Medical Imaging – SBE 4120

Fall 2024 – 2025

Task 2 – Ultrasound Simulation

Pressure Fields of a Phased Array Transducer

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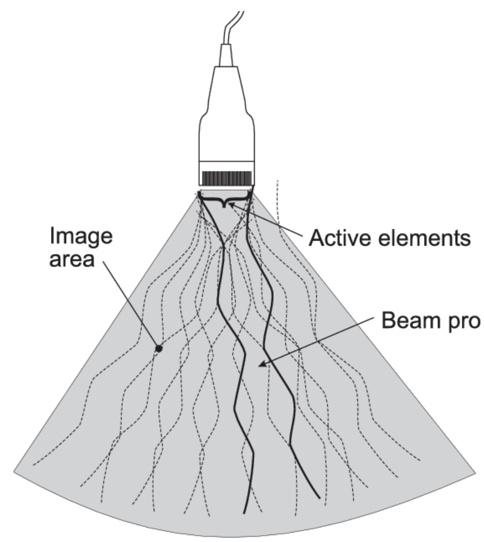
Introduction:

Ultrasound imaging is a widely used diagnostic tool in medical applications, due to its non-invasive nature, real-time capabilities, and versatility. It employs high-frequency sound waves to create detailed images of internal structures. By interpreting the reflections of these waves' ultrasound provides insights for diagnoses and therapeutic interventions. One of the key aspects of ultrasound imaging is the manipulation of **acoustic fields**, which can be focused, diverging, or multi-focal, depending on the application.

In this task, we utilize a simulation toolbox named "The **M**ATLAB **U**ltra**S**ound **T**oolbox (**MUST**)." And it is an open-source simulator that enables modeling and testing of ultrasound systems. This report uses MUST to explore focused, diverging, and multi-focus pressure fields, showcasing their principles and applications in ultrasound imaging.

Explanation of Concepts:

1. Phased Array Transducers



A phased array transducer consists of multiple small ultrasound elements (or **Piezoelectric crystals**) that can be fired individually in a specific sequence in order to direct the sound wave in a specific direction. The relative timing of signals sent to each element can be controlled to focus the beam, steer it in a specific direction, or create a diverging wave.

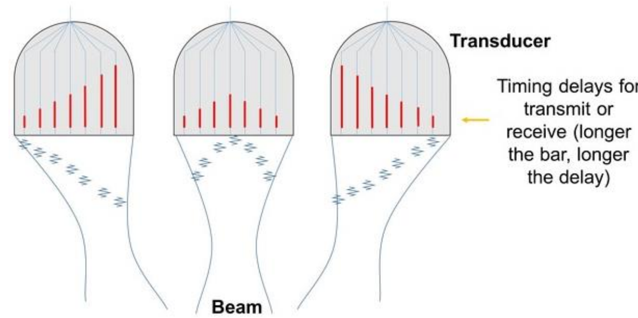
Which are important for these reasons:

- **Precision:** precise control of the pressure field to generate clear and accurate images of structures within the body.
- **Efficiency in therapy:** Focused and diverging fields are critical for delivering energy precisely to a target area or distributing it across a large region.
- **Flexibility:** By using phased array transducers, ultrasound systems can dynamically adjust beam properties to suit specific imaging or therapeutic requirements.

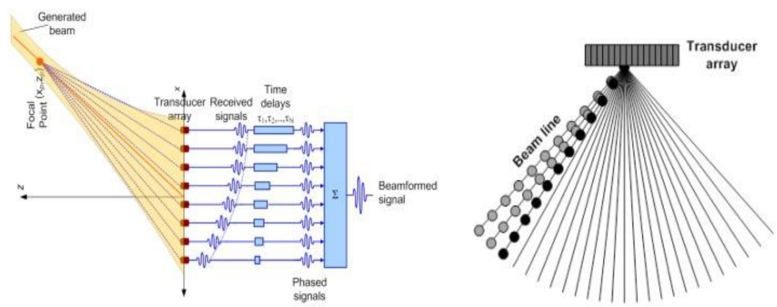
Its properties:

- **Frequency Range:** Low Frequency "1 – 8 MHz"
- **Penetration Depth:** Up to 35cm
- **Field of View (FOV):** Sector with expanded field of view in deeper regions
- **Beamforming Techniques:** Steering Techniques

2. **Steering Techniques:** Beam steering refers to altering the angle of the ultrasound beam with respect to the transducer without moving the probe. Beam steering allows a point on an image to be insonated from multiple angles from a single probe and a single position of the probe. Beam steering is accomplished by adding delays to the transmit and receiving timing of the ultrasound beam.

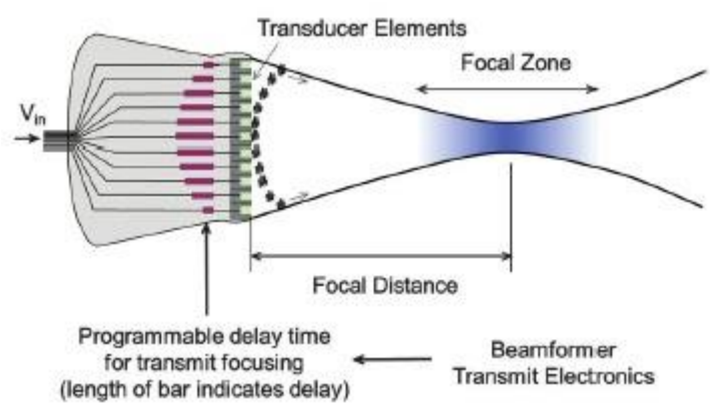


3. **Beamforming:** is the process of manipulating the phase and amplitude of waves emitted from individual elements to control the shape and direction of the ultrasound beam. Simulated by summing signals from scatterers with appropriate delays.



(a) (b)

4. **Transmit Delays:** Precise control of the timing of wave emission from each element is the foundation of beamforming. Delays determine the direction and shape of the ultrasound beam. When ultrasound waves are emitted simultaneously from all elements in an array, the resulting wavefront is planar or spherical, depending on the configuration. To shape the wavefront—for example, to focus it at a specific point—each element must emit its wave at a precisely controlled time. This time difference, or delay, ensures that the waves from all elements constructively interfere at the desired location. Delay for each element is calculated as:

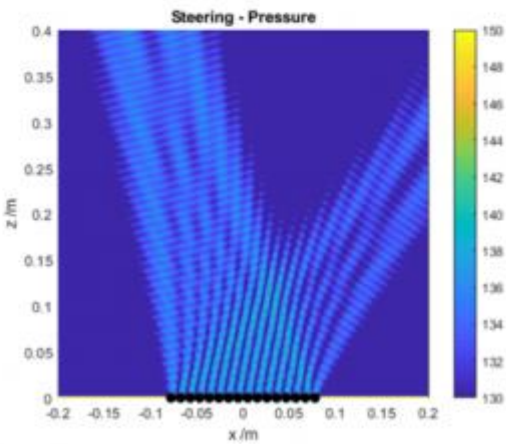


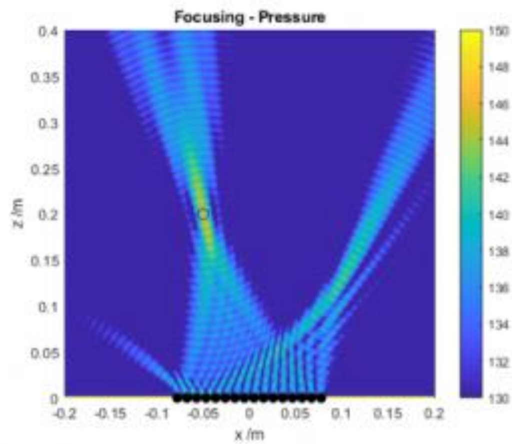
$$delay_i = \frac{distance_i - distance_{min}}{c}$$

Where:

– $distance_i$: The distance from the i-element element to the target focal point.
– $distance_{min}$: The shortest distance among all elements to the focal point.
– c : The speed of sound in the medium.

5. **Pressure Field:** The pressure field represents the intensity of ultrasound waves in the medium, computed by considering the transducer parameters, delays, and grid settings.

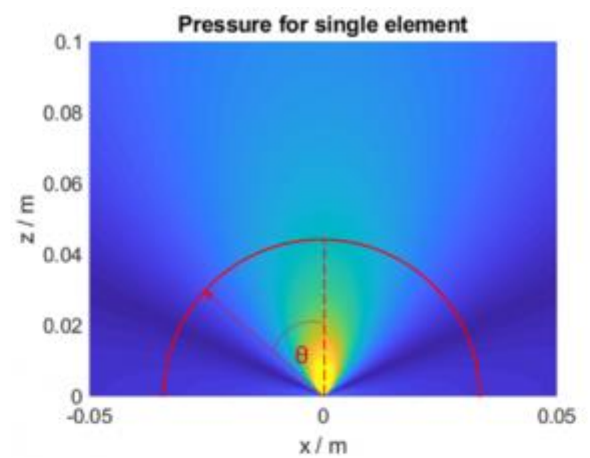




6. **Root Mean Square (RMS) pressure:** RMS pressure is the average magnitude of the oscillating ultrasound pressure field over a period, providing a measure of the effective pressure intensity.

Comparison Between Pressure Fields:

1 - 2D Focused Pressure Field (Single Focused Pressure):



A focused pressure field concentrates ultrasound energy at a specific point in space (the focal point). This is achieved by controlling the timing (delays) of the ultrasound waves emitted from each element of the phased array transducer.

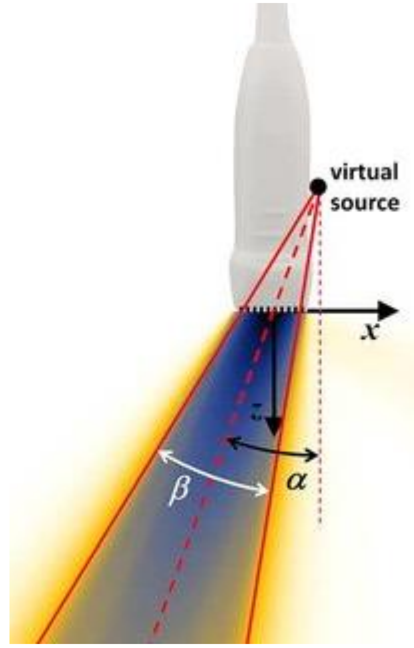
How It Works:

- **Wavefronts and Focus**:
  - Ultrasound waves travel at a constant speed (speed of sound in the medium).
  - By delaying the emission of waves from specific elements, the waves arrive simultaneously at the focal point, causing constructive interference.

- **Beam Narrowing**:
  - The energy is concentrated in a small region around the focal point, which improves resolution and intensity.

2 - Diverging Pressure Field

A diverging pressure field spreads ultrasound energy outward from the transducer. Instead of focusing on a single point, the energy disperses over a wide field of view.

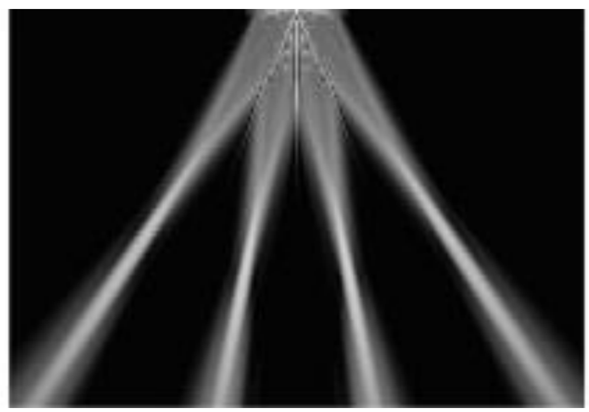


How It Works:

- **Wavefront Divergence**:
  – Delays are adjusted so that waves interfere destructively near the transducer's central axis and constructively at larger angles. This creates a diverging wavefront.
- **Wide-Angle Coverage**:
  – The energy spreads across a large area, resulting in a lower intensity compared to focused fields but covering a broader region.

3 - Multi-Focus Pressure Field

A multi-focus pressure field uses multiple focal points to achieve high resolution at several depths simultaneously. Instead of focusing all energy at a single point, the transducer alternates focus across multiple zones.



How It Works:

- **Sequential Beamforming**:
  – Delays are calculated for each focal depth. The transducer focuses at one depth at a time, and the resulting pressure fields are combined to cover the entire region of interest.

Methods and Results:

This section details the process of simulating various pressure fields using the MUST toolbox. The aim was to model different beam configurations, including a single focal point, a diverging beam, and multiple focal points, and to analyze the resulting pressure fields. The simulations utilized a phased array transducer, enabling precise beam control through the adjustment of transmit delays.

Phased Array Transducer General Parameters

- **param = getparam('P4-2v'):** Loads parameters for a 64-element phased-array transducer, specifically a cardiac phased array.
- **Key Parameters Used:**
  - param.fs: Sampling frequency, defined as 4 times the central frequency (param.fc).
  - param.c: Speed of sound, set to 1540 m/s, typical for soft tissues.
  - grid_points: Defines the resolution of the simulation grid (e.g., 256x256 grid points).
- **Code:**

```
% Define transducer parameters
param = getparam('P4-2v'); % Phased array transducer parameters
param.fs = 4 * param.fc; % Sampling frequency
param.c = 1540; % Speed of sound [m/s]
% Simulation settings
depth = 10e-2; % Depth of simulation area [m]
width = 10e-2; % Width of simulation area [m]
grid_points = [256, 256]; % Grid resolution
```

Focused Pressure Field (Single Focus)

- **Concept:**

  A focused pressure field occurs when the ultrasound waves emitted by all the elements in a phased array transducer converge at a specific focal point. This results in a concentrated region of high pressure at the focal point. The aim was to simulate an ultrasound beam focused at a single point in space. This configuration is ideal for high-resolution imaging of a specific region of interest.

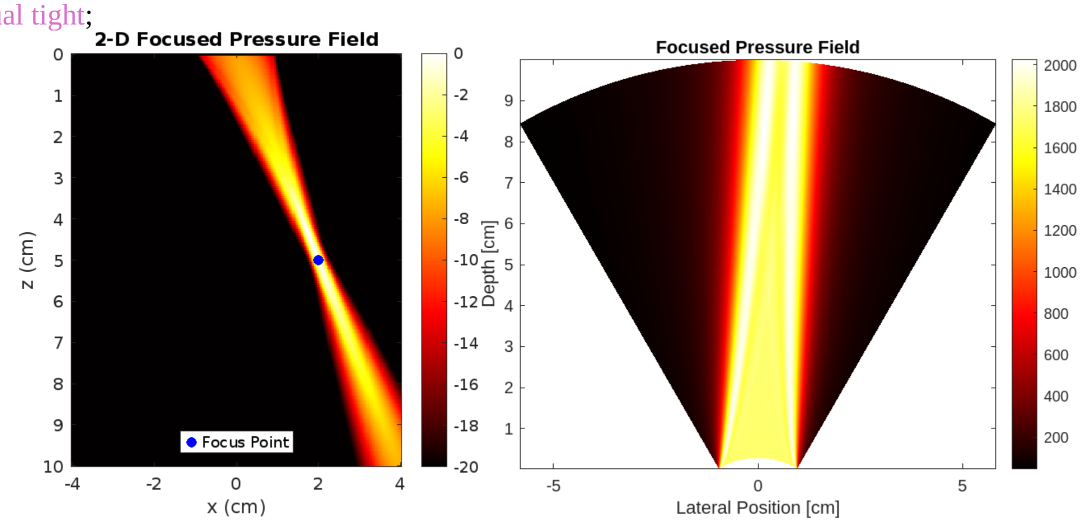
- **Implementation of the Code:**
  - The focus depth is set to `focus_depth = 6e-2` (6 cm).
  - The `txdelay` function calculates the transmit delays for each transducer element to ensure the waves arrive simultaneously at the focal point.
  - A polar grid for the simulation is created using `impolgrid`, defining the field of view and grid resolution.
  - The `pfield` function simulates the pressure field for the focused beam.

- ## Key Steps:

1. Use the same transducer parameters as for the focused beam.
2. Set the focus depth to zero and specify the beam angle.
3. Calculate delays for the diverging beam using txdelay.
4. Create a grid for the diverging field.
5. Compute the pressure field with pfield.
6. Visualize the diverging field using a heatmap.

- ## Code:

```
% Focused pressure field
focus_depth = 6e-2;            % Focal point depth [m]
txdel_focused = txdelay(param, focus_depth);  % Transmit delays for focus
[x_focused, z_focused] = impolgrid(grid_points, depth, pi/3, param);  % Simulation grid
p_focused = pfield(x_focused, z_focused, txdel_focused, param);       % Compute pressure field
% Visualize the focused pressure field
figure;
pcolor(x_focused * 100, z_focused * 100, p_focused);  % Heatmap visualization
shading interp;
colormap hot;
colorbar;
title('Focused Pressure Field');
xlabel('Lateral Position [cm]');
ylabel('Depth [cm]');
axis equal tight;
```



- ## Notes:

  – The focused pressure field results in a sharp, high-intensity focal zone, providing excellent resolution along the lateral and axial axes.
  – Energy disperses beyond the focal point, causing a reduction in intensity in the far-field region.
  – Ideal for applications requiring precise energy delivery (e.g., ultrasound imaging, tissue ablation).
  – Could be used in medical imaging (e.g., echocardiography) to achieve high spatial resolution at a specific depth.

Diverging Pressure Field

• Concept:

In a diverging pressure field, the ultrasound waves spread out from the transducer elements, creating a wide-angle field of view. This is achieved by setting the transmit delays such that the waves are out of phase with each other.

• Implementation of the Code:

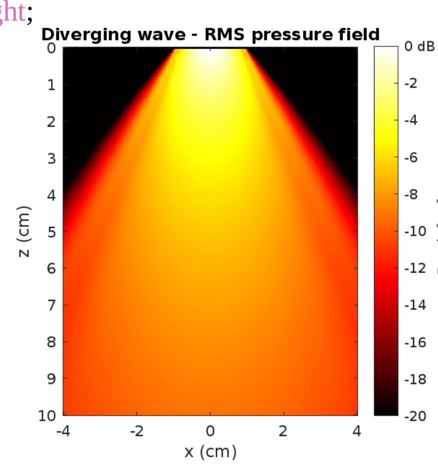
- The transmit delays for a diverging wave are calculated using `txdelay` with a focal depth of 0 (`txdelay(param, 0, pi/3)`).
- A polar grid is created similarly to the focused field.
- The `pfield` function simulates the diverging wave.

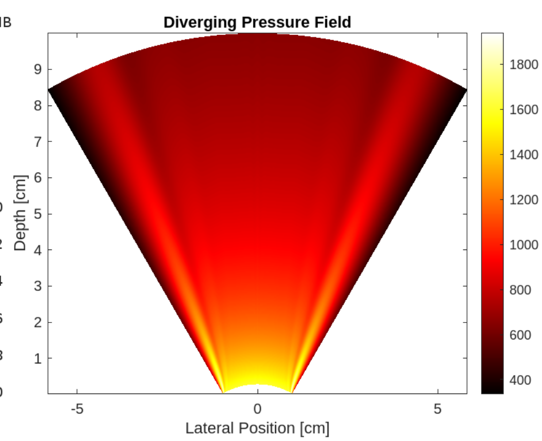
• Key Steps:

1. Use the same transducer parameters as for the focused beam.
2. Set the focus depth to zero and specify the beam angle.
3. Calculate delays for the diverging beam using txdelay.
4. Create a grid for the diverging field.
5. Compute the pressure field with pfield.
6. Visualize the diverging field using a heatmap.

• Code:

```
beam_angle = pi/3;              % Diverging beam angle (60 degrees)
txdel_diverging = txdelay(param, 0, beam_angle);   % Transmit delays for diverging beam
[x_diverging, z_diverging] = impolgrid(grid_points, depth, beam_angle, param);  % Grid
p_diverging = pfield(x_diverging, z_diverging, txdel_diverging, param);        % Compute field
% Visualize the diverging pressure field
figure;
pcolor(x_diverging * 100, z_diverging * 100, p_diverging);  % Heatmap visualization
shading interp;
colormap hot;
colorbar;
title('Diverging Pressure Field');
xlabel('Lateral Position [cm]');
ylabel('Depth [cm]');
axis equal tight;
```





- **Notes:**

– The energy is distributed over a larger area, resulting in a lower intensity compared to a focused field.
– The beam maintains a broad coverage, making it less precise but more useful for wide-area imaging.
– Could be used for large-field-of-view imaging or therapeutic applications requiring ultrasound over a broad area.

Multi-Focus Pressure Field

- **Concept:**

A multi-focus pressure field uses multiple focal points to enhance resolution and coverage across varying depths. Each focal point requires its own set of transmit delays, and the resulting pressure field is the superposition of individual focal fields.

- **Implementation in Code:**

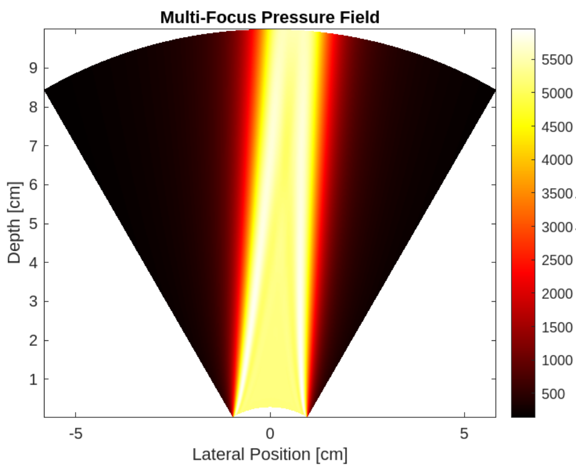
  - Multiple focal depths are defined (focus_depths = [4e-2, 6e-2, 8e-2]).
  - For each depth, the transmit delays are calculated using txdelay.
  - The pressure fields for all focal depths are summed together.

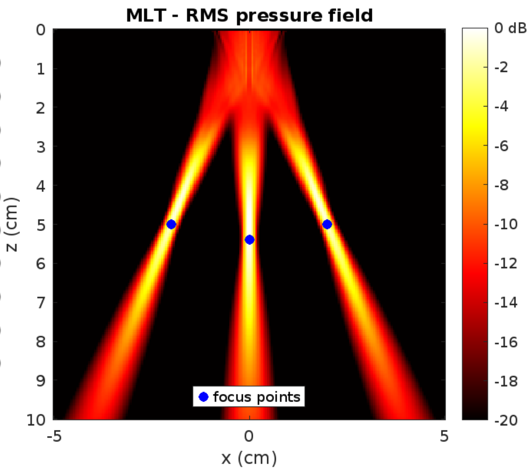
- **Key Steps:**

1. Define multiple focal depths.
2. For each focal depth, calculate delays and compute the pressure field using `txdelay` and `pfield`.
3. Sum the pressure fields for all focal depths.
4. Visualize the resulting multi-focus pressure field.

- **Code**

```
focus_depths = [4e-2, 6e-2, 8e-2]; % Multiple focal points [m]
p_multifocus = zeros(size(x_focused));
for focus = focus_depths
   txdel_multi = txdelay(param, focus); % Transmit delays for each focal point
   p_multifocus = p_multifocus + pfield(x_focused, z_focused, txdel_multi, param);
end
% Display multi-focus field
figure;
pcolor(x_focused * 100, z_focused * 100, p_multifocus);
shading interp;
colormap hot;
colorbar;
title('Multi-Focus Pressure Field');
xlabel('Lateral Position [cm]');
ylabel('Depth [cm]');
axis equal tight;
```





- **Notes:**
  - Each focal region exhibits lower intensity than a single focus because the total energy is divided among the multiple foci.
  - This configuration is ideal for scenarios requiring consistent imaging or therapeutic effects across different depths.
  - Could be used in advanced medical imaging to scan structures at different depths with high resolution (e.g., scanning an entire organ).

Observation

PROPERTY	FOCUSED PRESSURE FIELD	DIVERGING PRESSURE FIELD	MULTI-FOCUS PRESSURE FIELD
FIELD SHAPE	Small, concentrated	Wide, spreading	Multiple high-intensity zones
INTENSITY	High at the focal point	Lower, spread across a region	High at each focal depth
RESOLUTION	High at the focus	Lower, uniform	High at multiple depths
FIELD OF VIEW	Narrow, limited	Wide, extensive	Balanced, depth-specific
APPLICATIONS	Targeted imaging, therapy	Broad scans, therapeutic use	Depth-specific imaging

Reference:

[1] https://www.sciencedirect.com/science/article/pii/S1936878X14004410

[2] https://www.researchgate.net/publication/291148938_Staggered_Multiple-PRF_Ultrafast_Color_Doppler

[3] https://support.ultraleap.com/hc/en-us/articles/360004369058-The-Science-of-Phased-Arrays

[4] https://radiopaedia.org/articles/phased-array

[5] https://radiopaedia.org/articles/beam-steering?lang=us

[6] https://radiopaedia.org/articles/beam-focusing?lang=us

[7] https://www.sciencedirect.com/science/article/abs/pii/B9781845691868500041

[8] https://www.sciencedirect.com/sdfe/pdf/download/eid/3-s2.0-B9781845691868500041/first-page-pdf

[9] https://www.researchgate.net/publication/226463215_Ultrasound_Imaging_and_Its_Modeling