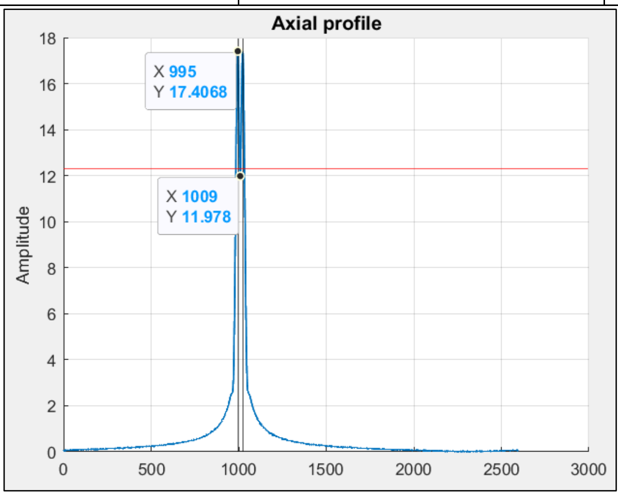
At 5MHz:

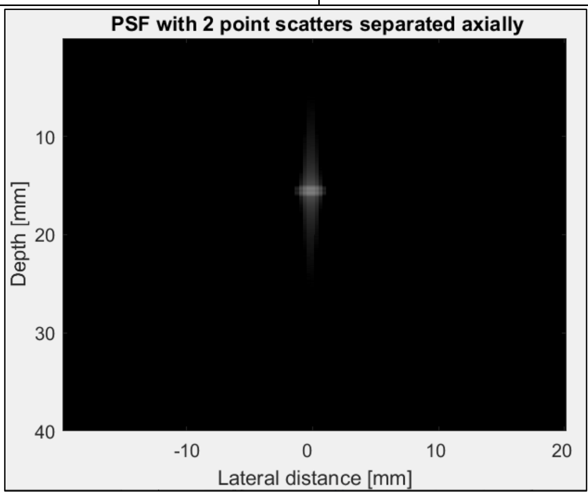
No. of pixels (matrix rows) corresponding to 40mm: 2599

Axial distance in mm corresponding to y pixels = 40/2599*y

20 pixels = 0.3078 mm

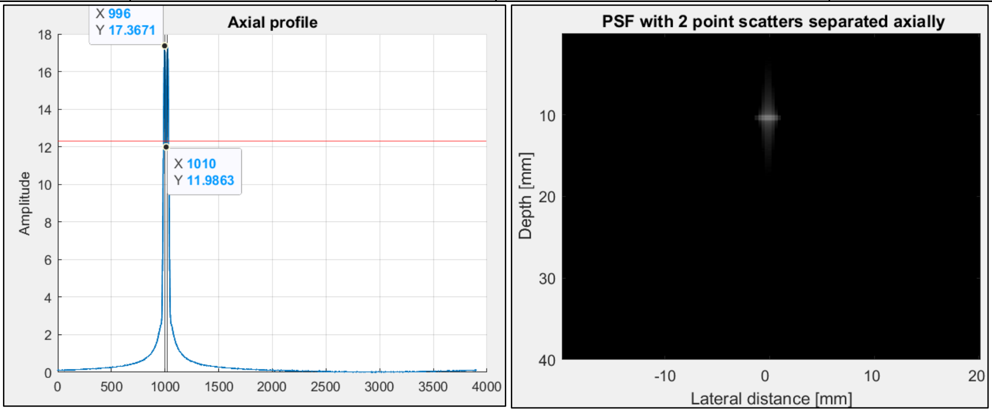
Distance in pixels	Maxima of axial profile	Max (Axial profile) /√2	Separation
19	17.5762	12.4282	13.744
20	17.4068	12.308	11.9780
21	17.3134	12.2424	10.2938





At 7.5MHz:
No. of pixels (matrix rows) corresponding to 40mm: 3898
Axial distance in mm corresponding to y pixels = 40/3898*y
20 pixels = 0.2052

Distance in pixels	Maxima of axial profile	Max (Axial profile) $/\sqrt{2}$	Separation
19	17.5858	12.435	13.7265
20	17.3671	12.2804	11.9863
21	17.3283	12.2596	10.2759



Lateral Resolution
Frequency fixed at 3MHz. Wavelength = 5.1333e-04

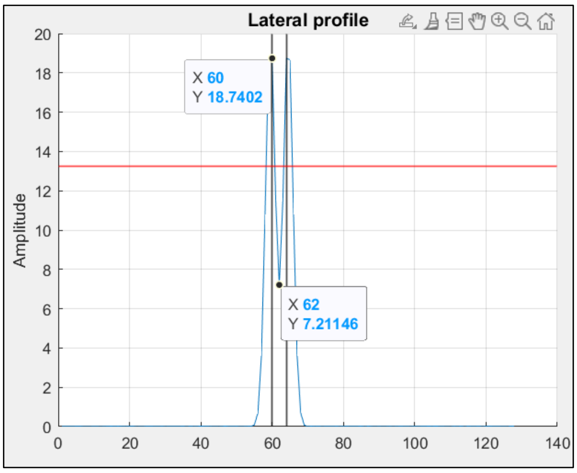
Beamwidths: 1mm, 5mm, 7mm

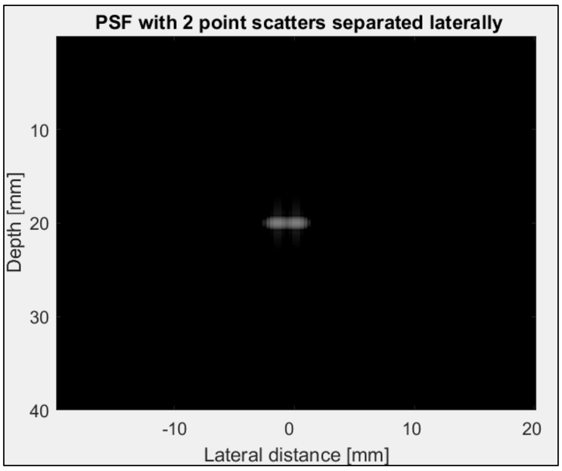
Beamwidth (mm)	Theoretical lateral Resolution (mm) ~beamwidth	Practical Axial Resolution (mm) (from simulation)
1	**1**	**1.5625**
5	**5**	**6.25**
7	**7**	**8.75**

Calculations:
No. of pixels (matrix columns) corresponding to 40mm: 128
Lateral distance in mm corresponding to x pixels = 40/128*x

At 1mm:
5 pixels = 1.5625mm

Distance in pixels	Maxima of axial profile	Max (Lateral profile) $/\sqrt{2}$	Separation
4	19.3497	13.6823	14.3846
5	18.7402	13.2445	7.2115
6	18.6661	13.1989	4.2853

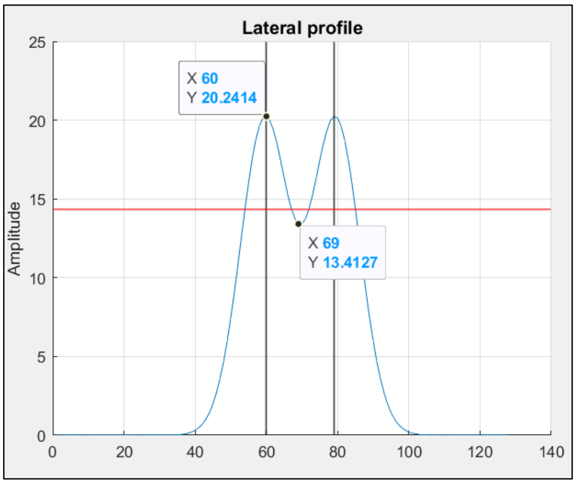


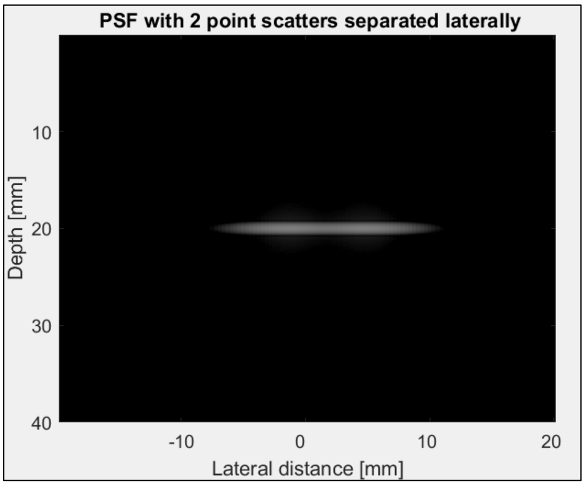


At 5mm:

20 pixels = 6.25 mm

Distance in pixels	Maxima of axial profile	Max (Lateral profile) /√2	Separation
19	20.4101	14.432	14.8824
20	20.2414	14.3128	13.4127
21	20.113	14.222	11.9424

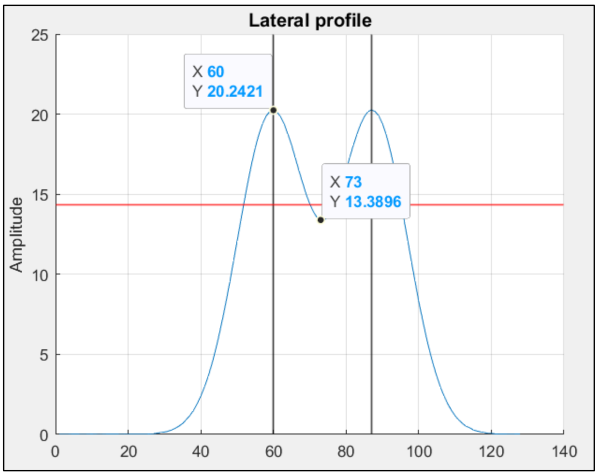


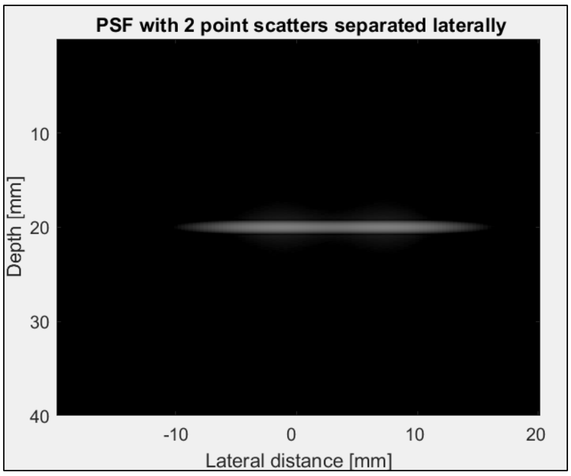


At 7mm:

28 pixels = 8.75

Distance in pixels	Maxima of axial profile	Max (Axial profile) /√2	Separation
27	20.3486	14.3886	14.4432
28	20.2416	14.3130	13.3868
29	20.179	14.268	12.3322





CONCLUSIONS:

1. The practical axial and lateral resolution have been determined from the US simulation.
2. As the frequency increases axial resolution improves. Therefore, the highest frequency, in this case 7.5MHz has the best axial resolution (Theoretical: 0.0855, Practical: 0.2052 mm).
3. As the beam width increases lateral resolution degrades. Therefore, the smallest beam width in this case 1mm has the best lateral resolution (Theoretical: 1mm, Practical: 1.5625 mm).
4. The theoretical values estimate the theoretical best resolution possible. In reality, the resolution depends on the point spread function and is affected by other factors such as random noise (added in the simulation), the correct placement of the transducer perpendicular to the surface, variations in approximated speed of sound in the medium. In addition, the lateral resolution depends on the depth of the target, in the near zone vs the far zone.