Verasonics EoUSI Simulator User Manual

D00223 Rev. B

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Introduction

Welcome! This manual describes the Verasonics Essentials of Ultrasound Imaging (EoUSI) simulator software package designed to offer an experiential way of learning about ultrasound imaging. Additional information about the simulators and their operation can be found in the course textbook, Essentials of Ultrasound Imaging, by Szabo and Kaczkowski (Elsevier, 1st Edition, 2023), available for purchase on the book website. Throughout the manual, the user can find references to the book for each of the simulators described.

The simulators and book are part of the EoUSI Curriculum offered by Verasonics, which is designed to enable students and industry professionals to learn about basic ultrasound concepts. The course curriculum couples education in ultrasound theory with numerical experiments using the Simulators described in this manual. Additionally, the course offers hands-on experiences using the Verasonics Vantage® or Vantage® NXT Research Ultrasound System in a laboratory setting.

About Simulators

The Simulators are built using the MATLAB® App Designer and deployed with the MATLAB Compiler (MathWorks®, www.mathworks.com), and the simulator package is provided in an executable form so that a MATLAB license is not required for it to run. A runtime engine, freely available from MathWorks, is required to be installed on the user's computer to provide the computational libraries needed to make the simulator package operate. Verasonics offers this package in two versions (Windows and macOS). Individual simulators can be accessed through the Simulator Launcher GUI.

User options on each simulator GUI fall into three general selection categories: control of input variables, output variables, and display options as shown in Figure 1. Equations or a sequence of computational steps are represented by the purple block. Detailed information about these equations, specific to each simulator, can be found in the course book and references.

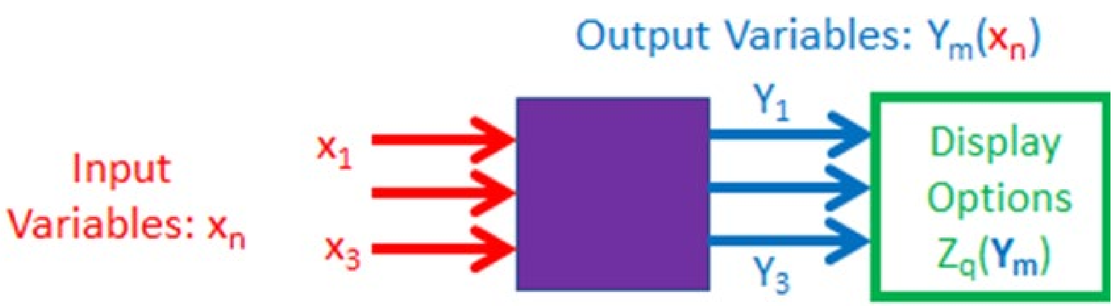

Figure 1: Simulator Variables

Using simulator GUI controls, the user can vary the input variables xn—such as sliders, knobs, dropdown selections, and edit windows (that provide options to input specific numerical values). In some simulators, the user has the option to select output variables (Ym) as a function of a subset of selected input variables xn and to choose from various output display options. Most simulators operate like virtual laboratories in that they present quantitative measures of the output.

For detailed information on simulator concepts, refer to Section 1.4.1: Introduction to Simulators; and for an example of selection options, refer to Section 5.3.1 Field Simulator control panel in the course textbook, Essentials of Ultrasound Imaging.

These simulators offer the equivalent of, in some cases, thousands of combinations of variables for explorations. The user is encouraged to experiment with different inputs to observe how they affect the output.

Initiating the Simulator Launcher

NOTE: Close any running instances of the simulator before upgrading.

To install the Simulators:

1. After downloading the installer as a .zip file *(Available on [Essentials of Ultrasound Imaging Simulators](#))* extract its contents by unzipping the folder.
2. Find the Verasonics_*EoUSI_Simulator_Installer* file within the unzipped folder and double-click on it. This launches the installation window.
3. In the installation window, it is recommended that you accept the default installation location for the EoUSI Simulator and MATLAB Runtime. The installer checks if the MATLAB Runtime is already installed; if not, it will download and install the appropriate version. Note that this is a free distribution available for download on the Mathworks website. **NOTE:** *The installation window may take a while to appear. Please wait and do not click on the icon repeatedly, as this may delay the installation even further.*
4. Click the Start Installation button. The installation should start immediately.
5. Once the installation is complete, the installer may display additional steps for configuration. Skip these instructions and simply close the installation window.
6. Finally, open the installation folder, and click on the Essentials of Ultrasound icon to launch the Simulator Launcher window (as shown in *Figure 2*). The Simulator Launcher window presents all the simulators categorized under various course modules.
7. To display only the course modules, click the Collapse All button.
8. To display all the simulators categorized under the course modules, click the Expand All button. Alternately, click on the expansion arrow next to a module to display all simulators listed under that module.

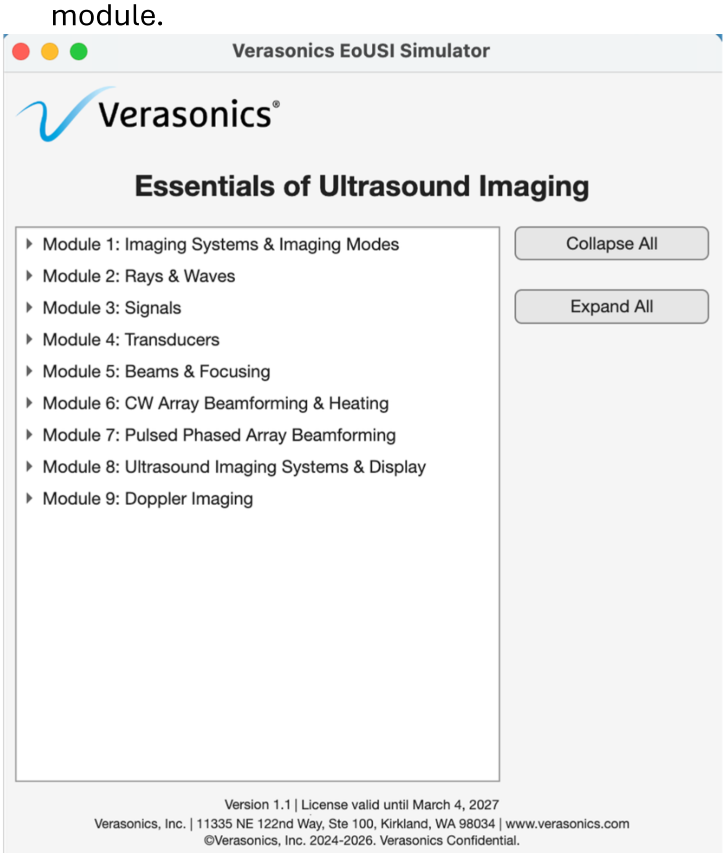

Figure 2: Simulator Launcher Window

Expiration of simulators

Simulators have an expiration date, which is displayed in the footer of the simulator launcher, as shown in Figure 2. The user will receive a warning starting 14 days prior to the expiration date; a pop-up window will appear when launching the simulator launcher with a message to warn the user about the expiration and instructions on how to obtain a new version. This new version can be downloaded from the Verasonics website (https://verasonics.com/essentials-simulators-2/).

Resizing the Simulator Window

The simulator GUI window automatically adjusts to fit the computer screen; therefore, when using the simulator GUI on a smaller screen, the user should resize the simulator window accordingly.
To resize the simulator GUI Window-

1. Right-click on the lower-left corner of the simulator GUI. A resizing cursor will appear.
2. Drag the cursor to resize the simulator GUI window.

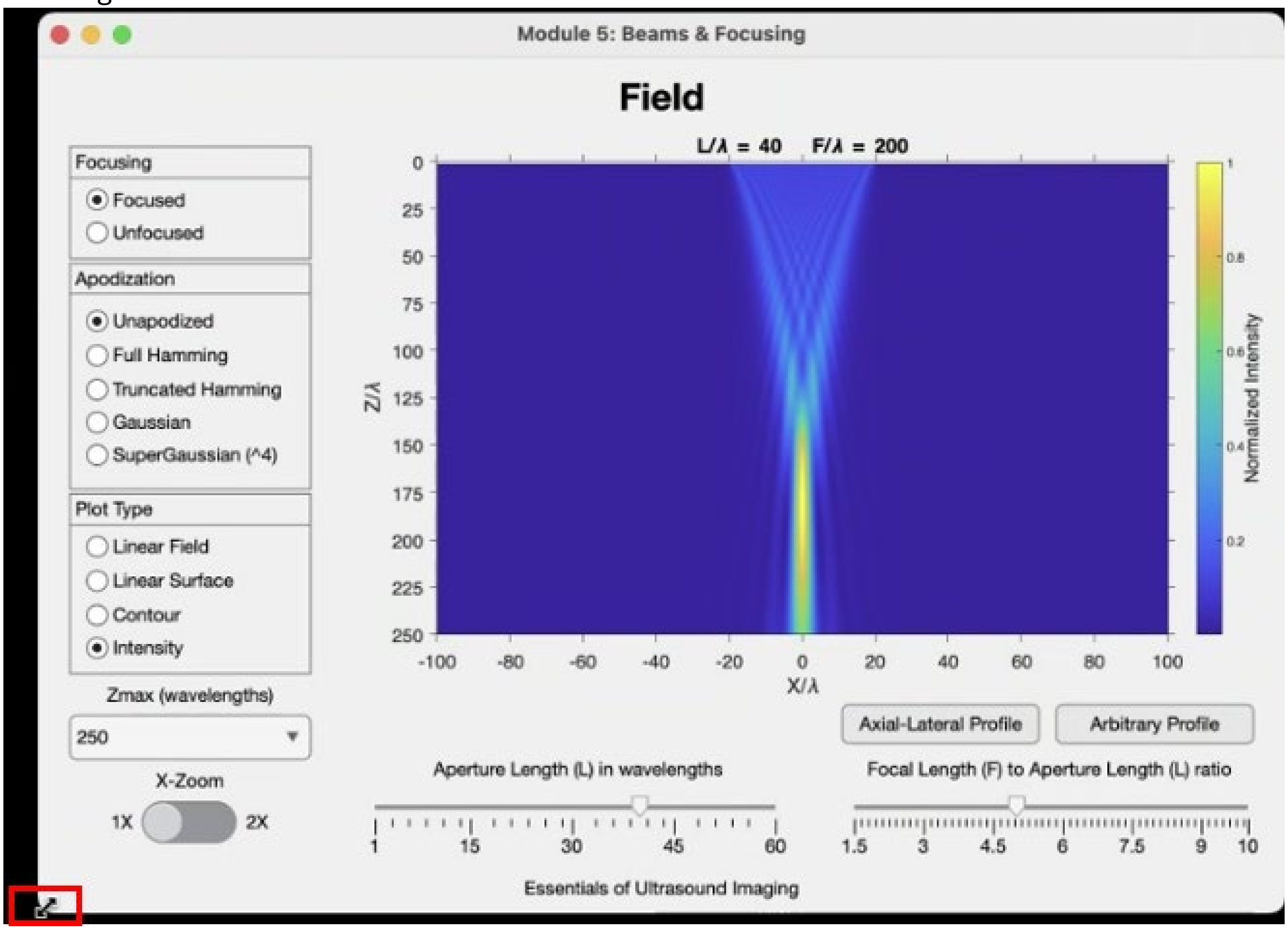

Figure 3: Cursor on the lower-left corner of the simulator window

Utilizing MATLAB Axes Toolbar for Plot Analysis

MATLAB software features a specialized toolbar for each set of plot axes. The axes toolbar includes several built-in tools displayed as a line of icons, as shown Figure 4. The user can access the toolbar by hovering over the plotted area. For more information on the axes toolbar, visit the MATLAB webpage.

Figure 4: MATLAB Axes Toolbar

The data points tab on this toolbar (3rd from left) can be used to derive quantitative data from the output curves in an output display. Because of quantization, the value at the desired input variable may not be available; the user is encouraged to use the nearest value.

Module 1: Introduction to Imaging and Imaging Systems

Imaging Systems Simulator

Using the Imaging Systems simulator, the user can simulate the brain-eye imaging system.
The frequency spectra of the key components of the brain-eye imaging system (transmitter, reflective target, and receiver) are multiplied together to generate an output spectrum. The resulting spectrum is then translated to a known color patch. *For detailed information on this simulator module, refer to Section 1.4.2: First Example of a Simulator in the course textbook, Essentials of Ultrasound Imaging.*
To launch the Imaging Systems simulator, click the Imaging Systems button on the Simulator Launcher window. The Imaging Systems simulator launches sequentially with three tabs (the Transmitter tab, the Reflector tab, and the Receiver tab) on the upper left corner of the GUI and defaults to the Transmitter tab.

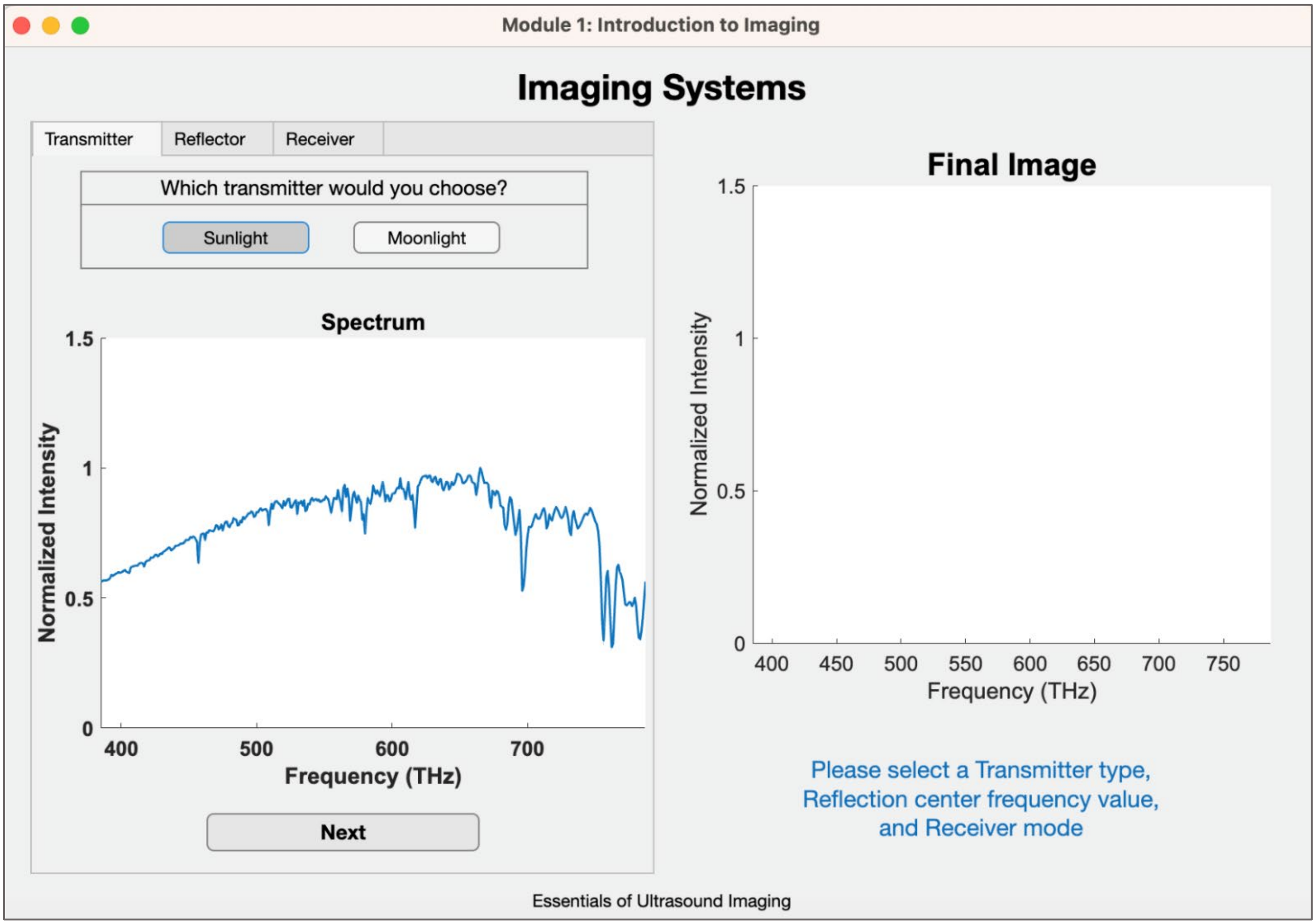

Figure 5: Imaging Systems Simulator - Transmitter Tab

As with all other simulators, the user is encouraged to experiment with different inputs to see how the output is affected. A typical workflow for using this simulator is as follows:

1. Select a transmitter source option.

Table 1: Imaging System Simulator: Transmitter Source Options

UI control	Description
Sunlight	Select the Sunlight button to obtain the transmitter spectrum using the sunlight source.
Moonlight	Select the Moonlight button to obtain the transmitter spectrum using the moonlight source.

2. Upon selecting the transmitter source option, the transmitter spectrum is displayed on the left side of the GUI.
3. Click the Next button to proceed to the Reflector tab. Alternatively, select the Reflector tab on the top upper left corner of the GUI.
4. In the Reflector tab, use the slider (or the input field located next to the slider) to set the object reflection color of a reflective target.

Table 2: Imaging Systems Simulator - Reflector Tab Controls

UI Control	Description
Change Object Reflection Color	Adjust the slider to select the center frequency (in THz) of the reflective target. Alternatively, enter the center frequency value in the input field.

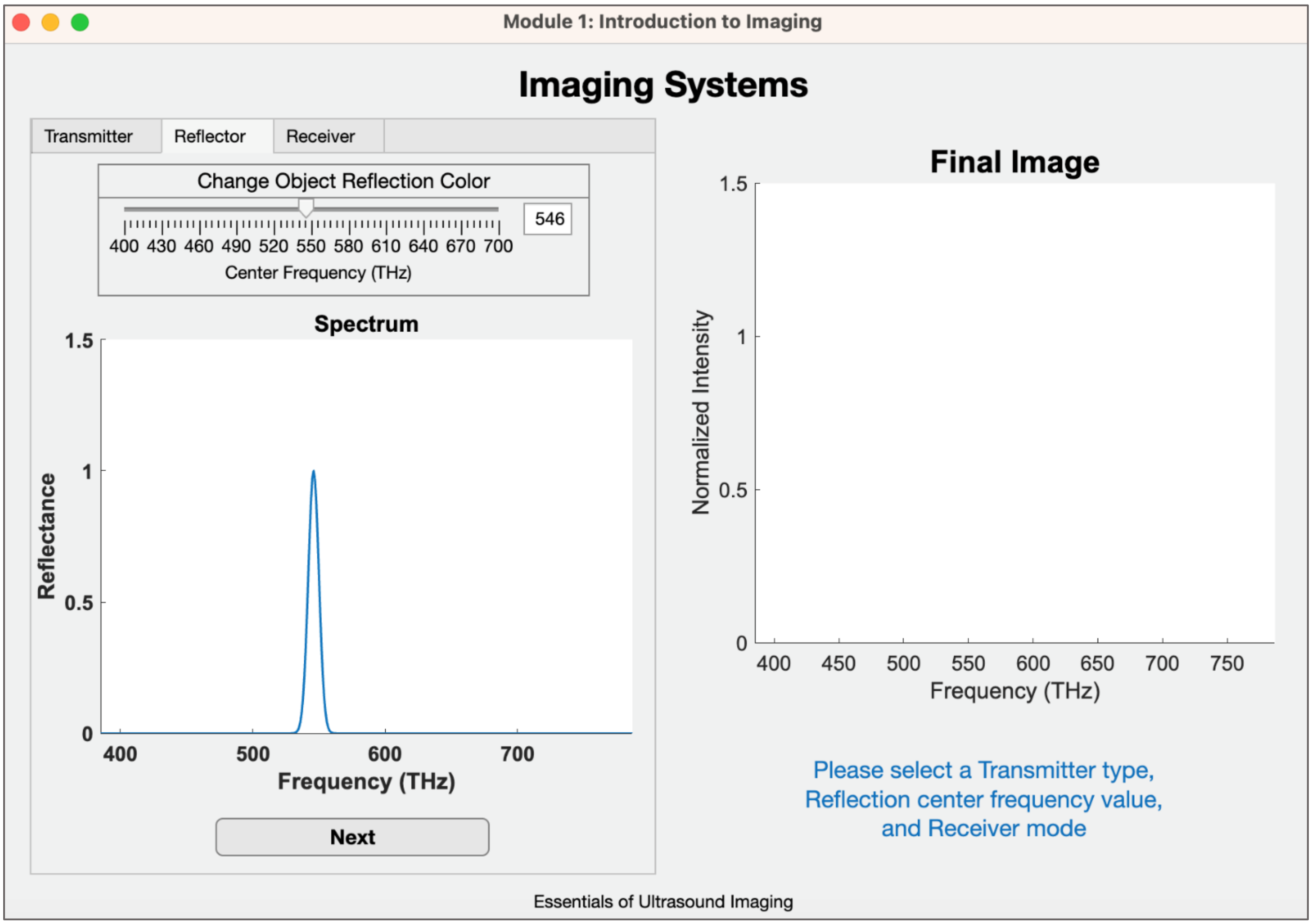

Figure 6: Imaging Systems Simulator - Reflector Tab

5. Observe that the sensitivity spectrum is displayed on the left side of the GUI.
6. Click the Next button to proceed to the Receiver tab; alternatively, select the Receiver tab on the top left corner of the GUI.
7. In the Receiver tab, select the Sun Mode or the Moon Mode option.

Table 3: Imaging Systems Simulator - Receiver Tab Controls

UI Control	Description
Sun Mode	Select the Sun Mode button to obtain the daylight response.
Moon Mode	Select the Moon Mode button to obtain the nightlight response.

8. Observe the receiver spectrum on the left side of the GUI.
9. To view the outcome, click the Generate Image button.

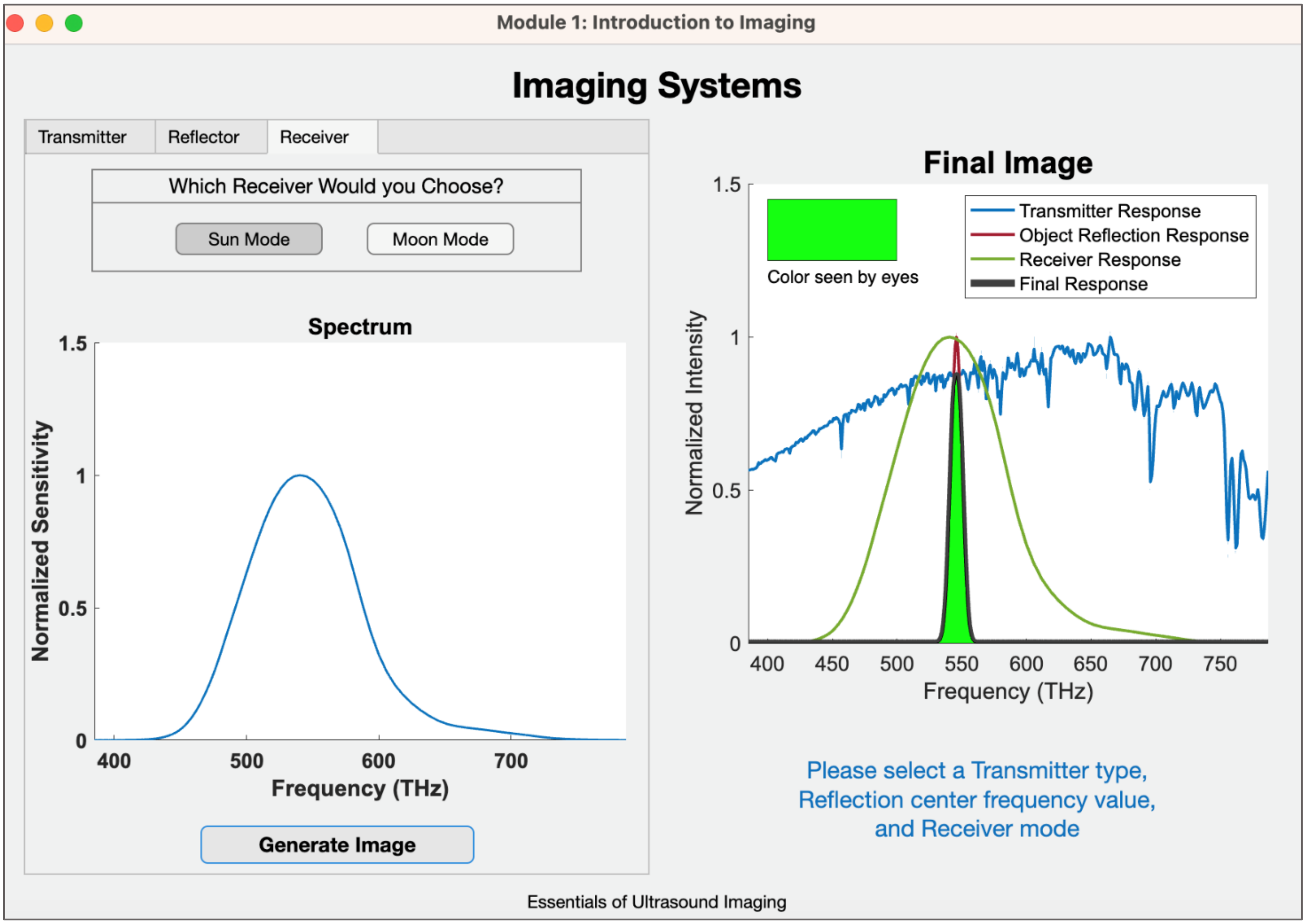

Figure 7: Imaging Systems Simulator - Receiver Tab

To the right of the GUI, the overall output response is plotted as a filled-in black curve, which is the product of three individual factors: solar response indicated by the blue curve, reflector object response (centered at 546 THz) indicated by the red curve, and daylight response indicated by the green curve. The final output response as indicated by the black curve is filled in by the perceived color—the perceived color is also shown as a patch in the upper left corner of the plot.

3D Imaging Modes Simulator

The 3D Imaging Modes simulator allows users to view the selected object in three different imaging modes (A-mode, B-mode, and C-mode). This simulator familiarizes the user with the different scanning modes and trains them to determine the 3D object based on its 2D scans. *For detailed information on this simulator module, refer to Section 1.7.2: Three-Dimensional Imaging Modes Simulator in the course textbook, Essentials of Ultrasound Imaging*.

To launch the 3D Imaging Modes simulator, click the 3D Imaging Modes simulator on the Simulator Launcher window.

A typical workflow to use the simulator is as follows:

1. From the Shape Selection menu, select the shape of the 3D object under examination.

Table 4: 3D Imaging Modes Simulator - Shape Selection

UI Control	Description
Object 1	Select Object 1 to view a teardrop-shaped object in the 3D cartesian coordinate system.
Object 2	Select Object 2 to view a cylindrical-shaped object in the 3D cartesian coordinate system.
Object 3	Select Object 3 to view an irregularly shaped object (digital bunny) in the 3D cartesian coordinate system.

2. Select a scanning mode from the three different scanning mode options.

Table 5: 3D Imaging Modes Simulator - Scanning Mode Options

UI Control	Description
A Mode	Select the A Mode option to view an A-mode image. When the A Mode option is chosen, the simulator displays a single line through the 3D object. The observer views it from an array situated in the x-y plane, gauging the depth of the object along the z-axis.
B Mode	Select the B Mode option to obtain object perspective in the x-z scan plane, at a location Y selected using the Position slider.
C Mode	Select the C Mode option to obtain object perspective in the x-y scan plane, again using the Position slider to set the Z coordinate value.

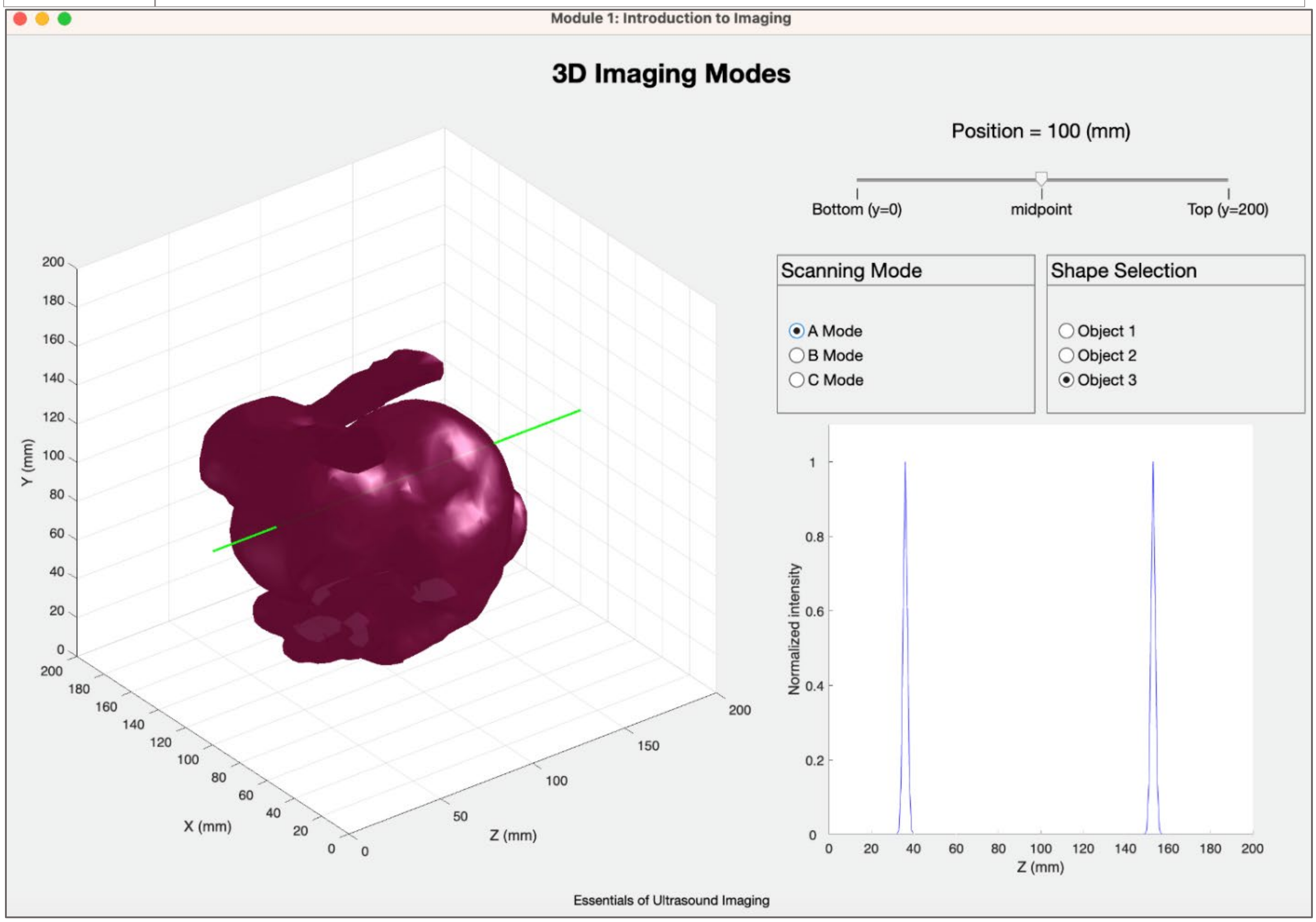

Figure 8: 3D Imaging Modes - A-Mode Selection

3. Adjust the Position slider.
   - In A Mode, adjust the slider to move the green scan line along the y-axis.
   - In B Mode, adjust the slider to move the green x-z scan plane along the y-axis.
   - In C Mode, adjust the slider to move the green x-y scan plane along the z-axis.

For B Mode and C Mode selections, as the user adjusts the slider, the green scan plane shifts its position through the object, and a corresponding 2D image is displayed on the lower left corner of the GUI. For A Mode selection, a 2D plot of normalized intensity along the z-axis is displayed.

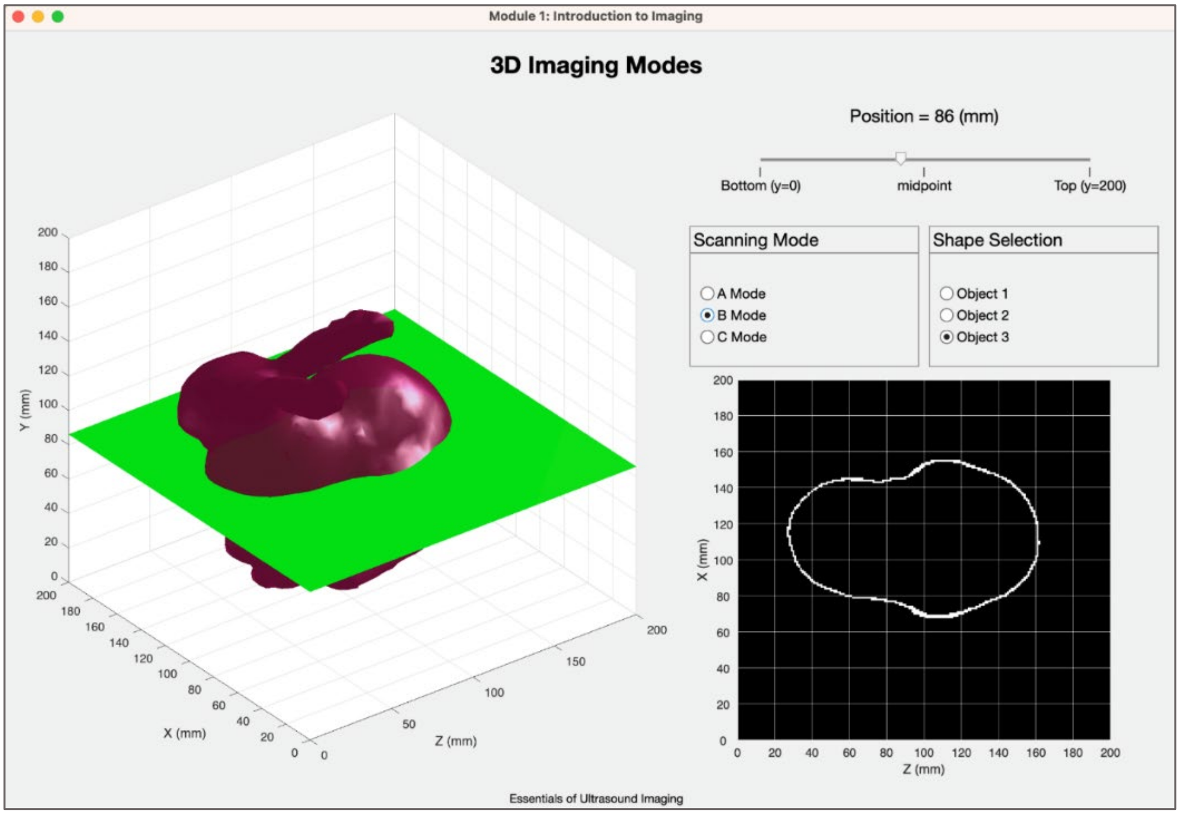

Figure 9: 3D Imaging Modes Simulator - B Mode Selection

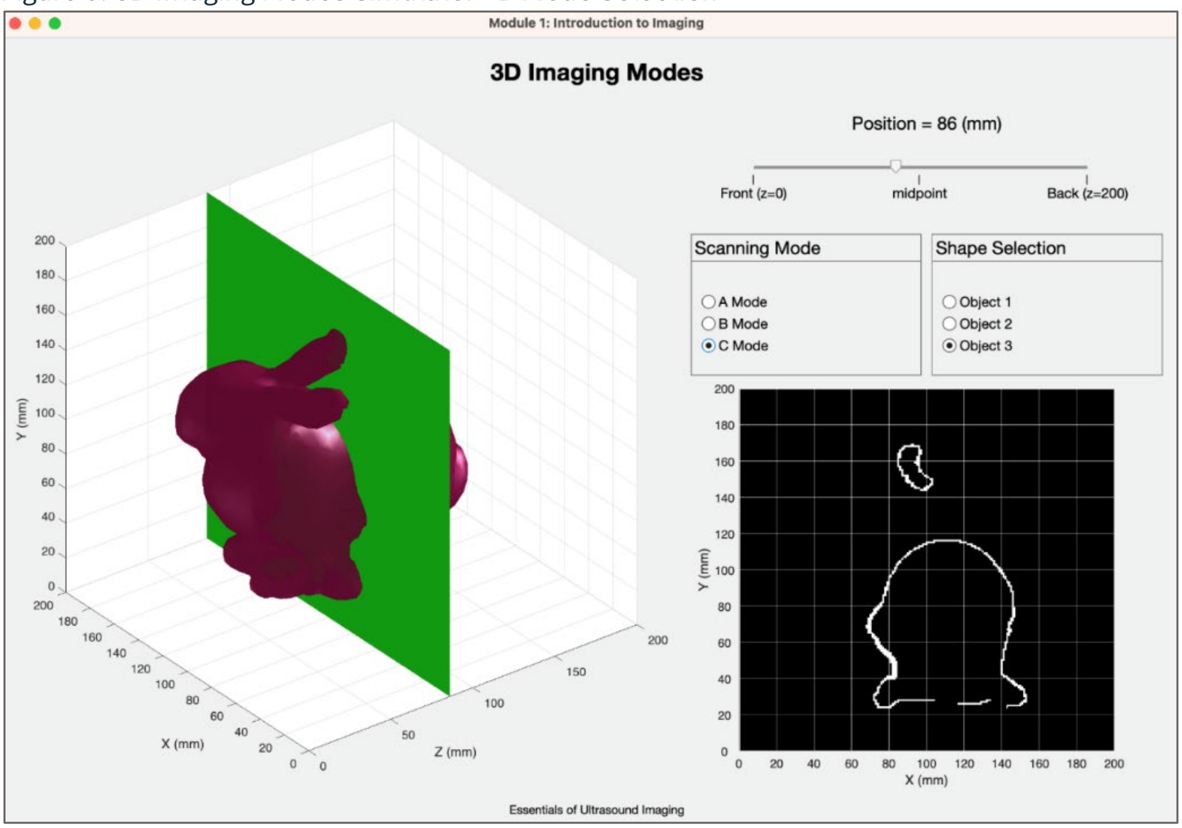

Figure 10: 3D Imaging Modes Simulator - C Mode Selection

Secret Object Simulator

Using the Secret Object simulator, the user can examine a concealed 3D object in various imaging modes. After analyzing data from 1D and 2D scans of the object and identifying the object, the user can reveal the object. This simulator allows users to improve their ability to visualize and interpret ultrasound images. *For detailed information on this simulator module, refer to Section 1.9.1.1: Secret Object Simulator in the course textbook, Essentials of Ultrasound Imaging.*

A typical workflow for using the simulator is as follows:

1. Select a 3D object using the Secret image menu options—Object 1, Object 2, Object 3, Object 4, or Object 5.
2. Select a scanning mode (A Mode, B Mode, or C Mode) to view the concealed object in one or two dimensions.
3. Adjust the Position slider.
   - In A Mode, adjust the Position slider along the y-axis to view the normalized intensity plot.
   - In B Mode, adjust the Position slider along the y-axis to view 2D x-z slices of the object at various positions along the y-axis direction.
   - In C mode, adjust the Position slider along the z-axis to view 2D x-y slices of the object at various positions along the z-axis direction.
4. After examining the object in various scanning modes, attempt to identify/guess the object.
5. Select the Reveal Answer button to reveal the actual 3D shape of the object that appears as a 3D object in a separate popup window.

Note: The user has the option to rotate the view angle of the 3D object in this window by selecting Tools: Rotate 3D from the upper toolbar.

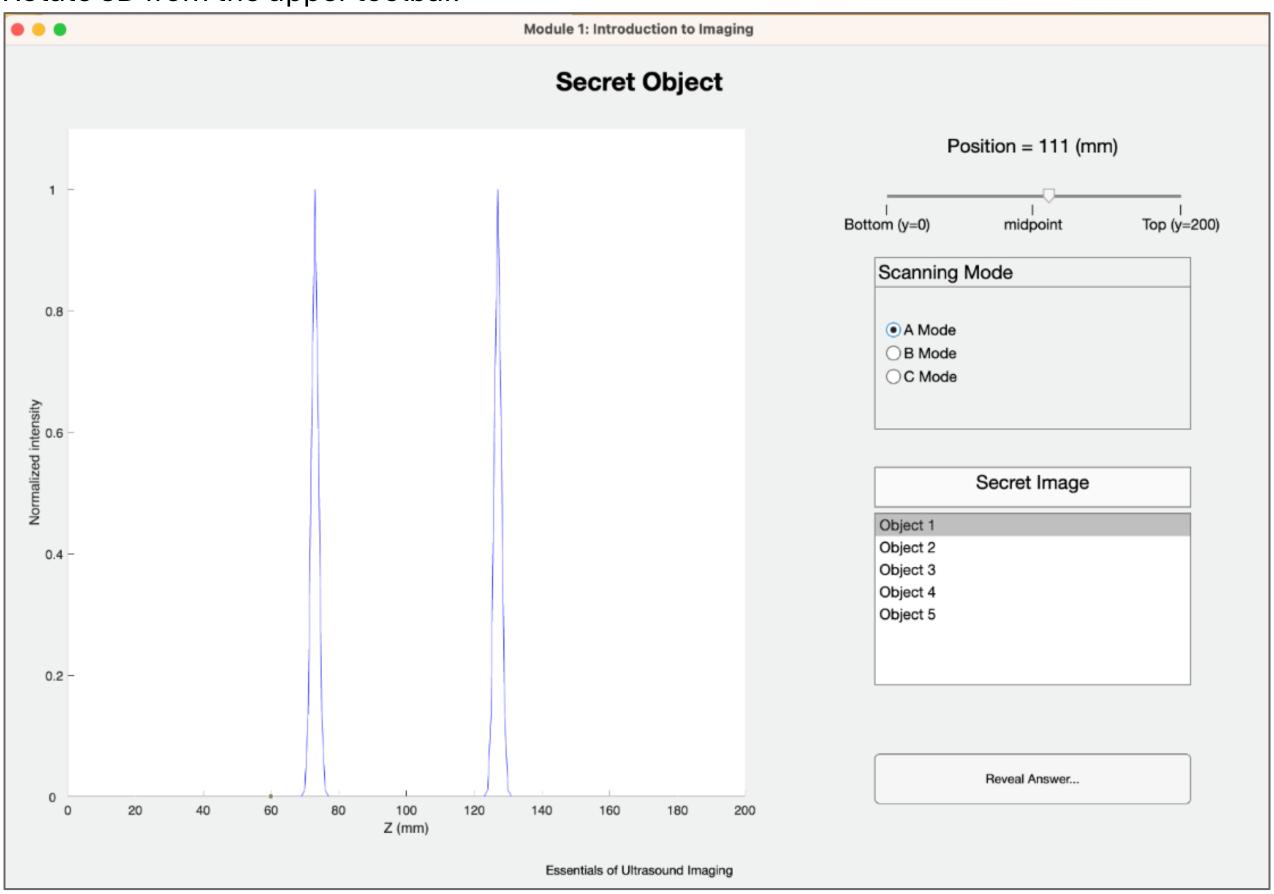

Figure 11: Secret Object Simulator - A Mode Selection

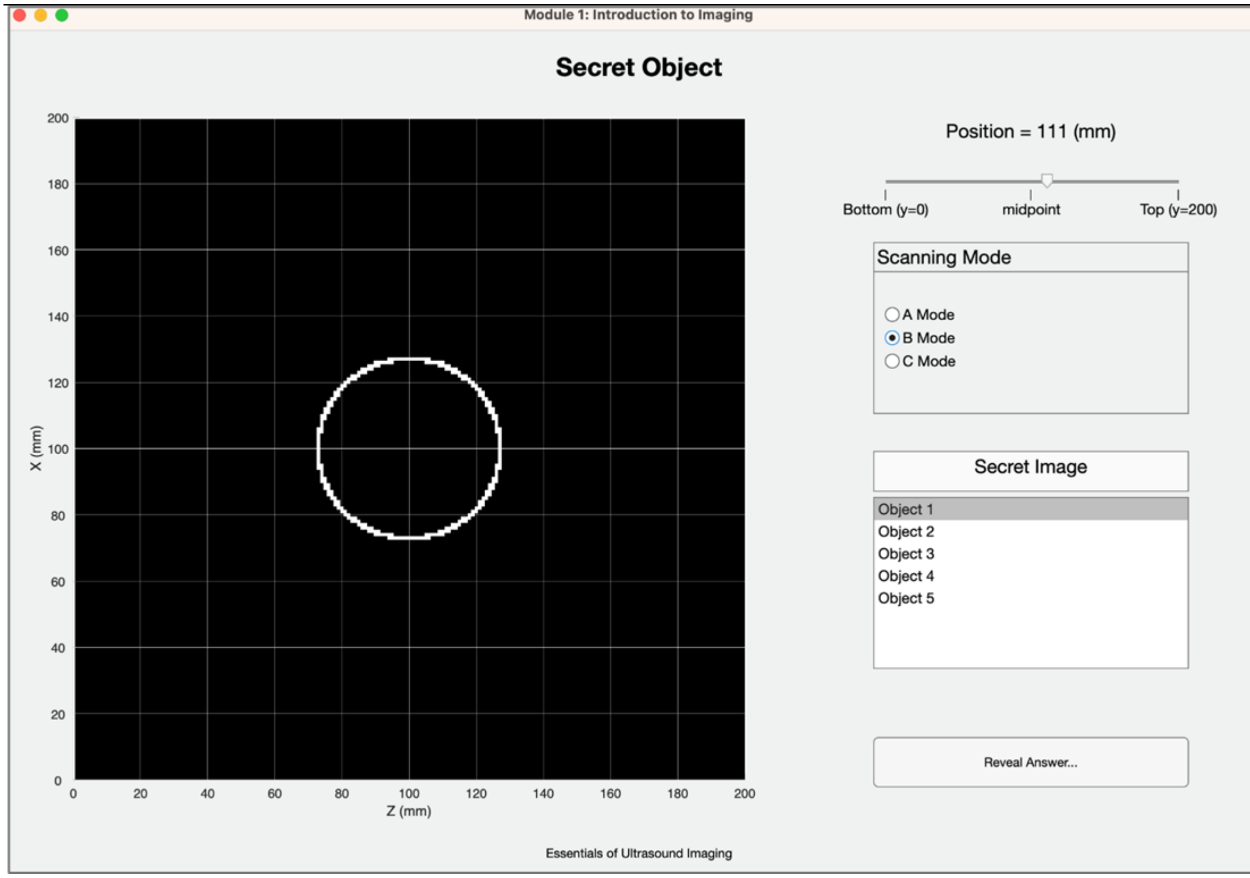

Figure 12: Secret Object Simulator - B Mode Selection

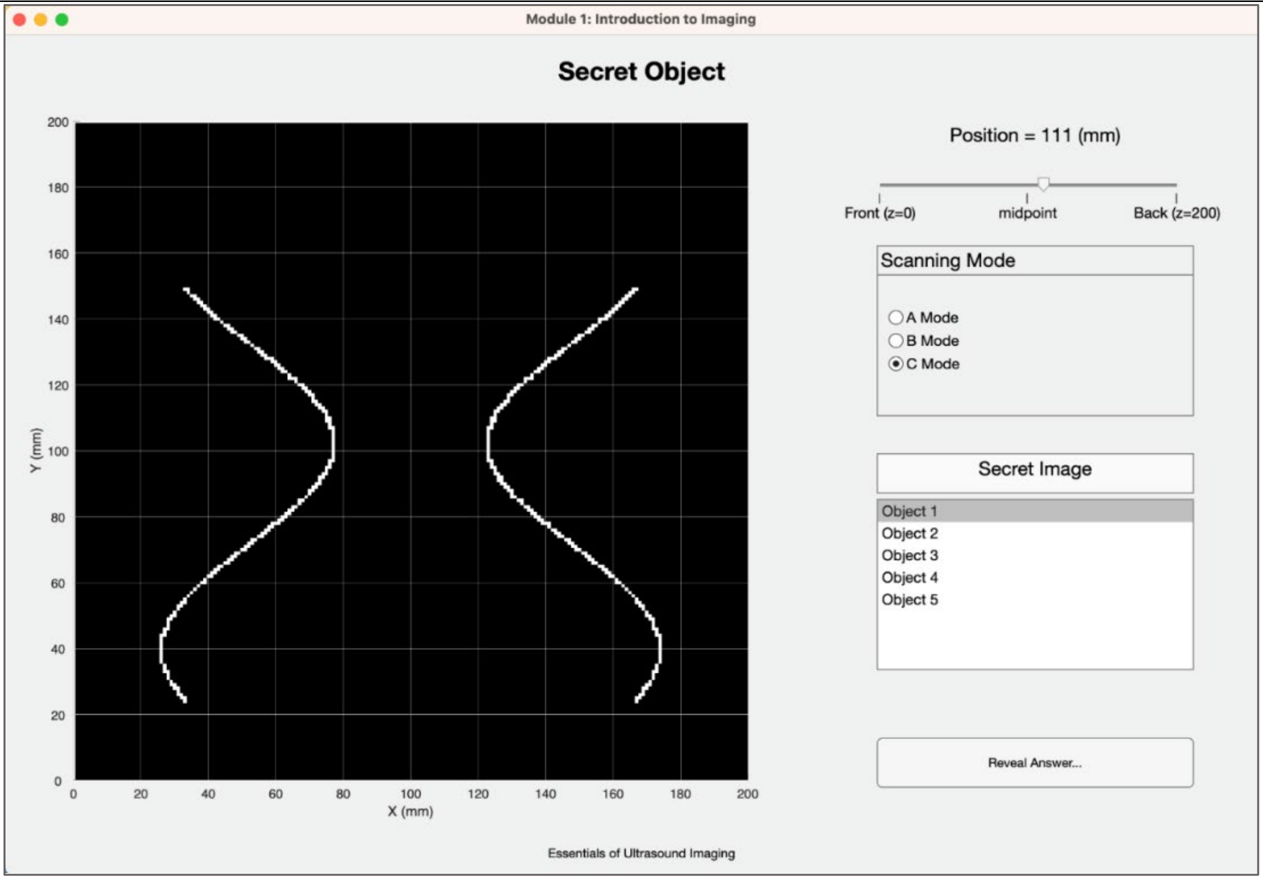

Figure 13: Secret Object Simulator - C Mode Selection

Module 2: Rays and Waves

Pulse Delay Simulator

The Pulse Delay simulator replicates the motion of a pulse as it propagates to the right, according to t=z/c where c=1.5mm/μs. Using this simulator, the user can observe a single cycle of a sine wave or an impulse wave propagating to the right along the z-axis direction.

For detailed information on this simulator module, refer to Section 2.1.2: Pulse Delay Simulator in the course textbook, Essentials of Ultrasound Imaging.

A typical workflow for using the simulator is as follows:

1. Select the input signal using the Wave Type toggle switch.
2. Click the Start Simulation button to initiate the simulation.

Table 6: Pulse Delay Simulator - GUI Control Options

UI Control	Description
Sine Wave	Slide the toggle switch to the left to select a bipolar sine wave.
Impulse	Slide the toggle switch to the right to select a monopolar impulse wave.
Start Simulation	After selecting the wave type, click the Start Simulation button to view the motion of a single cycle of the selected wave type to the right as time progresses.

The plot indicates a correlation between time and distance. For instance, a pulse delay time of 9 microseconds results in a wave propagation distance of 13.5 millimeters.

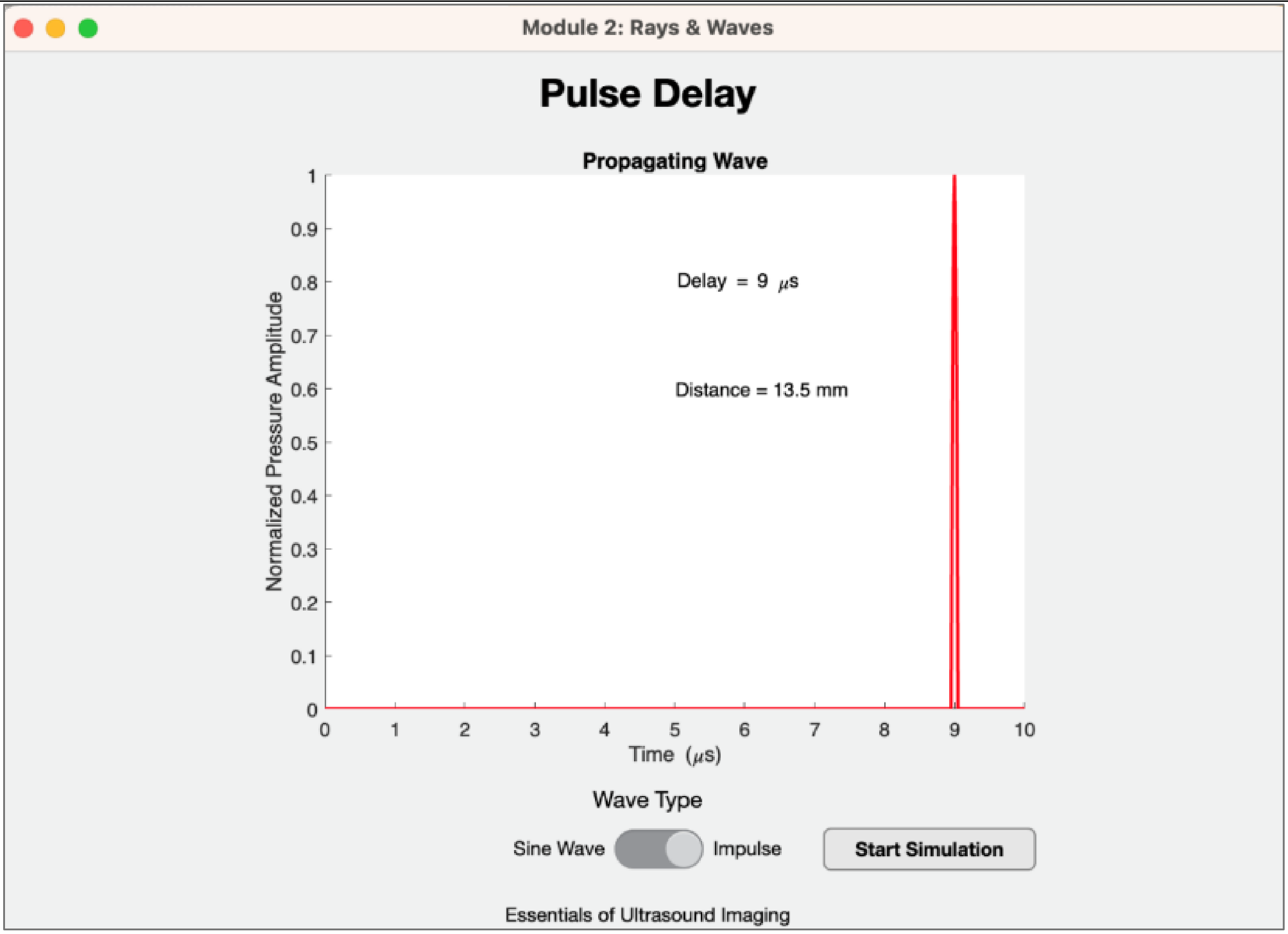

Figure 14: Pulse Delay Simulator - Impulse Wave Selection

Expanding Waves Simulator

The Expanding Wave simulator shows a time-sequence animation of an expanding or propagating wavefront. Using the simulator, the user can choose from three different forms of wavefront geometries (spherical, cylindrical, and plane) and observe the corresponding expanding wavefront.

For detailed information on this simulator module, refer to Section 2.3.1: Type of Propagating Wavefronts and Expanding Waves Simulator in the course textbook, Essentials of Ultrasound Imaging.

From the top portion of the simulator GUI, select a spherical wave, a cylindrical wave, or a plane wave. On the left side of the GUI, the corresponding 3D representation of the expanding wavefront surface is displayed. On the right side of the GUI, a time-sequenced 2D depiction of the expanding wavefront in the x-y plane at z=0 is displayed.

Table 7: Expanding Waves Simulator - GUI Control Options

UI Control	Description
Spherical Wave	Click the Spherical Wave button to view an animation of the propagation of a spherical wave (transmitted from a point source or a tiny three-dimensional source).
Cylindrical Wave	Click the Cylindrical Wave button to view an animation of the propagation of a cylindrical wave (transmitted from an infinitely long line source along the z-axis).

UI Control	Description
Plane Wave	Click the Plane Wave button to view an animation of the propagation of a plane wave (transmitted from a planar source that emits waves uniformly in a direction perpendicular to its plane).

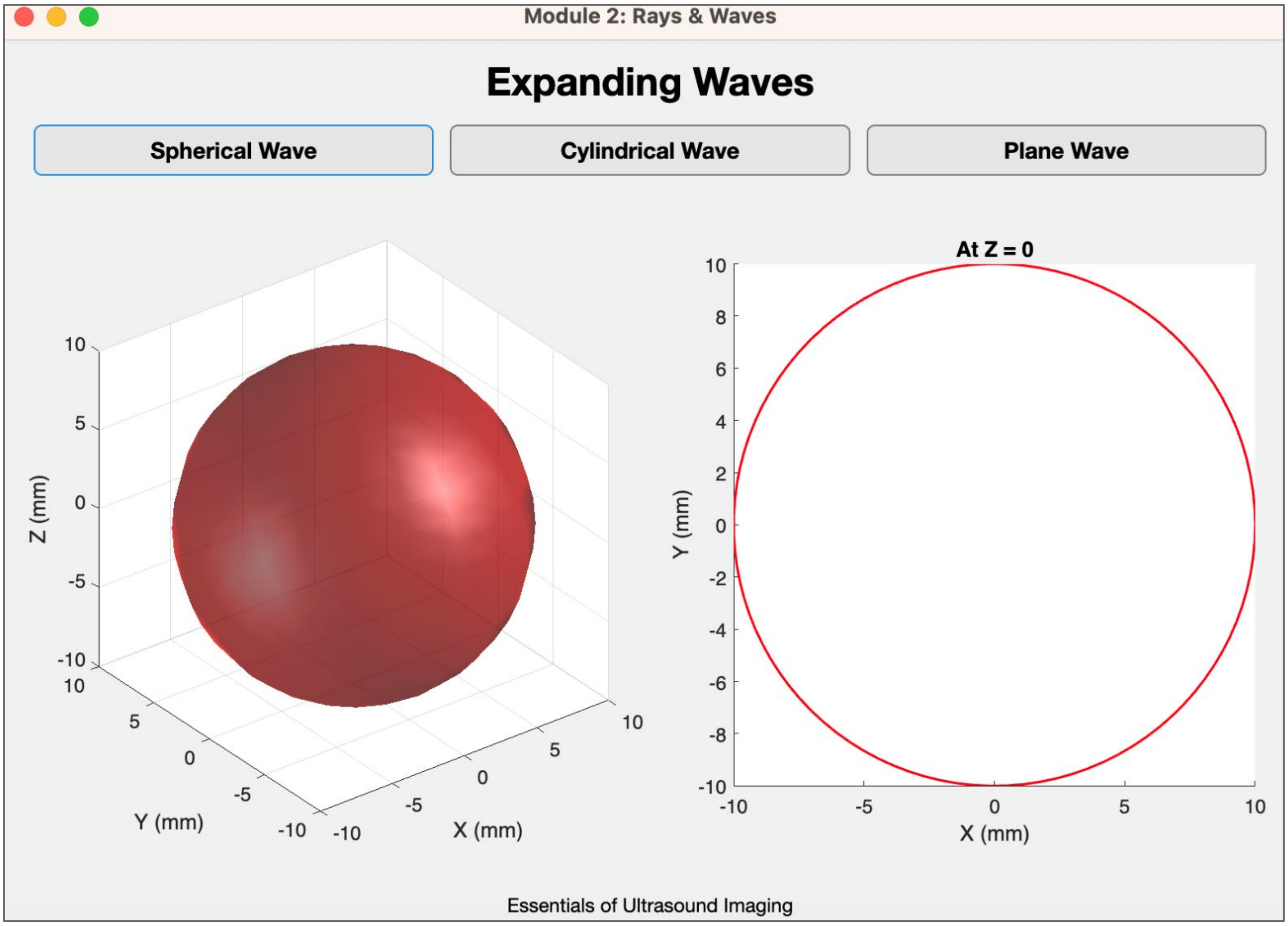

Figure 15: Expanding Wave Simulator GUI - Spherical Wave Selection

Elastic Waves Simulator

Using the Elastic Waves simulator, the user can visualize the propagation of shear waves and longitudinal waves. Shear waves propagate by causing particles in the medium to move perpendicular to the axis of propagation with no accompanying change in material volume. Longitudinal waves propagate by causing particles in the medium to move in the same direction as the wave propagation in a compression-dilatation mode. *For detailed information on this simulator module, refer to Section 2.3.3: Elastic Waves and Elastic Wave Simulator in the course textbook, Essentials of Ultrasound Imaging.*

To view the animation, click the Animate button located above the wave selection choice in the GUI.

Table 8: Elastic Waves Simulator - UI controls

UI Control	Description
Animate (X-polarized shear wave propagating in the z-axis direction)	Click the animate button to obtain an animated view of the propagation of a shear vertical wave (with sinusoidal particle vibrations occurring in the x-axis direction and wave propagation in the z-axis direction).

UI Control	Description
Animate (Y-polarized shear wave propagating in the z-axis direction)	Click the animate button to obtain an animated view of the propagation of a shear horizontal wave (with sinusoidal particle vibrations occurring in the y-axis direction and wave propagation in the z-axis direction).
Animate (Z-polarized longitudinal wave propagating in the z-axis direction)	Click the animate button to obtain an animated view of the propagation of a longitudinal wave (with particle motion in the z-axis direction and wave propagation in the z-axis direction).

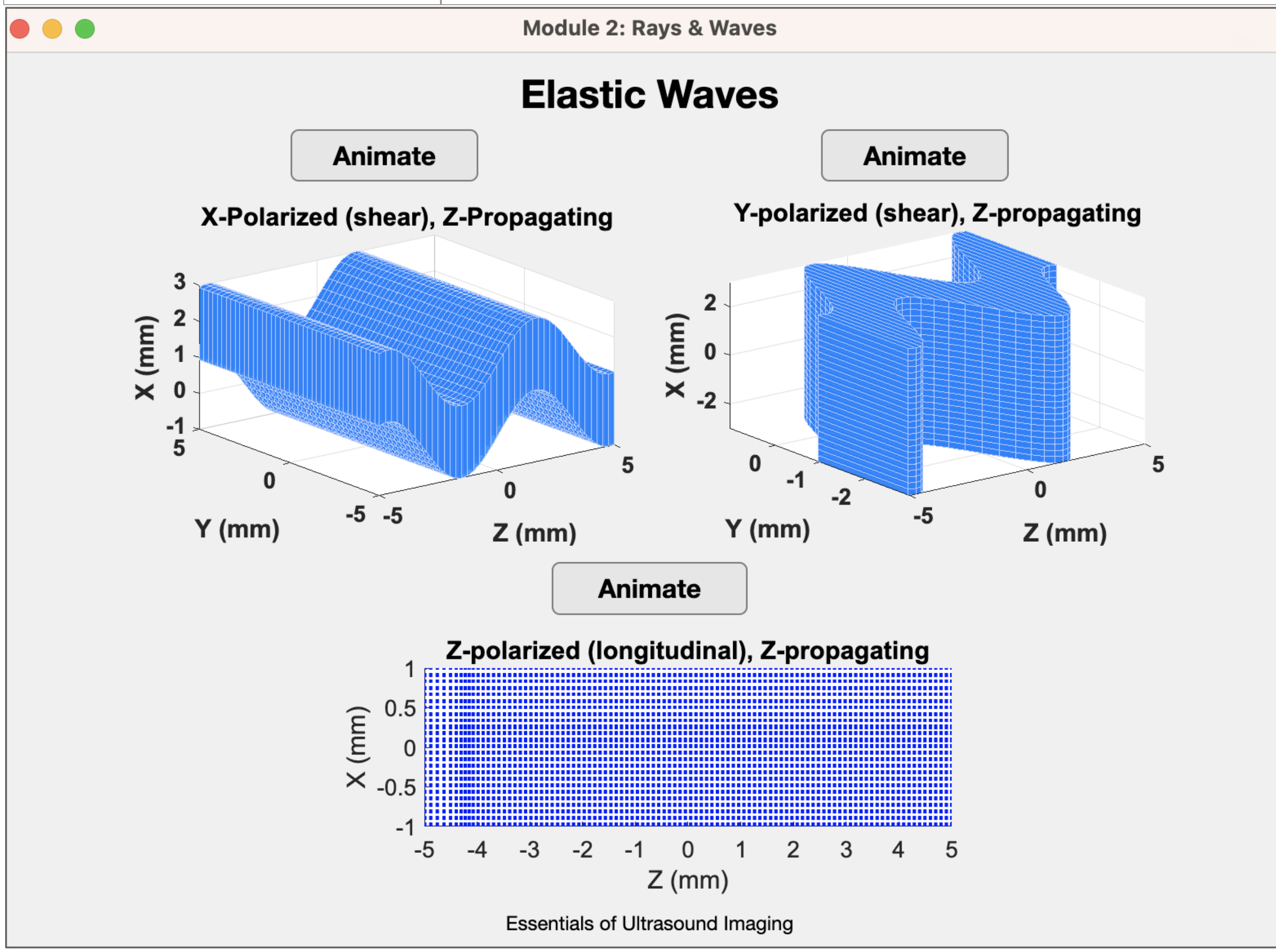

Figure 16: Elastic Waves Simulator GUI

Oblique Refraction Simulator

The Oblique Refraction simulator illustrates how a k-ray incident on a boundary between two media is reflected and refracted. It combines two principles: transmission and reflection at the boundary for different angles, and acoustic Snell's law for longitudinal waves to determine transmission angles. Using the simulator GUI the user can define the media and the angle of incidence value, and the simulator calculates and displays the percentage of reflected power, the percentage of refracted power, the angle of reflection, and the angle of refraction values.

All angles are defined relative to the surface normal and are indicated by colored arcs. On the lower left of the GUI, the name of each angle is labeled in text; and the color of the text matches the color of the corresponding arc, making it easy to visually identify which angle is being referred to. The quantitative values for the angles and power ratios (as percentages) are also displayed in this panel.

For detailed information on this simulator module, refer to Section 2.4.4: Oblique Simulator in the course textbook, Essentials of Ultrasound Imaging.

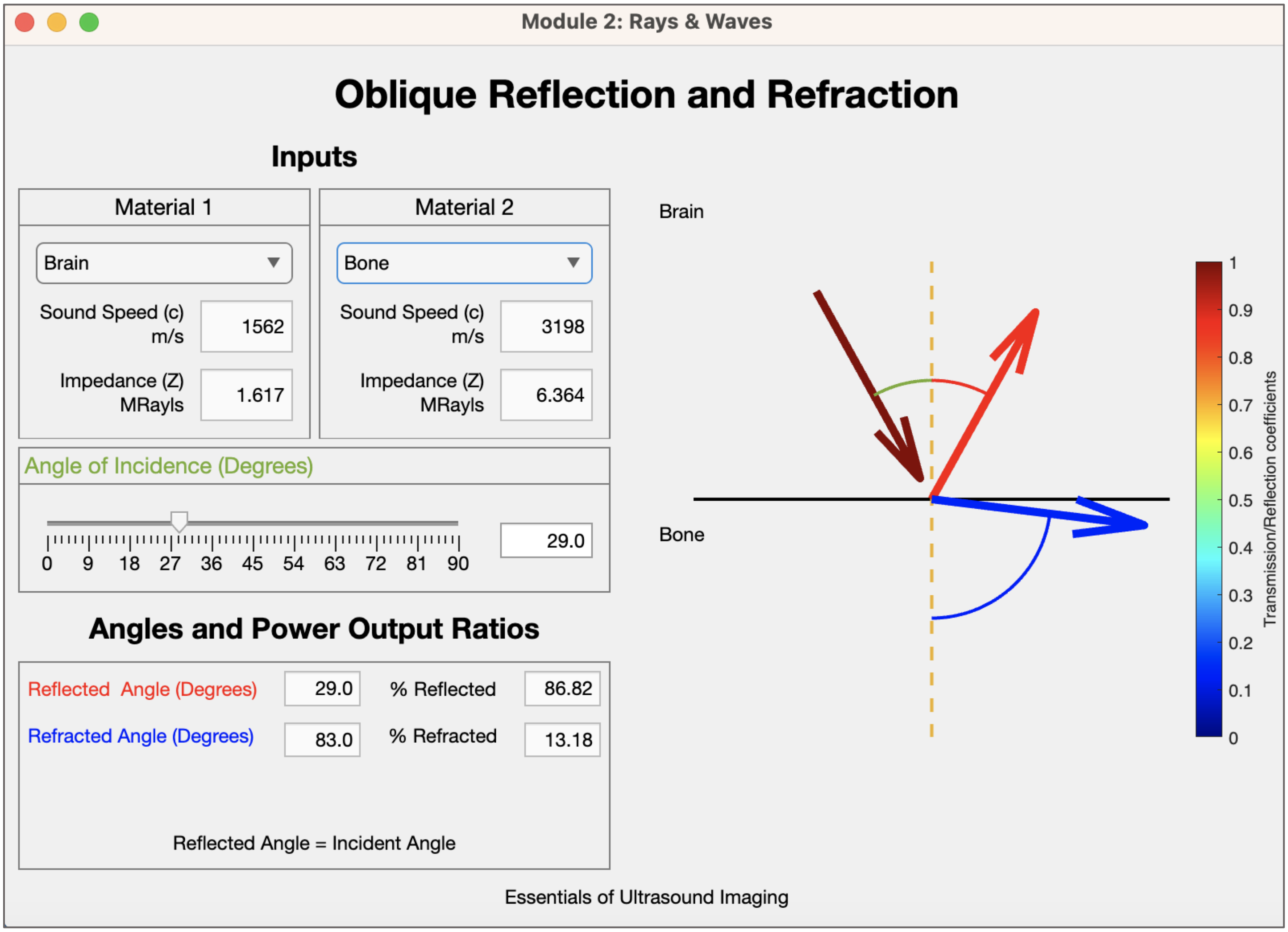

Figure 17: Oblique Refraction Simulator GUI

A typical workflow for using this simulator is as follows:

1. To start with, use the medium input values shown in Figure 17 to define the media. Note that the Material 1 Type corresponds to the top layer and the Material 2 Type corresponds to the bottom layer of the layered medium. Once a medium is selected, its speed of sound and impedance values are displayed.
2. Adjust the angle of incidence value. As the incident angle is changed, observe that the colors of the vectors on the right side of the GUI change immediately to show the ratio of reflected and transmitted (refracted) power (relative to incident power), according to the color bar displayed.
3. Modify the medium input values and the angle of incidence value to study changes in the corresponding output values.

Table 9: Oblique Refraction Simulator – Input Controls

UI Control	Description
Material 1 Type	Select the material 1 type from the dropdown menu options—Blood, Bone, Brain, Breast, Fat, Kidney, Liver, Muscle, and Air.
Material 1 Sound Speed	When the material type is chosen, the input field displays the default value of the sound speed associated with the selected material type.

UI Control	Description
Material 1 Impedance	When the material type is chosen, the input field displays the default value of the impedance associated with the selected material type.
Material 2 Type	Select the material 2 type from the dropdown menu options—Blood, Bone, Brain, Breast, Fat, Kidney, Liver, Muscle, and Air.
Material 2 Sound Speed	When the material type is chosen, the input field displays the default value of the sound speed associated with the selected material type.
Material 2 Impedance	When the material type is chosen, the input field displays the default value of the impedance associated with the selected material type.
Angle of Incidence	Move the angle of incidence slider or enter the angle of incidence value in the input field.

Layer Pulse Simulator

The Layer Pulse simulator aids in analyzing the reverberation behavior of a short pulse within a layer bound by other materials. This pulse passes into the layer and reflects many times at the top and bottom boundaries. Its journey is animated by a bright spot that travels along the zigzag reflection path and passes into the third medium as shown in the Spatial Representation diagram (as displayed on the right side of the GUI). Note that the actual path is perpendicular to the boundaries (for calculations), but it is exaggerated by oblique angles (shown in Figure 18) for educational purposes. The positive and negative pulses passing through Layer 3 are shown in the Transmission Time Series graph.

Using this simulator, the user can alter the characteristics—such as the impedances of multiple media (Layer 1, Layer 2, Layer 3), speed of sound of Layer 2, and layer thickness—and observe how these changes influence the simulation outcomes.

For detailed information on this simulator module, refer to Section 2.5.2: Layer Pulse Simulator in the course textbook, Essentials of Ultrasound Imaging.

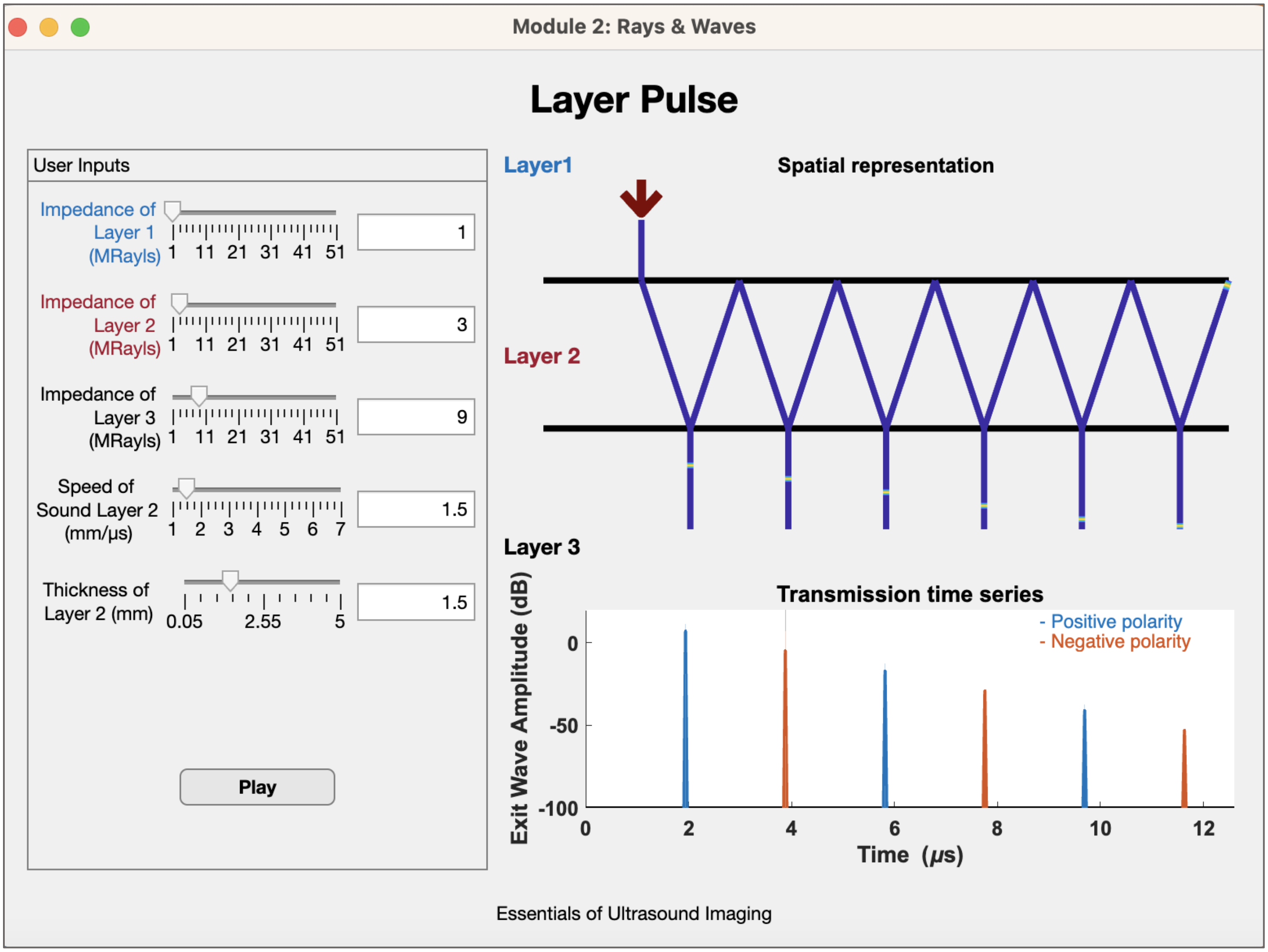

Figure 18: Layer Pulse Simulator GUI

A typical workflow for using this simulator is as follows:

1. Define the impedance values of Layer 1, Layer 2, and Layer 3; and the speed of sound and thickness values of Layer 2.

Table 10: Layer Pulse Simulator GUI – Input Controls

UI Control	Description
Impedance of Layer 1	Set the impedance value of Layer 1 using the slider. Alternatively, enter the value in the input field next to the slider (and press the Enter key).
Impedance of Layer 2	Set the impedance value of Layer 2 using the slider. Alternatively, enter the value in the input field next to the slider (and press the Enter key).
Impedance of Layer 3	Set the impedance value of Layer 3 using the slider. Alternatively, enter the value in the input field next to the slider (and press the Enter key).
Speed of Sound Layer 2	Set the speed of sound value of Layer 2 using the slider. Alternatively, enter the value in the input field next to the slider.
Thickness of Layer 2	Set the thickness of Layer 2 using the slider. Alternatively, enter the value in the input field next to the slider.
Play	After setting the inputs, select the Play button to visualize the reverberation behavior of the impulse within and transmission through the layered structure and resulting pulses in the transmission time series graph.

2. After entering the input parameters, click the Play button.
3. After clicking the Play button (use default settings to start with), observe that at the top of the Spatial representation diagram, a pulse (represented by a moving dot animation) strikes the Layer 1-Layer 2 interface that then reverberates within Layer 2. Upon each collision of the impulse on the lower boundary of Layer 2, it propagates to Layer 3. Note that the Transmission time series graph shows the exit pulses as they appear attenuated after multiple reflections and transmissions. The color changes in the time series graph indicate shifts in signal polarity (stemming from reflection at the layer interfaces). The ratio of the impedances of Layer 1 and Layer 2 impacts the shift in the polarity of the pulse. Note that these color changes are only seen after the entire simulation is complete. Also, the final relative positions of the dots of the transmission paths in Layer 3 indicate relative delay times for each pulse transmission.

CW Layer Simulator

The CW Layer simulator demonstrates how sound propagates under continuous wave conditions through a three-layer configuration. In this simulation, propagation is strictly perpendicular to the boundaries of the three layers. The transmission of sound through the central layer is controlled by the selected impedance values for the three layers and the thickness of the central layer in wavelengths.

On the right side of the GUI, the vectors depicting the ratios of incident power, reflected power, and transmitted power for normal incidence are displayed. These vectors are color-coded according to a power scale ranging from zero to one, as indicated in the color bar to the left. In the Outputs panel of the GUI, the reflected power ratio and the transmitted power ratio numerical values are shown.

This simulator opens in a default example configuration. The colors in Layer 2 represent the pattern of absolute pressure distribution within the layer. The color bar to the right shows the normalized pressure envelope. For the default setting, the thickness of Layer 2 is 1.5 wavelengths. This can be interpreted as a frozen cosine wave with an amplitude starting at its peak (yellow-white) at the top, descending in a downward direction to zero over half a wavelength, returning to yellow after the completion of one wavelength, and ending at zero (black) at the lower boundary after the completion of 1.5 wavelengths.

For detailed information on this simulator module, refer to Section 2.6.2: Continuous Wave Layer Simulator in the course textbook, Essentials of Ultrasound Imaging.

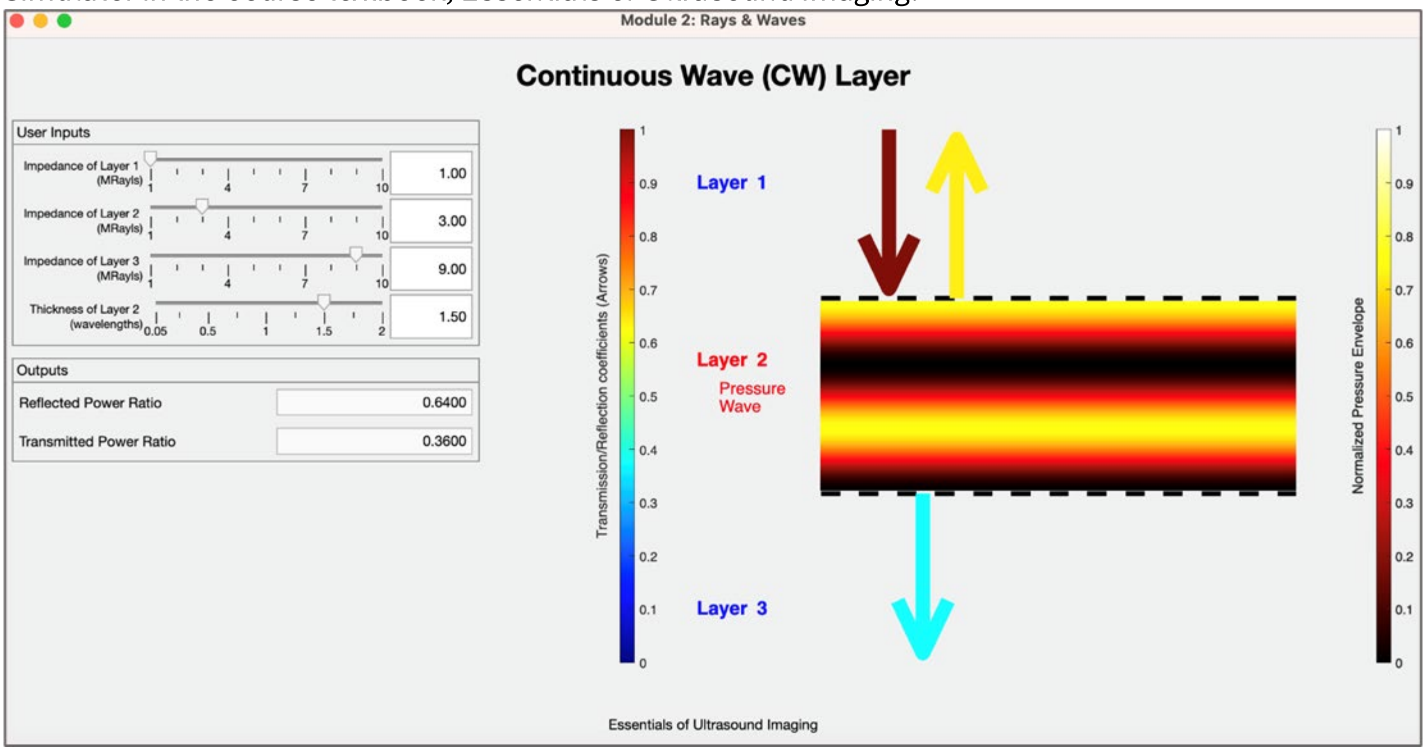

Figure 19: CW Layer Simulator GUI

A typical workflow for using this simulator is as follows:

1. Define the impedance and the thickness of Layer 2 in wavelengths, and the impedances of Layer 1 and Layer 3 using the sliders in the GUI.
2. Study the pattern of the absolute pressure distribution within Layer 2.

Table 11: CW Layer - GUI Controls

UI Control	Description
Impedance of Layer 1	Define the impedance value of Layer 1 using the slider or enter the value in the input field.

UI Control	Description
Impedance of Layer 2	Define the impedance value of Layer 2 using the slider or enter the value in the input field.
Impedance of Layer 3	Define the impedance value of Layer 3 using the slider or enter the value in the input field.
Thickness of Layer 2	Define the thickness of Layer 2 in wavelengths using the slider or enter the thickness value in the input field.
Reflected Power	The reflected power value is displayed based on the inputs provided.
Transmitted Power	The transmitted power value is displayed based on the inputs provided.

Module 3: Signals

Fourier Transform Simulator

The Fourier Transform simulator graphically illustrates the relationship between the Fourier Transform domains: time and frequency. Using the simulator GUI, the user can define an input signal and visualize the time domain plot and its corresponding frequency spectrum (expressed in dB).

For detailed information on this simulator module, refer to Section 3.2.1: Fourier Transform Simulator in the course textbook, Essentials of Ultrasound Imaging.

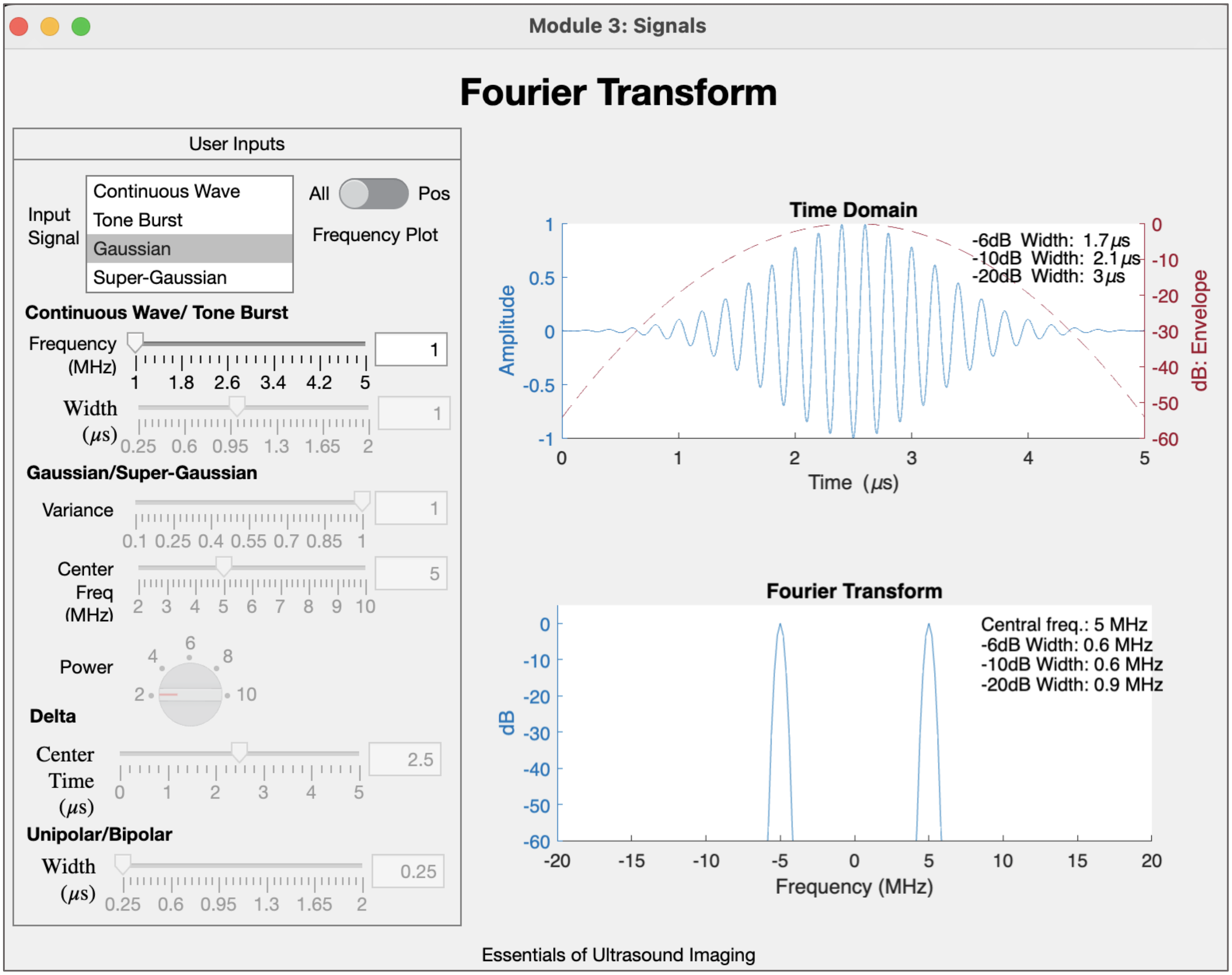

Figure 20: Fourier Transform Simulator GUI

A typical workflow for this simulator is as follows:

1. In the User Inputs section, select the input signal type from the dropdown menu, fine-tune signal parameters such as frequency and temporal duration ("Width" for the Tone Burst, Unipolar, and Bipolar pulses; and "Variance" for the Gaussian signals).
   Note that upon selecting a signal type, the parameters that are adjustable for the selected signal type are enabled and all other parameters are disabled. A Gaussian signal is presented as the default input signal.

2. Observe that the time domain and frequency domain plots are displayed in the Time Domain and Fourier Transform sections on the right side of the GUI.

The Y-axis scale for the waveform is shown on the left in blue. For many waveforms, its analytic envelope is displayed as a red-dashed line, with the envelope value in dB indicated on the scale in red to the right of the plot. Note that if the envelope were expressed in linear units, the curve would outline the blue signal curve. Quantitative annotations on the graph—such as the -6dB width, -10dB width, and -20dB width—provide insights into the signal bandwidth, frequency spread, signal decay rate, and shape characteristics. The user can explore the relationship between the time domain signal and the frequency domain plots using these values.

Table 12: Fourier Transform Simulator: UI Controls and Description

UI Control	Description
Input Signal	Select an input signal in the time domain from the dropdown menu options—Continuous Wave, Tone Burst, Gaussian, Super-Gaussian, Delta, Unipolar, or Bipolar. <u>Continuous Wave:</u> A Continuous Wave is a sine wave with constant frequency and amplitude plotted on a finite time window. The frequency of this signal type is adjustable. <u>Tone Burst:</u> A Tone Burst is a sine wave that is truncated and has a finite duration. The frequency and the duration of this signal type are adjustable. <u>Gaussian:</u> A Gaussian wave is a continuous wave windowed by a Gaussian function—it is a bell-shaped curve that is symmetric around its mean value. In the time domain plot, the blue line indicates the amplitude of the actual waveform as a function of time and the red line indicates the envelope of the waveform. Note that the envelope is expressed in decibels and not in linear units. The variance and the center frequency of this signal type are adjustable. <u>Super-Gaussian:</u> A Super-Gaussian wave is a form of the regular Gaussian signal that has a bell-shaped curve with a faster decay rate at its tails, resulting in sharper transitions. The user can adjust these transitions using the using the power knob. Note that when the knob is set to 2, the waveform reverts to an ordinary Gaussian function. The variance and center frequency of the signal are also adjustable. <u>Delta:</u> A Delta function is just a single point in the time domain. The user can change the delay of the Delta function in the time domain using the Center Time slider. Note that this adjustment only alters the phase of the signal without affecting the value of the magnitude of the spectral amplitude. (The phase of the signal is not plotted.) <u>Unipolar:</u> A unipolar pulse is a square pulse in the time domain and is always positive. The user can adjust the width of the pulse and observe the effect on the Fourier spectrum. <u>Bipolar:</u> A bipolar pulse is a square waveform characterized by alternating positive and negative excursions from a zero level. The user can adjust the width of the pulse and observe the effect on the Fourier Transform of the signal.
Frequency	Adjust the Frequency slider to change the frequency of a Continuous Wave or Tone Burst input signal.
Width	Adjust the Width slider to change the width of a Tone Burst input signal.

UI Control	Description
Variance	Adjust the Variance slider to change the width of the peak of a Gaussian or Super-Gaussian input signal. Observe that as the width of the peak increases, the Fourier Transform becomes narrower.
Center Frequency	Adjust the Center Frequency slider to change the center frequency of a Gaussian or Super-Gaussian input signal.
Power	This control is enabled for the Super-Gaussian signal type selection only. The higher-order Gaussian shape (often determined by the exponent parameter that controls the rate of decay of the tails) can be controlled using the knob. Adjust the Power knob to change the transition of the Super-Gaussian signal at its ends, from smoother transitions resembling a regular Gaussian signal to sharper transitions characteristic of a Super-Gaussian signal. This feature allows users to understand the impact of transition adjustments in the frequency domain.
Center Time	Adjust the Center time slider to change the center time of a Delta input signal.
Width - Unipolar/Bipolar	Adjust the Width slider to change the width of a Unipolar input signal or a bipolar input signal.
All/Pos Frequency Plot	In the frequency domain plot, the user has the option to view only positive frequency components or view all the frequency components. Slide the Frequency Plot Slider to the left to display all the frequency components or slide the Frequency Plot slider to the right to display positive frequency components only.

Fourier Filter Simulator

Using the Fourier Filter simulator, various filters can be applied to input signals, and the resultant time domain and frequency domain plots can be studied. The input signals are nearly identical to those of the Fourier Transform Simulator, so the user is referred to that simulator for detailed information about the Input Signals section. *For detailed information on this simulator module, refer to Section 3.3.2: Fourier Filter Simulator in the course textbook, Essentials of Ultrasound Imaging.*

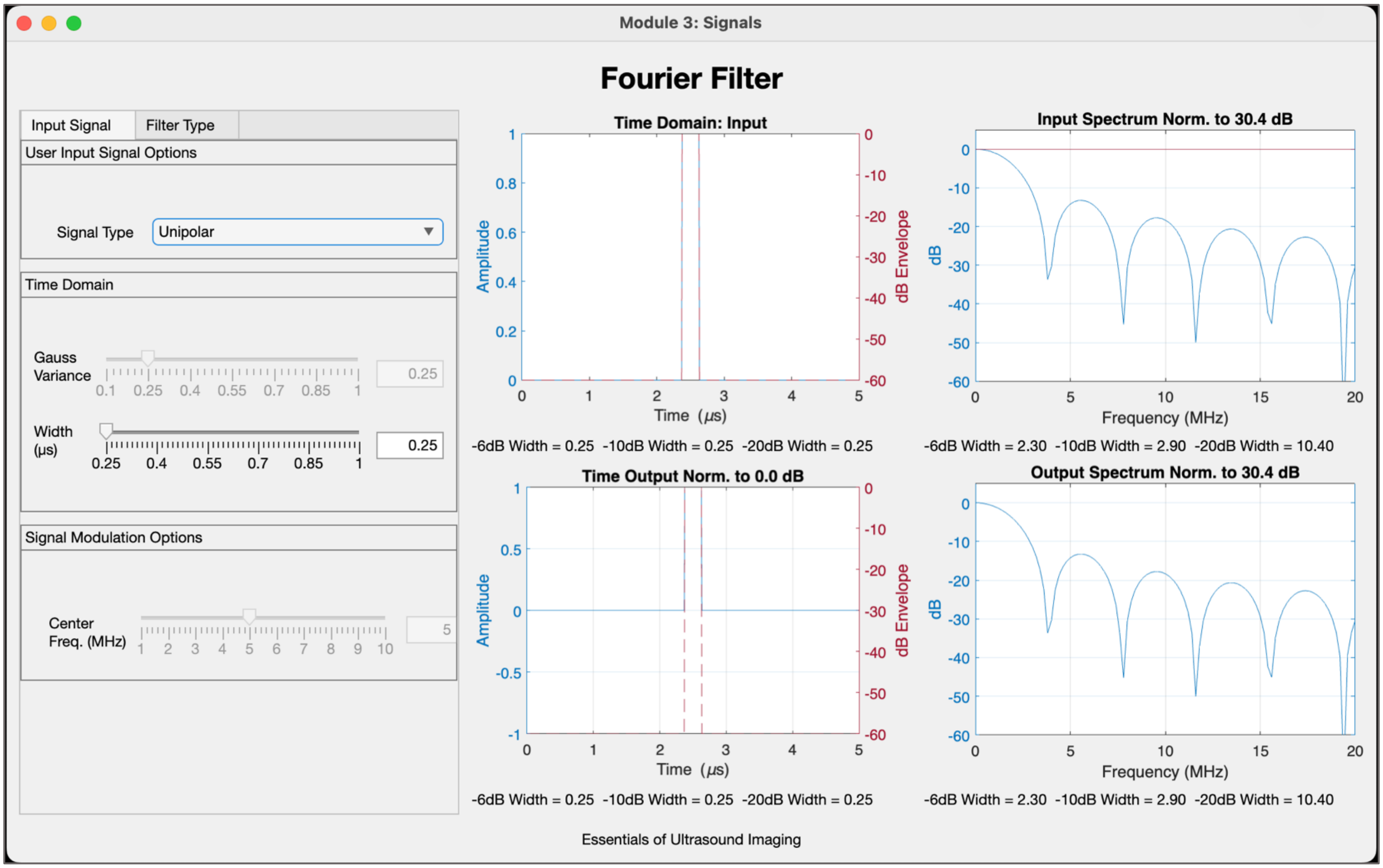

Figure 21: Fourier Filter Simulator GUI - Input Signal Tab

To obtain the time domain and frequency domain plots:

1. Select the Input Signal tab on the top left of the GUI.
2. From the Signal Type dropdown menu, select an input signal. The default signal type is preset to unipolar input (as shown in Figure 21 **Error! Reference source not found.**).
3. Note that upon selecting a signal type, the parameters available for adjustment of the selected signal type are enabled, while the remaining parameters are disabled.
4. Select the Filter tab on the top left of the GUI.
5. From the Filter Type dropdown menu, select the input filter. The default lowpass filter is suggested.
6. Fine-tune the signal by adjusting its parameters. Upon selecting the input filter, the filter characteristic is displayed at the bottom left corner of the GUI in the Filter Design plot. The filter characteristic is also displayed on the frequency domain plot of the input signal. See Figure 21 for default options.
7. On the right side of the GUI, the following plots are displayed:
   Time Domain Input Signal: This plot shows the input signal (and its envelope) in the time domain, illustrating how the signal varies over time.

Time Output (Filtered Time Domain Signal): This plot displays the result of applying the filter to the input signal in the time domain.

Input Spectrum (Frequency Domain Input Signal): This plot represents the input signal in the frequency domain, depicting the distribution of the signal frequency components.

Output Spectrum (Filtered Frequency Domain Signal): This plot shows the frequency domain representation of the filtered signal.

Quantitative values of pulse lengths and bandwidths are presented below the plots for comparisons. For the Input signal tab selection, refer to Table 12 for detailed descriptions of the GUI controls.

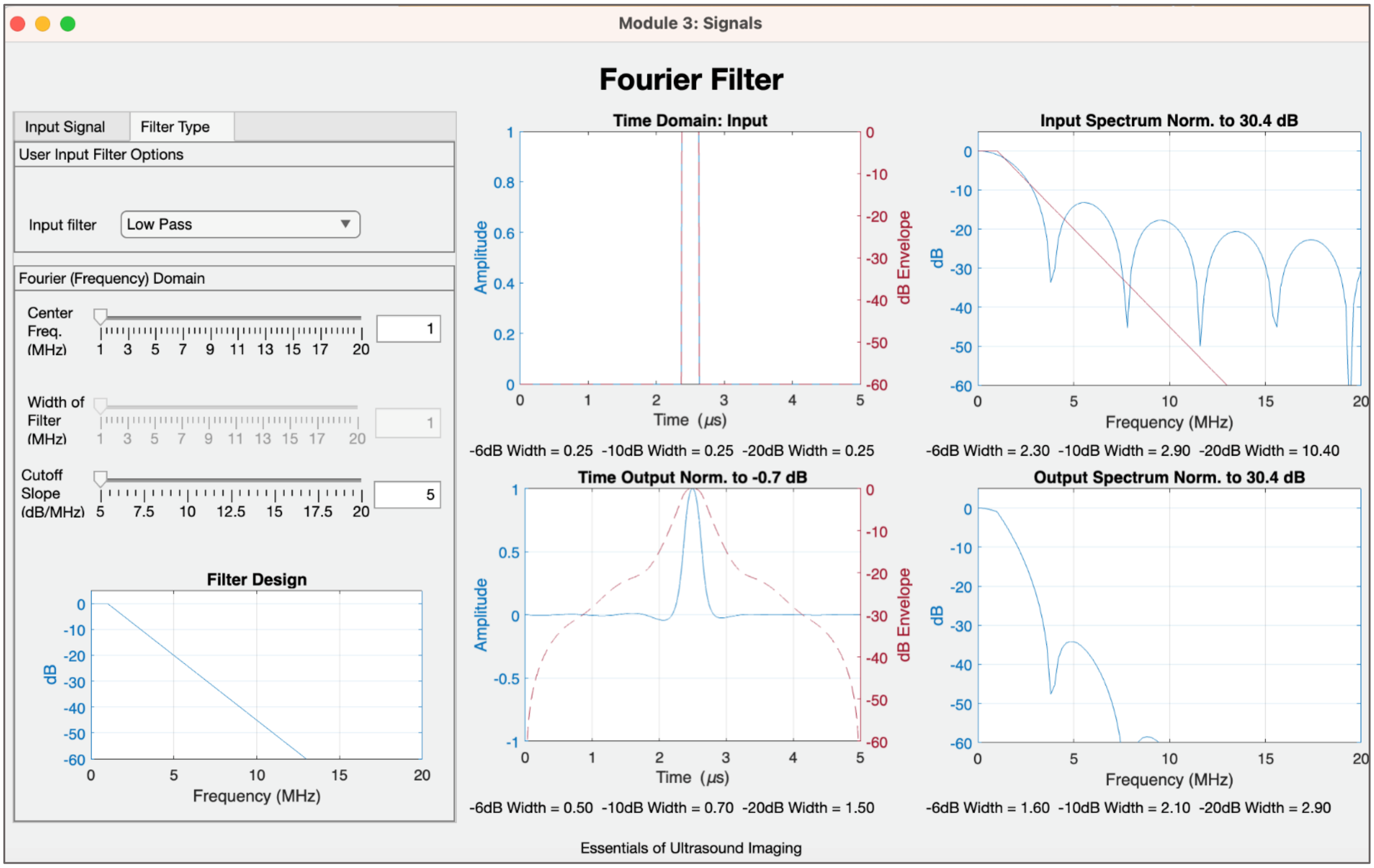

Figure 22: Fourier Filter Simulator - Filter Type Tab

Table 13: Fourier Filter Simulator: Filter Type Tab - UI Controls and Description

UI Control	Description
Filter Type	Select the Filter Type tab to select a filter option.
Input Filter	From the Input Filter dropdown menu, select an input filter from the following Input Filter options: No Filter: Filter characteristic is not applied to the input signal. Low Pass: A low pass filter allows signals with frequencies lower than the cutoff frequency and attenuates frequencies higher than the cutoff frequency. Adjust the cutoff frequency and the cutoff slope of the filter to get the desired filter characteristic. High Pass:

UI Control	Description
	A High Pass filter allows frequencies higher than the cutoff frequency and attenuates frequencies lower than the cutoff frequency. Adjust the cutoff frequency slider and the cutoff slope to get the desired filter characteristic. Band Pass: The Band Pass filter limits the passband to a particular region. Adjust the center frequency and observe that the passband in the frequency representation also changes. Note that the frequency peaks at the bandpass frequency region. Band Stop: The Band Stop filter or the notch filter attenuates a specific range of frequencies while allowing the frequencies outside that range to pass. Adjust the width of the notch and center the frequency to get the desired filter characteristic. Gaussian: The Gaussian filter applies a Gaussian function (a bell-shaped curve), resulting in a smoother output and attenuating high-frequency noise; it has center frequency and width adjustments. Kaiser: The Kaiser filter can be used as a bandpass filter—the Kaiser window function enables fine-tuning of the filter frequency response. Adjust the center frequency of the filter to get the desired filter characteristic. Transducer: The transducer filter has the L11_ 5-v transducer filter characteristics. The L11_5-v transducer is used in the Essentials of Ultrasound course. There are no adjustments available for this setting.
Center Frequency	Adjust the center frequency of the selected filter type using the Center Frequency slider.
Width of Filter	Adjust the Width of the Filter of the selected filter type using the Width of the Filter slider.
Cutoff Slope	Adjust the Cutoff Slope of the selected filter type using the Cutoff Slope slider. Ideally, a steeper filter slope seems desirable but when the filter characteristic is observed in the time domain, the steeper slope corresponds to increased oscillation amplitude and duration—the user must carefully weigh these trade-offs.

ABCD Simulator

The ABCD simulator illustrates the ABCD matrix method of computing transfer functions of electrical circuits. Using this simulator, the user initially assembles a passive electrical circuit by selecting up to three components using the UI elements. Subsequently, the simulator displays the transfer function magnitude plotted against frequency.

For detailed information on this simulator module, refer to Section 3.4.3: ABCD Simulator in the course textbook, Essentials of Ultrasound Imaging.

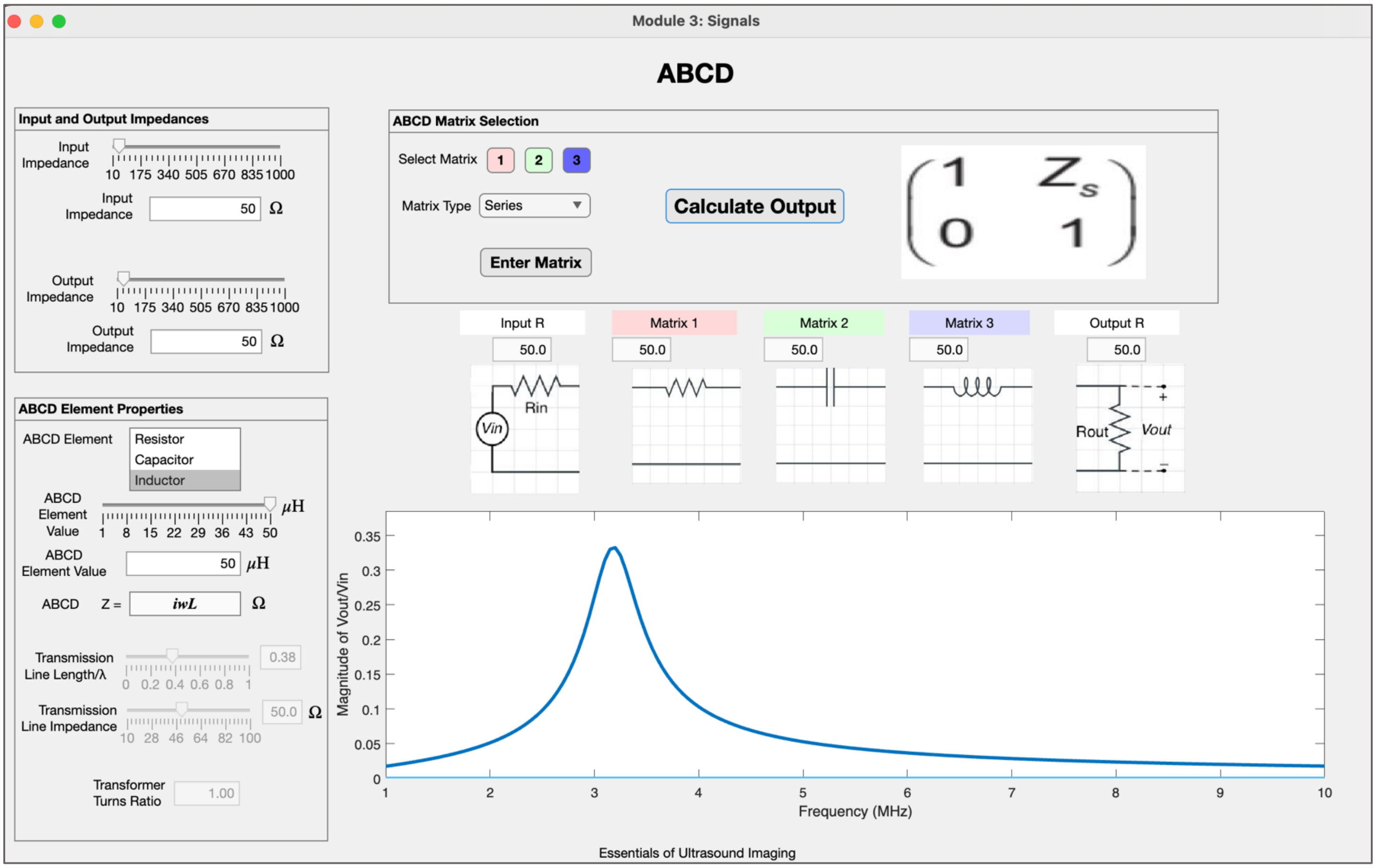

Figure 23: ABCD Simulator GUI

To assemble an electronic circuit:

1. In the Input and Output Impedances box, select the input impedance and output impedance values using the appropriate sliders or enter the impedance values in the corresponding edit fields.
   Note: Unless the user is working on a problem specifically involving these impedances, it is recommended to use the default value of 50 ohms. In this case, the input impedance and the output impedance values are resistive.
2. In the ABCD Matrix Selection panel, note that the three colored tabs correspond to the blank matrix positions 1, 2, and 3 on the circuit displayed below, tagged with the same colors. The user can select different types of components connected in series or shunt configurations to populate the matrices. If these selections are not chosen, then the matrix is filled by a simple direct connection to the next matrix component or output impedance. The user can start with the default values displayed in the GUI as an example.
3. To add a component to the circuit:

   a. Select the position of the component in the circuit by selecting a colored number in the Select Matrix field. For instance, if the user intends to add a component in the Matrix 1 position, they should select 1. After selection, the matrix tag color turns a deeper shade.
   b. After selecting the position, use the Matrix Type dropdown menu to select one of the following configurations: series, shunt, transmission line, or transformer. For this example, select the Series option.
   c. For series or shunt selections, select the component from the ABCD Element Properties section: Resistor, Capacitor, or Inductor. After selecting the ABCD element, use the ABCD Element Value slider or ABCD Element Value input field to set the element value.
      For transmission line selection, use the Transmission Line Impedance slider or the input field to enter the impedance value.
      For transformer selection, enter the transformer turns ratio in the Transformer Turns Ratio field.
      For this example, the user can choose the default Resistor value of 50 ohms.
   d. After selecting the component values, click on the Enter Matrix button in the Matrix Selection section to add the component to the circuit. For this example, the user should see a resistor appear in the pink tagged Matrix 1, with a value of 50.
   e. Use the above procedure to select the components in Matrix 2 and Matrix 3 positions in the circuit. If the user chooses not to place a component in any one of the positions, the circuit will default to a short in that position. As an example, for the Matrix 2 selection; select option 2 (highlighted in green) under Select Matrix, select the series option from the dropdown menu, and select a capacitor option with its value (default is 50 pf); enter this matrix. Repeat this process for Matrix 3 using the default inductor value of 50 μH.
4. After defining the circuit, select the Calculate Output button to display the frequency spectrum of the transfer function expressed as a relative ratio of the output voltage across the R_{out} terminal and the input voltage V_{in} shown as a plot at the bottom of the GUI. In this example, a resonance peak is displayed in Figure 23. Figure 23

Absorption Filter Simulator

The Absorption Filter simulator models acoustic waveforms propagating in attenuative media using a filter approach. This simulator is similar to a Fourier Filter Simulator, offering the same input options. However, the filters in this simulator model absorption and dispersion effects for different tissue options. Signal distortion increases with depth and is also adjustable. *For detailed information on this simulator module, refer to Section 3.5.3: Absorption Filter Simulator in the course textbook, Essentials of Ultrasound Imaging.*

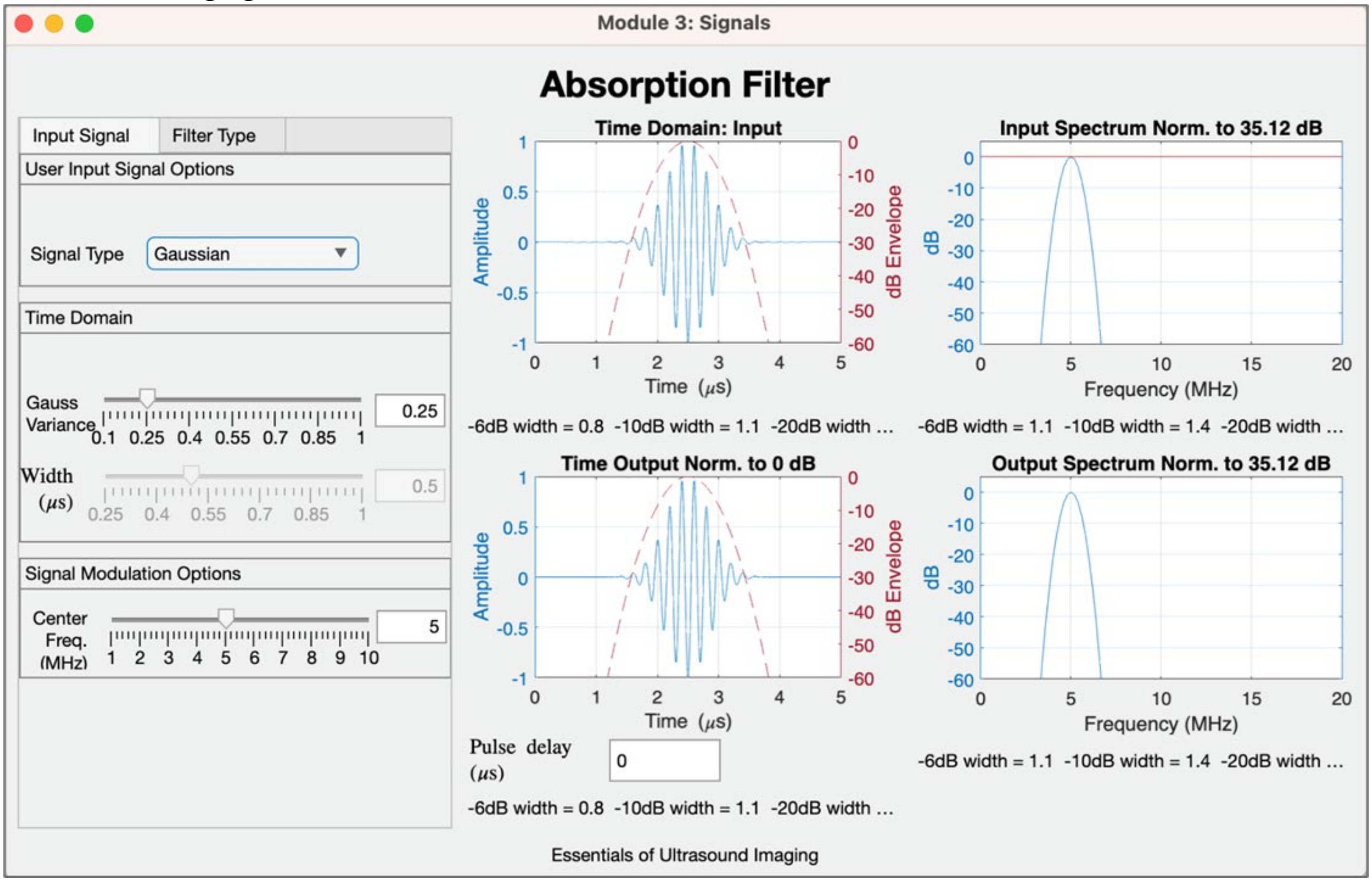

Figure 24: Absorption Filter Simulator GUI

The layout of the Absorption Filter Simulator is identical to the Fourier Filter Simulator; however, the filters in this simulator model absorption filters for various tissue selections. Here we emphasize only the differences between the filter simulators.

To obtain the time domain and frequency domain plots:

1. Select the Input Signal tab on the top left of the GUI.
2. From the Signal Type dropdown menu, select an input signal.
3. Note that upon selecting a signal type, the parameters available for adjustment of the selected signal type are enabled, while the remaining parameters are disabled.
4. Fine-tune the signal by adjusting its parameters.
5. Select the Filter Type tab on the top left of the GUI.
6. From the Material Selection dropdown menu, select the tissue type. Upon selecting the medium filter, the filter's spectral characteristic is displayed at the bottom left corner of the GUI. The same filter spectrum is also displayed on the frequency domain plot of the input signal. Note that once a tissue is

selected, the numerical values of its absorption properties and speed of sound are automatically presented but are grayed out.

7. Select the propagation distance Z (in cm) using the slider. Observe changes in the filter characteristic in the Filter Design plot shown at the bottom of the panel. For a pulse-echo or round-trip configuration, select Z to be twice the actual physical distance.
8. On the right side of the GUI, the following plots are displayed:

Time Domain Input Signal: This plot shows the input signal in the time domain (and its envelope), illustrating how the signal varies over time.
Time Output (Filtered Time Domain Signal): This plot displays the input signal after the filter has been applied, highlighting the effects of the filter on the signal in the time domain.
Input Spectrum (Frequency Domain Input Signal): This plot represents the input signal in the frequency domain, depicting the distribution of the signal's frequency components.
Output Spectrum (Filtered Frequency Domain Signal): This plot shows the frequency domain representation of the input signal after filtering, demonstrating the impact of the filter on the signal's frequency components.
Quantitative values of pulse lengths and bandwidths are presented below the plots for comparisons.

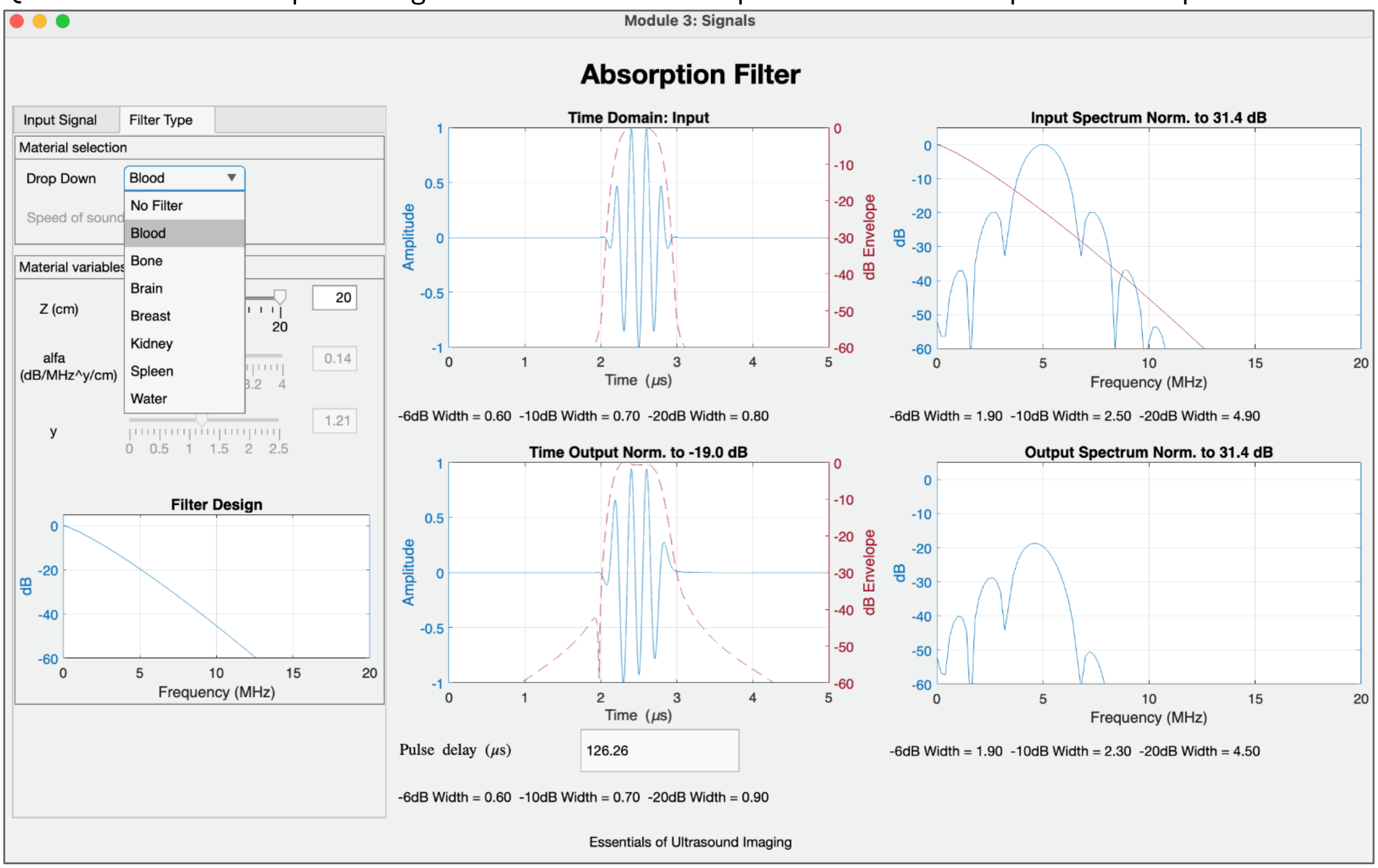

Figure 25: Absorption Filter GUI

Table 14: Absorption Filter - UI Controls and Descriptions

UI Control	Description
Input Signal	Refer to Table 12 for a description of the UI controls.
Width	

<table>
<tr><th>UI Control</th><th>Description</th></tr>
<tr><td>Variance</td><td rowspan="2"></td></tr>
<tr><td>Center Frequency</td></tr>
<tr><td>Pulse Delay</td><td>Display of propagation delay based on the speed of sound and distance.</td></tr>
<tr><td>Filter Type</td><td>Select a tissue type from the material dropdown menu.

<table>
<tr><th>Tissue Type</th><th>Attenuation
α(dB MHz-y cm-1)</th><th>Exponent y (no units)</th></tr>
<tr><td>Blood</td><td>0.14</td><td>1.21</td></tr>
<tr><td>Bone</td><td>3.54</td><td>0.9</td></tr>
<tr><td>Brain</td><td>0.58</td><td>1.3</td></tr>
<tr><td>Breast</td><td>0.75</td><td>1.5</td></tr>
<tr><td>Kidney</td><td>0.24</td><td>1.02</td></tr>
<tr><td>Spleen</td><td>0.4</td><td>1.3</td></tr>
<tr><td>Water</td><td>0.002</td><td>2</td></tr>
</table>
</td></tr>
<tr><td>Z (cms)</td><td>Use the slider to select the depth of the medium.</td></tr>
<tr><td>Alpha</td><td>For the User Selectable filter option, adjust the attenuation coefficient using the slider. For all other filter options, the attenuation coefficient is set by default.</td></tr>
<tr><td>y</td><td>Frequency power exponent for the absorption (unitless). For all other filter options, the exponent y is set by default.</td></tr>
</table>

Module 4: Transducers

Transducer Simulator

The Transducer simulator is an equivalent circuit model of a transducer that demonstrates the electrical and electro-acoustic characteristics of a piezoelectric transducer in both the time and frequency domains, for one-way and round-trip cases. The transducer design choices include options to vary the following: electrical impedances, tuning, matching layers, and center frequency.

For detailed information on this simulator module, refer to Section 4.2.5: Transducer Simulator in the course textbook, Essentials of Ultrasound Imaging.

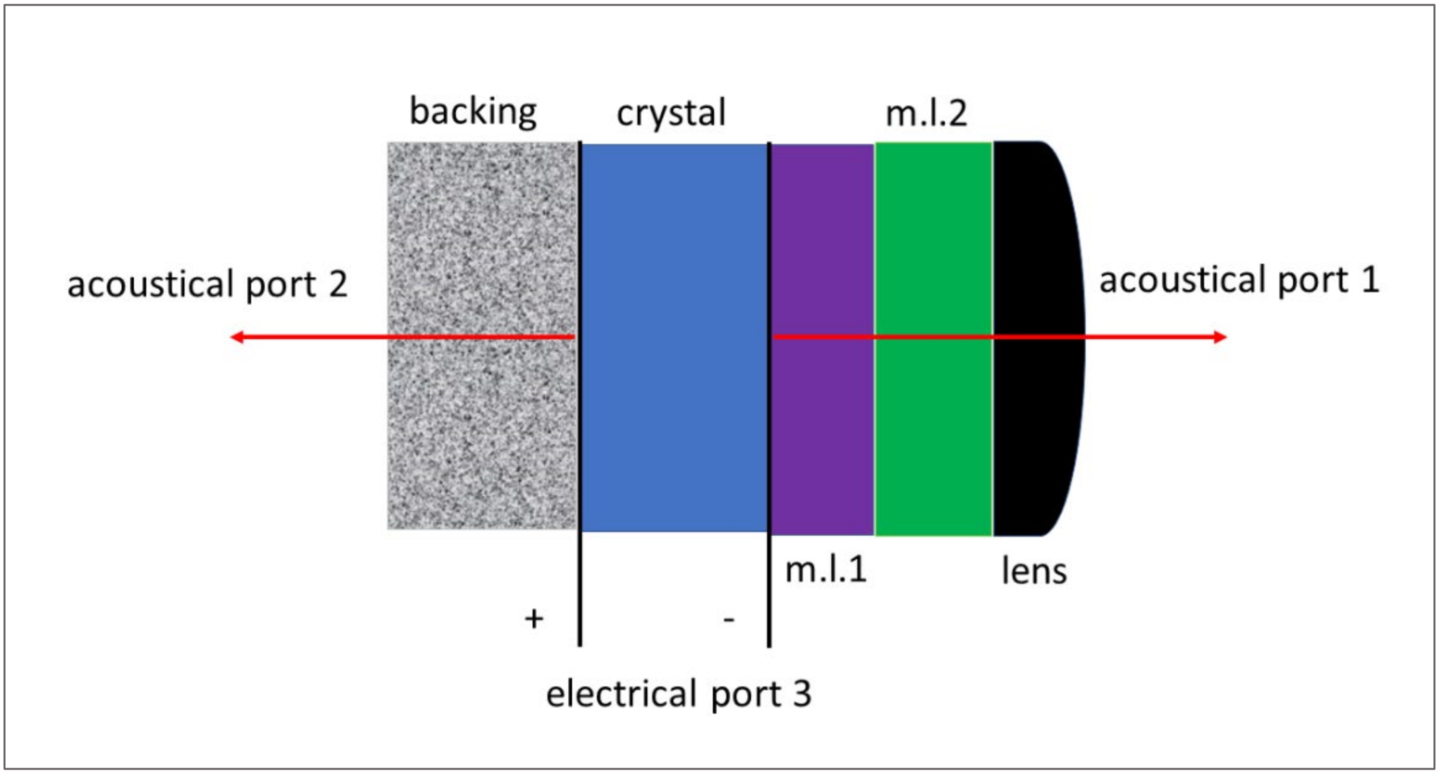

Figure 26: Transducer Model

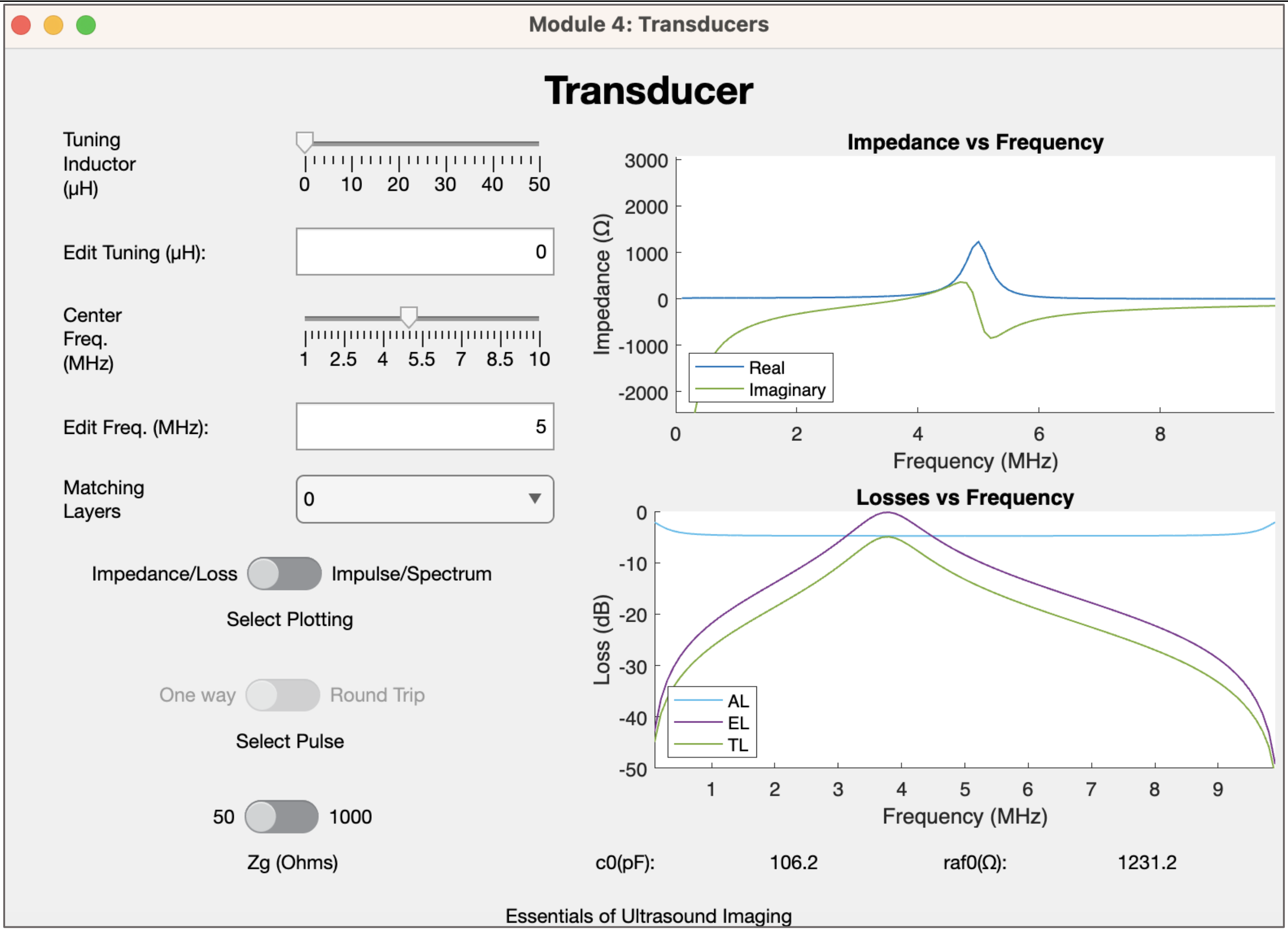

Figure 27: Transducer Simulator GUI in Impedance/Loss Mode

The simulator operates in two basic modes—Impedance/Loss mode and Impulse/Spectrum mode. It is recommended that the user begin with the Impedance/Loss mode.

A typical sequence of operations for the Impedance/Loss mode is as follows:

1. Select the electrical impedance value using the Z_g toggle switch. Typically, this value is set at 50 Ω unless a higher impedance value is required for a specific purpose.
2. Adjust the center frequency value using the slider. By default, this value is initially set to 5 MHz, which can be used as a starting point.
3. Using the Matching Layers dropdown menu, select the number of matching layers.
   The Matching Layers dropdown offers resonant design options from 0 to 2 layers and includes a special design (Optional Two) that simulates the L11-5v transducer design. By default, the number of matching layers is set to zero; in other words, there are no matching layers as demonstrated in Figure 26. Note that the resonant design only considers one or two matching layers (m.l.1 and /or m.l.2 as indicated in Figure 26). The simulator fixes the backing impedance at 3 MRayls and does not include a lens layer.
4. Based on the configured settings, the resulting impedance Vs. Frequency and Losses Vs. Frequency plots are shown on the right side of the GUI.

Impedance Vs. Frequency plot:

The Impedance Vs. Frequency plot shows the real part of the impedance: the radiation resistance as a function of frequency. The value of resistance at the resonant frequency is given below as raf0. The imaginary part of the impedance (the green curve) consists of two parts: a radiation reactance and the capacitive reactance of the transducer. At resonance, f0, the acoustic reactance is zero and the value of the capacitor, c0, is also displayed.

Losses Vs. Frequency plot:

The Losses Vs. Frequency plots include the Electrical Loss (EL), the Acoustical Loss (AL), and the total Transducer Loss (TL). The Losses panel illustrates that (one way) Transducer Loss is the product of Electrical Loss (determined by the transducer impedance (Zg) and the tuning inductor (if any)) and the Acoustical Loss (determined by transducer acoustical impedance, the matching layers, and the front (water) and back (backing) acoustic loads).

After studying the Impulse/Loss mode, the user can switch to the Impulse/Spectrum mode to analyze the One-Way Pulse Vs. Time and Losses Vs. Frequency plots.

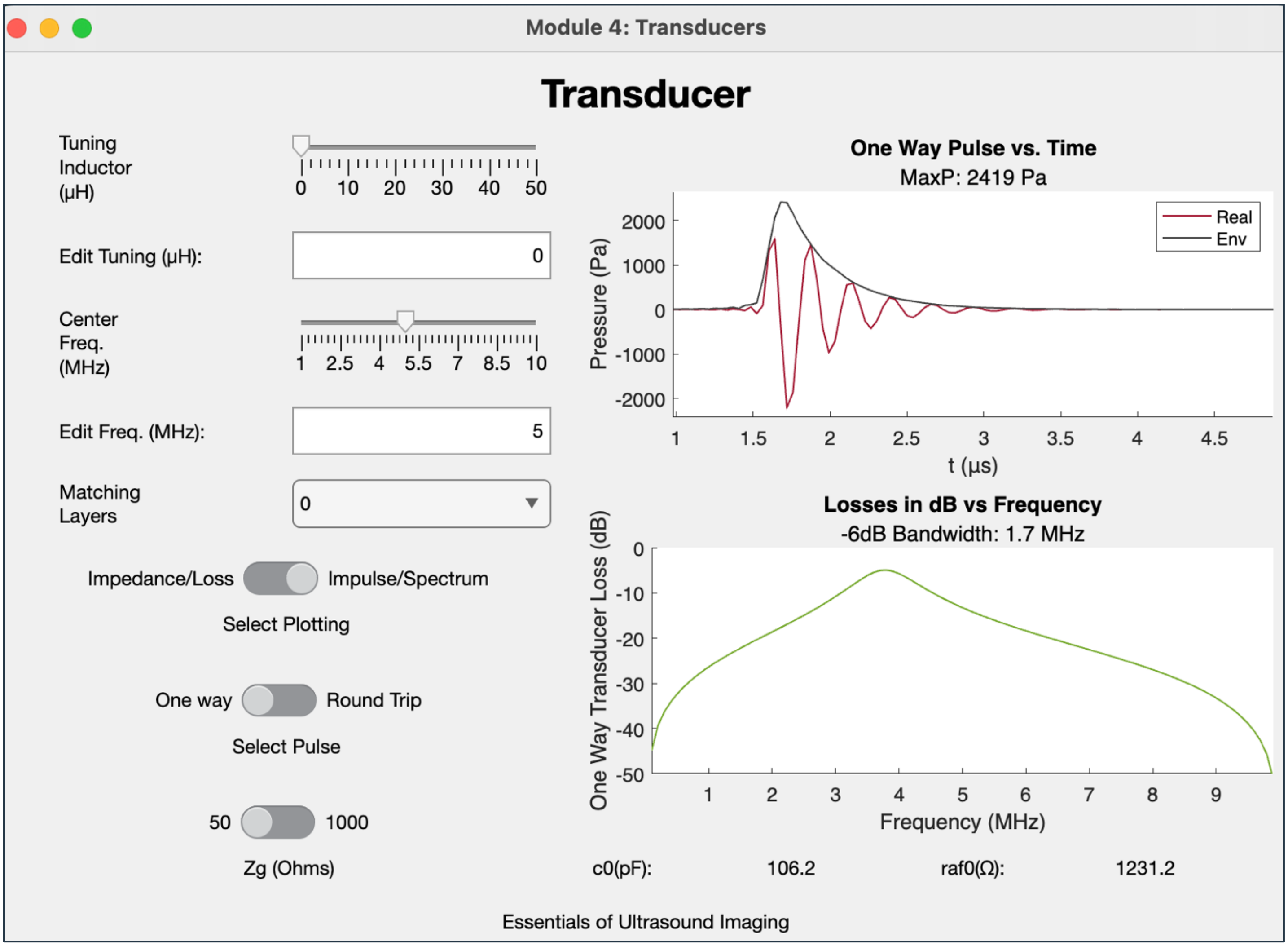

Figure 28 Transducer Simulator GUI in Impulse/Spectrum Mode

The sequence of operations for the Impulse/Spectrum mode is as follows:

1. Use the toggle switch to select the Impulse/Spectrum mode.
2. Use the Data Tips cursor to determine features of pulse amplitude and spectrum such as pulse envelope width and spectral peak frequency.

One-Way Pulse Vs. Time plot:

The Pulse Vs. Time plot shows the real pulse signal vs time (shown as a red curve) with its analytic envelope (shown in black). The maximum numerical value of the envelope peak is displayed above the plot. In the One-Way switch position, the pressure pulse is shown. In the Round-Trip switch position, the received voltage waveform is displayed. Identical transmit and receiver configurations are assumed.

Loss Vs. Frequency plot:

The Loss Vs. Frequency plot shows the loss as a function of frequency on a dB scale. The numerical value of the -6 dB bandwidth is given above the plot. In the One-Way switch position, the transducer loss is shown. In the Round-Trip switch position, the insertion loss is displayed.

Table 15: Transducer Filter - UI Controls and Description

UI Control	Description
Tuning Inductor	Adjust the tuning inductor slider to modify the inductance of the tuning inductor connected in series with the transducer model.
Edit Tuning	Enter the value of inductance of the tuning inductor connected in series with the transducer model.
Center Freq.	Adjust the Center Freq. slider to change the center frequency of the transducer.
Edit Freq.	Enter the value of the center frequency of the transducer in the input field.
Matching layers	From the Matching Layers dropdown menu, select the number of matching layers—0, 1, 2, or Optional 2.
Select Plot	Slide the toggle button to the right to select Impulse/Spectrum plots. Slide the toggle button to the left to select Impedance/Loss plots.
Select Pulse	Slide the Select Pulse toggle button to the right to select an ideal round-trip pulse echo from a perfect reflector. Slide the toggle button to the left to select a one-way pulse.
Zg (Ω)	Use the toggle switch to set the source impedance value to 50 ohms or 1000 ohms.

Module 5: Beams and Focusing

Field Simulator

The Field simulator calculates the two-dimensional acoustic field from a continuous wave line aperture source situated at z=0 in the x-z plane. It offers options to change the apodization (or weighting) of the amplitude, aperture, and focus. The simulator offers various display options, which include an option that allows the user to view the field along any line drawn in the field. Throughout this simulator GUI, wavelength-scaled parameters are used.

For detailed information on this simulator module, refer to Section 5.3: Field Simulator in the course textbook, Essentials of Ultrasound Imaging.

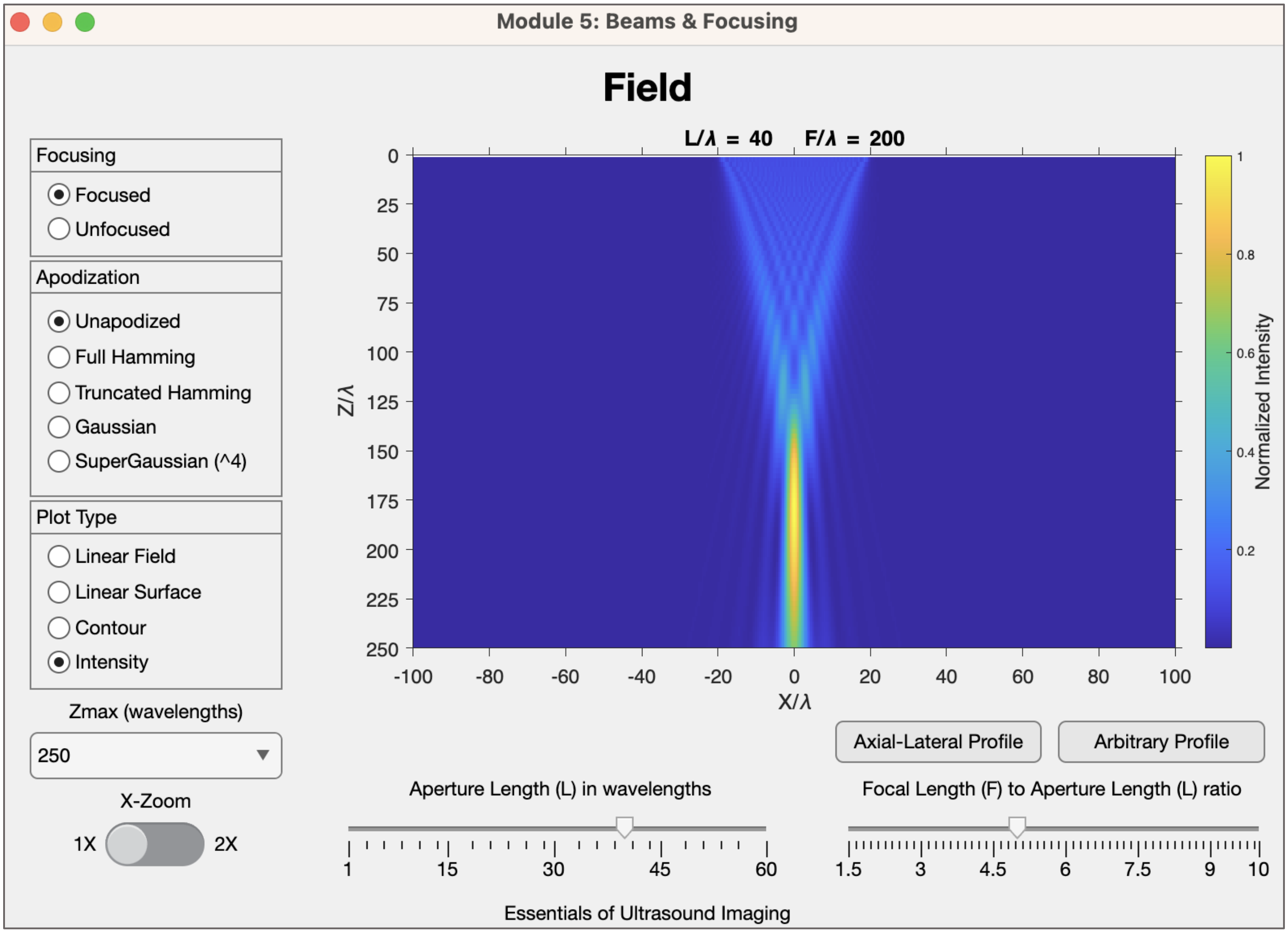

Figure 29: Field Simulator GUI

This simulator opens in default mode. Use the following instructions to explore the simulator:

1. From the Focusing panel, select the Focused (default) or Unfocused menu option.
2. From the Apodization panel, select an Apodization type. The default option is set to Unapodized.
3. In the Plot Type panel, select the desired display option to change the appearance of the field.
4. Define the depth of the field plot by selecting the Zmax value from the dropdown menu. (The default is 250).
5. Magnify (in the x-direction only) the central region of the field by using the Zoom slider. (The default setting is 1x).

6. Adjust the input variables: Aperture Length in wavelengths (Default=40) and Focal Length to Aperture Length ratio (Default=5) by using the corresponding sliders.
7. For the Intensity Plot Type:
    a. Click the Axial-Lateral Profile button to obtain a pop-out figure window with a cursor.
    b. Position the cursor at the desired location and right-click to get an axial profile and a lateral profile at the chosen point.
    c. Note that red bars in the visualization indicate the location where the axial and lateral profiles are taken.
    d. A data cursor can be used to obtain quantitative information from the plots.

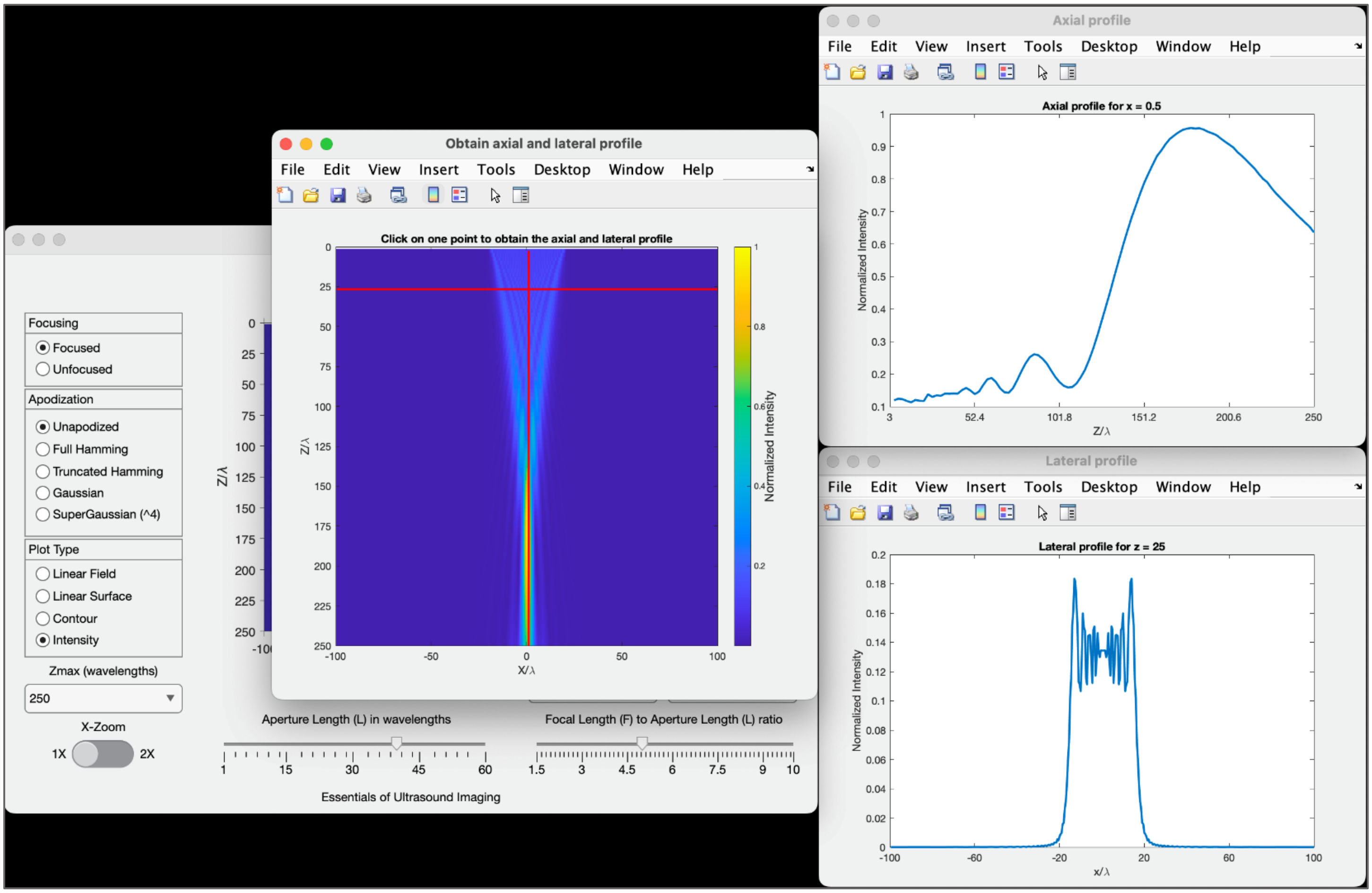

Figure 30: Field Simulator - Axial-Lateral Profile: Popup Window and Plots

    e. Click the Arbitrary Profile button to obtain a cursor in a pop-out figure that lets the user click on two different points (start point and end point) to obtain a transverse section through the field.

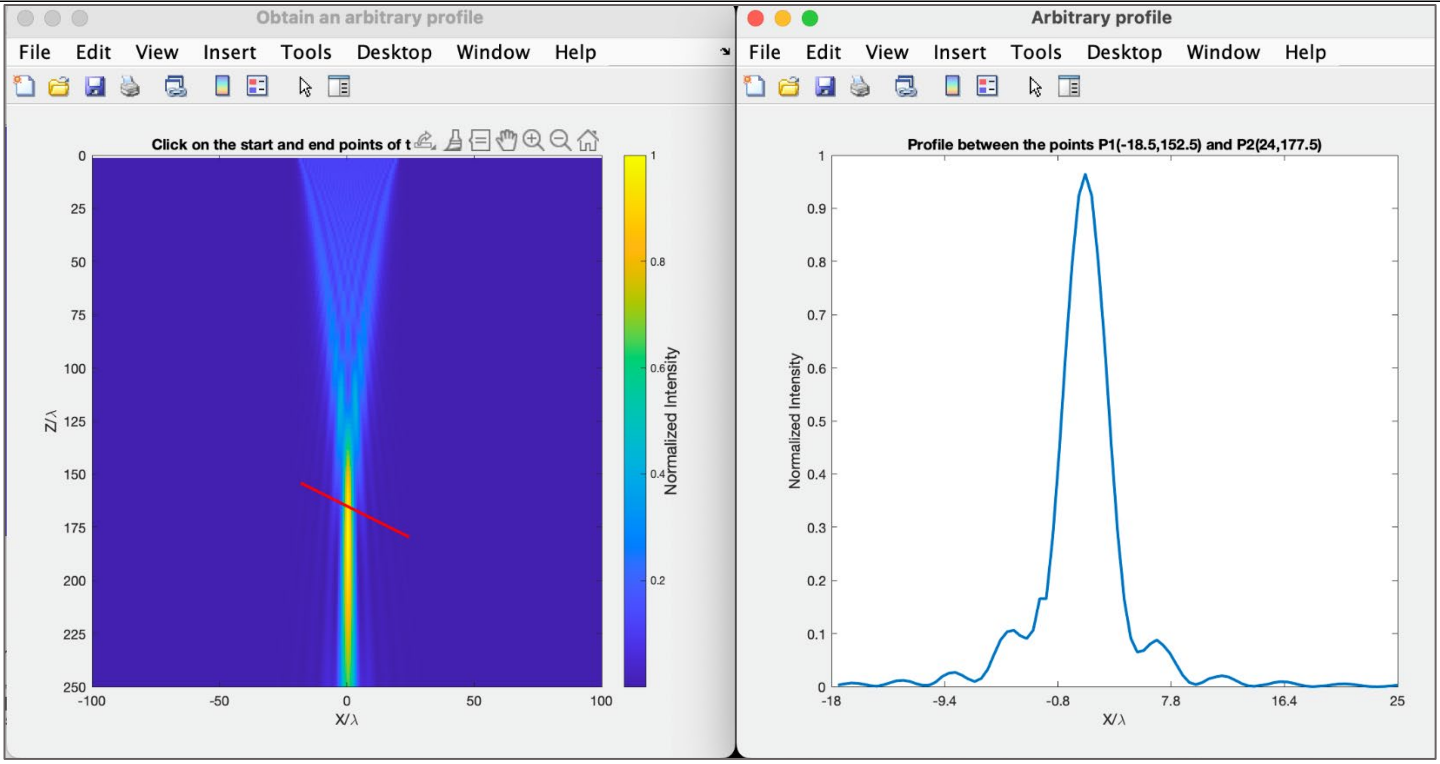

Figure 31: Field Simulator - Arbitrary Profile: Popup Window and Plot

Table 16: Field Simulator - UI Controls and Descriptions

UI Control		**Description**
Focusing	Focused	Select Focused to obtain a focused beam.
	Unfocused	Select Unfocused to obtain an unfocused beam.
Apodization		From the Apodization dropdown menu, select an Apodization option—Unapodized, Full Hamming, Truncated Hamming, Gaussian, Super-Gaussian. Each of the apodization types applies different mathematical functions to smoothly weigh the amplitude across the aperture.
Plot Type	Linear Field	Creates a waterfall array of lateral beam plots spaced at equal intervals along the z(propagating) axis with distances increasing in an upward direction. The aperture is diagrammed at the bottom.
	Linear Surface	Creates a surface plot of the field on a linear scale. The aperture is on the right side of the plot at $Z/\lambda=0$.
	Contour	Creates a contour plot with -6 dB, -10 dB, and -20 dB contours. This plot provides a quantitative interpretation of the field structure. The aperture is at the top.
	Intensity	Select Intensity to get a map of the field in a continuous color representation. The aperture is at the top. This selection adds the Axial-Lateral Profile option.
Zmax (wavelengths)		Select a specific Zmax value from the dropdown menu to compute the field over the selected propagation distance.
Zoom		Use the Zoom slider to change the scale of the X-axis (1x or 2x).
Aperture Length (L) in wavelengths		Use the slider at the bottom of the GUI to define the aperture length.
Focal Length (F) to Aperture Length (L) ratio		Use the slider at the bottom of the GUI to define the Focal Length to Aperture Length ratio.

UI Control	Description
Axial-Lateral Profile	Select the Axial-Lateral Profile to create a popup window in which you can position a cursor at any point to obtain axial and lateral profiles passing through that point. The red bars in the visualization indicate the location where the axial and lateral profiles are taken. See Figure 30.
Arbitrary Profile	This option allows the user to see the beam along a slice in any arbitrary direction or location. Clicking on this display option creates a popup window with a cursor. Place the cursor at the first desired location and click and then select the second point and click again. The resulting selected line is overlaid on the intensity plot and the plot of the profile along the line appears in a popup window. See Figure 31.

Beamplot Simulator

This simulator computes a lateral beam plot at an adjustable distance Z/λ from the transducer aperture at Z=0. This simulator shares the same input controls for the Focusing and Apodization panels as the Field simulator. Also, the Aperture Length in wavelengths and the F-number (equal to F/L) sliders are similar. A new slider for the distance in wavelengths for the placement of the beamplot has been provided. Compared to the Field Simulator, the Beamplot Simulator provides a handy way of seeing the apodization functions and obtaining quantitative information about beamplots. See the lower left panel for beam widths. Note that by placing the Z/λ slider at the scaled focal distance F/λ, the Fourier transform relationship between the apodization function and the focal beam plot can be observed as shown in Figure 32.

For detailed information on this simulator module, refer to Section 5.2.2: Beamplot Simulator in the course textbook, Essentials of Ultrasound Imaging.

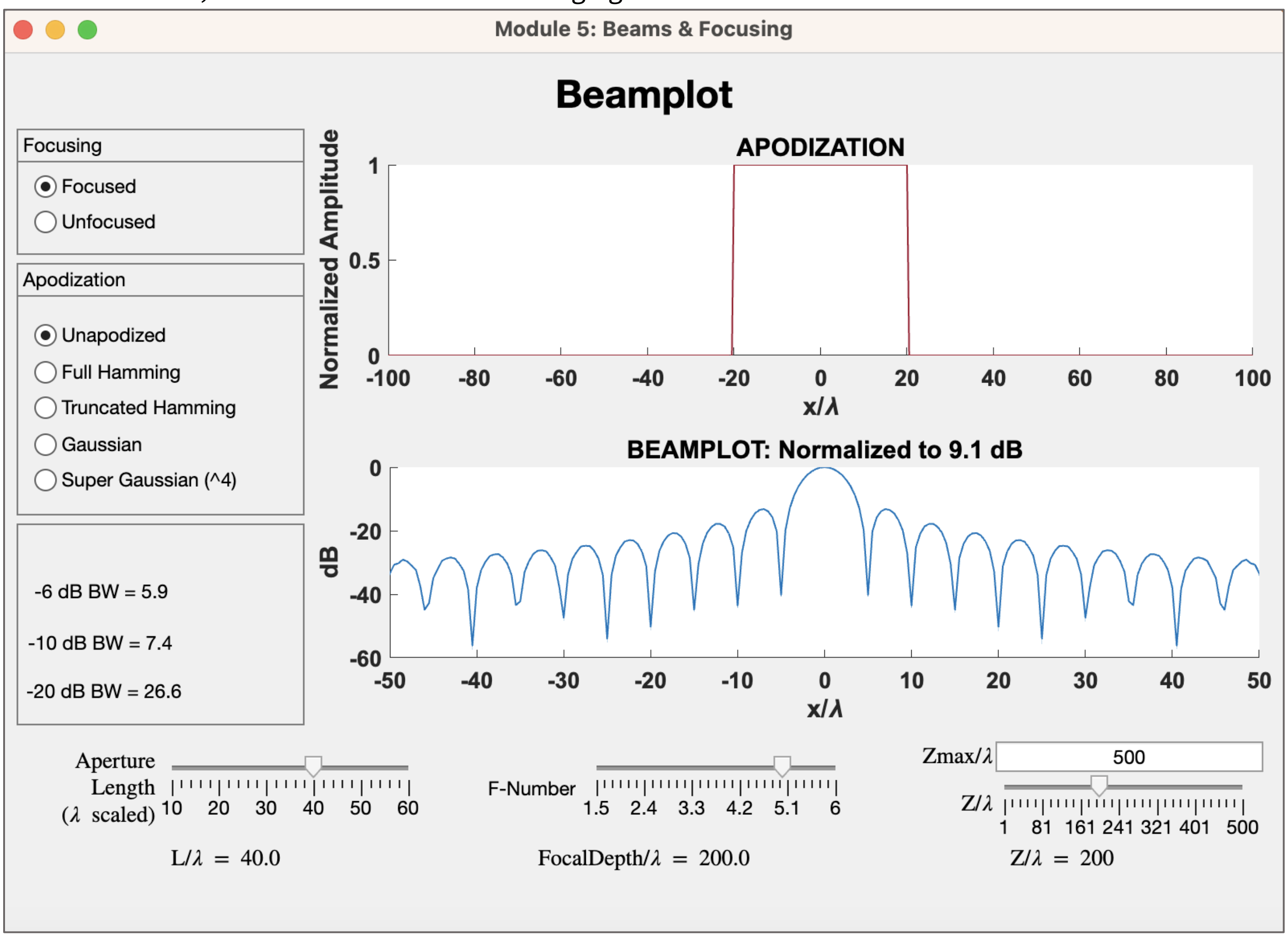

Figure 32: Beamplot Simulator GUI

A typical workflow for this simulator is as follows:

1. Select a focused beam or an unfocused beam option.
2. Select the apodization window type.
3. Define the aperture length, F-Number, and Z/λ value using the input sliders.
4. A data cursor can be used to obtain quantitative information from the plots.

Apodization Vs. x/λ plot:

The Apodization plot in the top right of the GUI shows the apodization function selected.

Beamplot Vs. x/λ plot:

The Beamplot on the lower right of the GUI shows a lateral slice of the field at the selected distance, Z/λ.

Table 17: Beamplot Simulator - UI Controls and Description

UI Control		Description
Focusing	Focused	Select Focused to obtain a focused beam.
	Unfocused	Select Unfocused to obtain an unfocused beam.
Apodization		From the Apodization dropdown menu, select an Apodization option—Unapodized, Full Hamming, Truncated Hamming, Gaussian, Super-Gaussian. Each of the apodization types applies different mathematical functions to smoothly weigh the amplitude across the aperture.
Aperture Length		Use the slider at the bottom of the GUI to define the aperture length in wavelengths. (Default=40)
F-number		Define the F-number value using the slider. The F-number is the ratio of the focal depth to the aperture length. (Default=5)
Z/λ		Define the Z/λ value using the slider. Z/λ value represents the distance from the array to the beamplot. (Default=150)

Module 6: Continuous Wave Array Beamforming and Heating

Wavefronts Simulator

The Wavefronts simulator demonstrates how fields from an array of point sources combine to form beams. The user can select an arrangement of point sources and watch as the selected set of expanding spherical wavefronts simultaneously form a beam in a time-sequenced animation. Once the animation is fully rendered, the graph can be rotated using the mouse (by clicking and dragging the cursor inside the plot axes) to see a different 3D view of the wavefront.

For detailed information on this simulator module, refer to Section 6.1.3: Wavefronts Simulator in the course textbook, Essentials of Ultrasound Imaging.

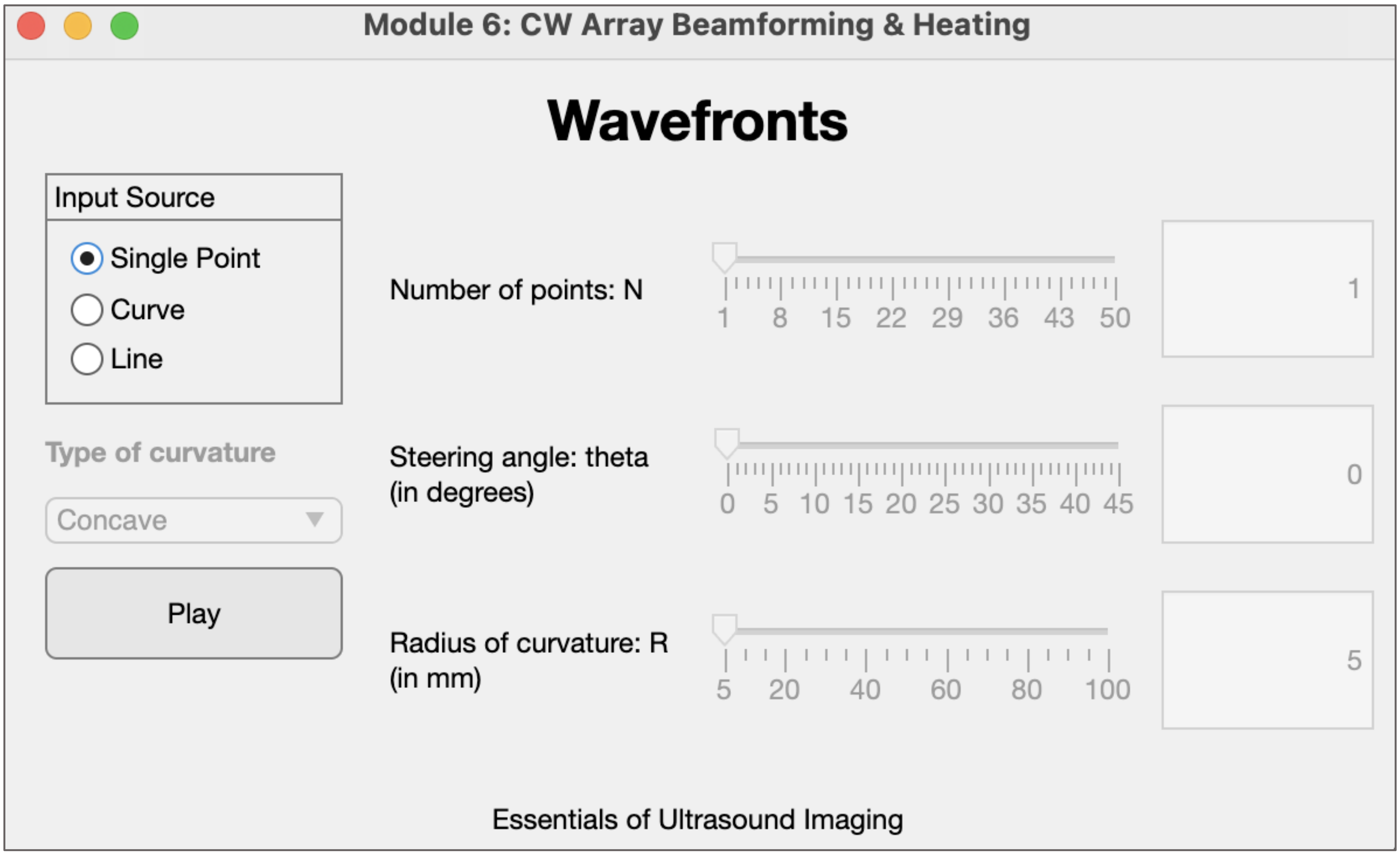

Figure 33: Wavefronts Simulator GUI

The Input Source panel on the left side of the GUI allows users to select an input source geometry. The sliders on the right side of the GUI allow adjustment of parameters associated with the input source selection. The spacing between source points is 0.5 mm. Quantities for the selected values are shown in the boxes on the right.

A typical sequence of operations for this simulator is as follows:

1. From the Input Source list, select the desired source arrangement.
2. Upon selecting the input source geometry, the adjustable parameters associated with the sources are enabled. Adjust the sliders to define the array. Select the number of points. For a line array, select the direction of propagation. (The default angle is zero degrees). For a curved array, define a radius of curvature and choose between a concave or convex curvature.
3. Click the Play button to visualize the animation of expanding spherical wavefronts from the selected geometry.
4. A recommended sequence is the Single Point, a Line Array with a Steering Angle, and a Curved Array.

Note: If the number of points chosen for an array is 1, then the graph looks identical to the animation of a single-point source.

Table 18: Wavefronts Simulator - UI Controls and Description

UI Control		Description
Input Source	Single Point	Check the Single Point radio button to select a single-point source.
	Curve	Check the Curve radio button to select a curve-shaped source (comprising of n points spaced half a wavelength apart). Be sure to select n, a radius of curvature and the concave/convex option before playing.
	Line	Check the Line radio button to select a line source (comprising of n points).
Number of points: N		Adjust the slider to select the number of points for Curve and Line source selections. Alternately, enter a value in the input field next to the slider.
Steering Angle: Theta (in degrees)		Adjust the slider to choose a steering angle for the Line source selection. Alternately, enter a steering angle value in the input field next to the slider.
Radius of Curvature: R		Adjust the slider to choose a radius of curvature for the Curve source selection. Alternately, enter a radius of curvature value in the input field next to the slider. A convex curvature will start as an expanding wavefront; a concave curvature may focus the wavefront before diverging again after the focal zone.
Play		After selecting an input signal/source and adjusting all parameters associated with it, click the Play button to visualize how beams are formed. Rotate the view using the mouse cursor (click and drag inside the plot).

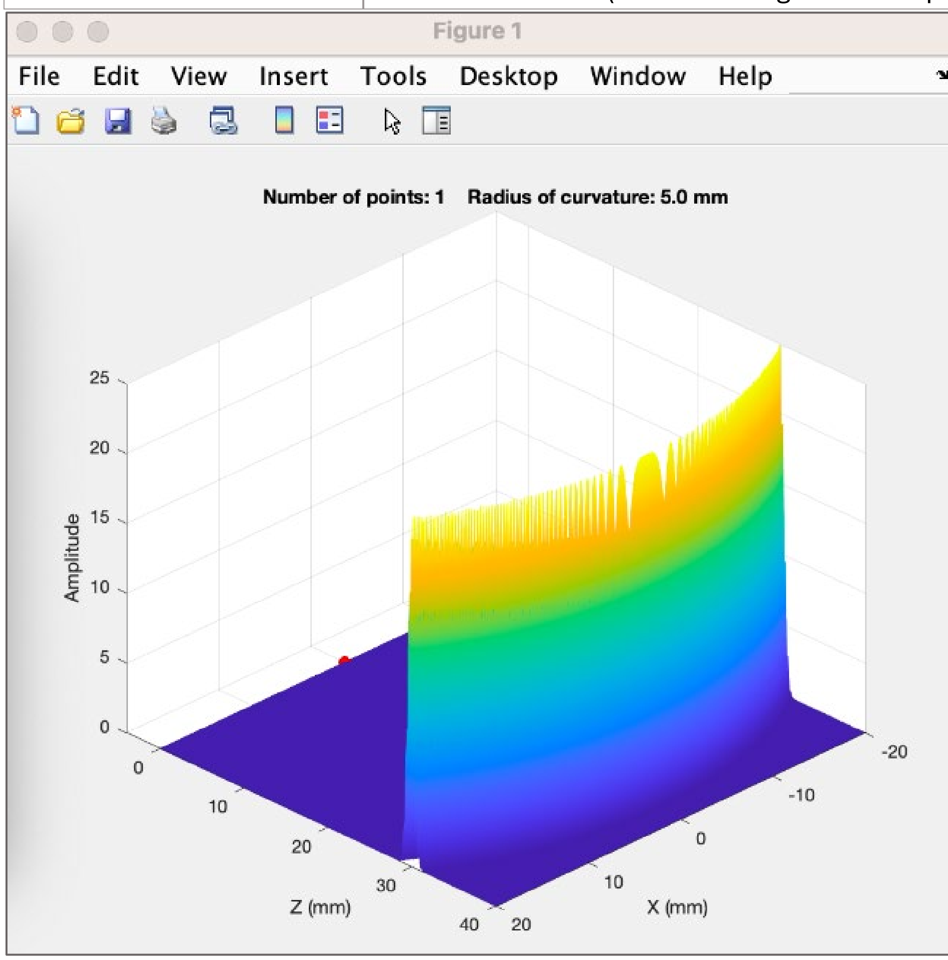

Figure 34: Curve Input Signal Selection with N=1

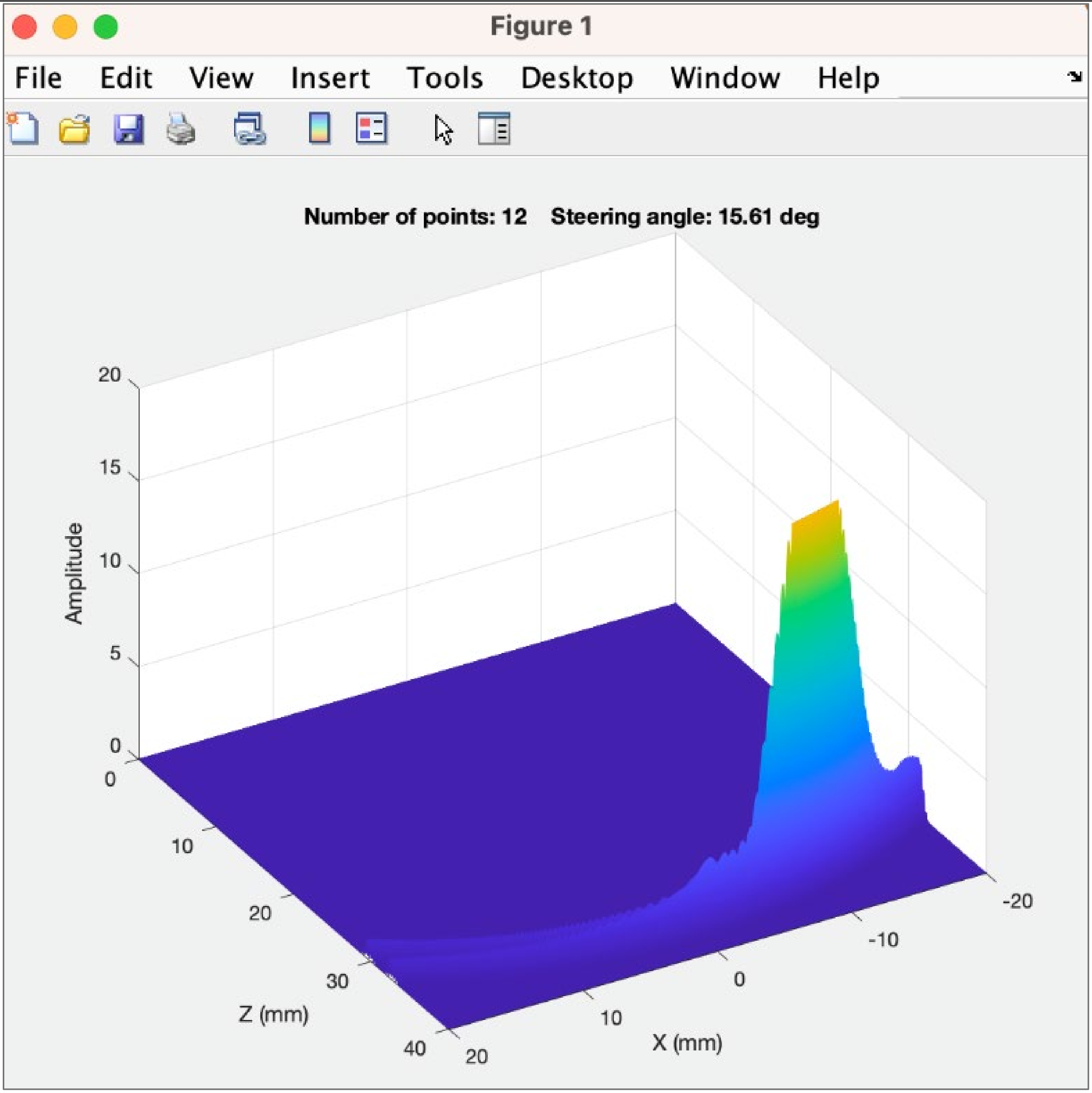

Figure 35: Line Input Signal Selection with a Steering Angle of 15.61 deg

Directivity Simulator

The Directivity simulator enables users to understand how array length, periodicity, element width, and directivity affect the radiation pattern of an array, and in particular, its directivity and grating lobes.

For detailed information on this simulator module, refer to Section 6.3.2: Directivity Simulator in the course textbook, Essentials of Ultrasound Imaging.

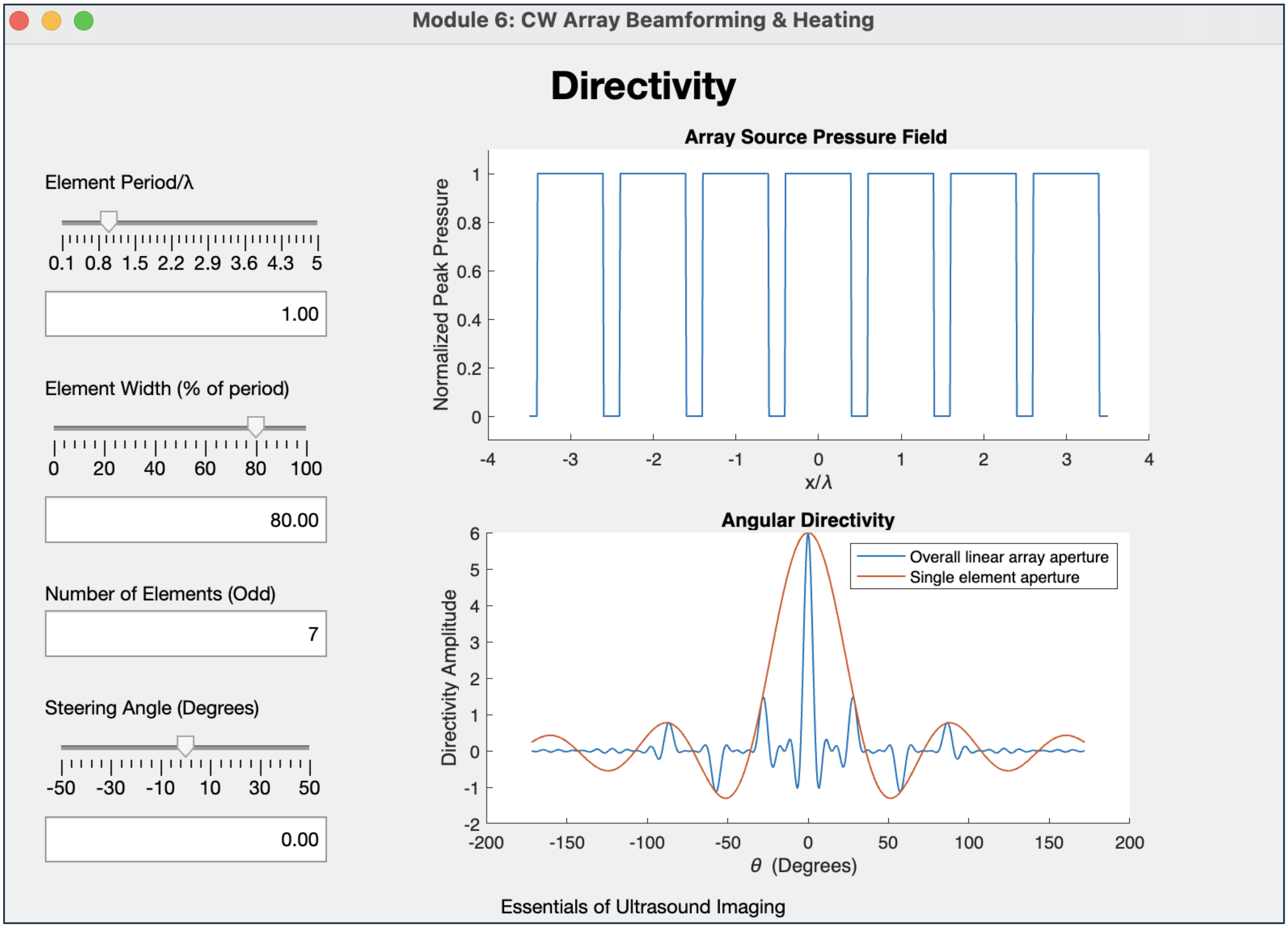

Figure 36: Directivity Simulator GUI

On the left side of the GUI, the user can set the input parameters—element period, element width (as a percent of the period), the number of elements in the array, and the steering angle of the array. As the inputs are set, the Array Source Pressure Field plot (on the top right of the GUI) reflects these input selections, and the corresponding Angular Directivity plot is displayed on the lower right of the GUI. Note that this simulator opens in a default mode. Quantitative data can be obtained by using the Data Tips tool.

A typical sequence of operations for this simulator is as follows:

1. Define the array elements using the input selections (sliders and edit boxes) on the left side of the GUI.
2. Observe that the input selections are represented in the Array Source Pressure Field plot.
3. Study the array radiation pattern in the Angular Directivity plot (as indicated by the blue curve for overall linear array directivity), where the strength of the beam in the far field is given by the Fourier transform of the source pressure as a function of angle with respect to the array normal direction. The

radiation pattern of a single element is presented for comparison (as indicated by the red curve). The Directivity amplitude of the linear never exceeds that of a single element.

4. Note that the steering angle (achieved by phasing of the array) input changes the beam pattern as seen in the Angular Directivity plot. While a single element cannot be steered, the array beam pattern can be steered by appropriately phasing individual elements.

Table 19: Directivity Simulator GUI

UI Control	Description
Element Period (Wavelength)	Adjust the slider to set the period of the element. An ideal value for phased arrays is half a wavelength.
Element Width (% of period)	Adjust the slider to set the element width. Typical practical values are .80-.90 of a wavelength.
Element Number (Odd)	Enter an odd number of array elements in the input field.
Steering Angle (degrees)	Adjust the slider to set the steering angle.

CW Array Simulator

The CW Array simulator models the full three-dimensional field characteristics of a continuous wave excited phased array (that includes realistic elements with elevational (y) dimension) propagating as a three-dimensional beam into a selectable absorbing medium as well as the resultant heating.

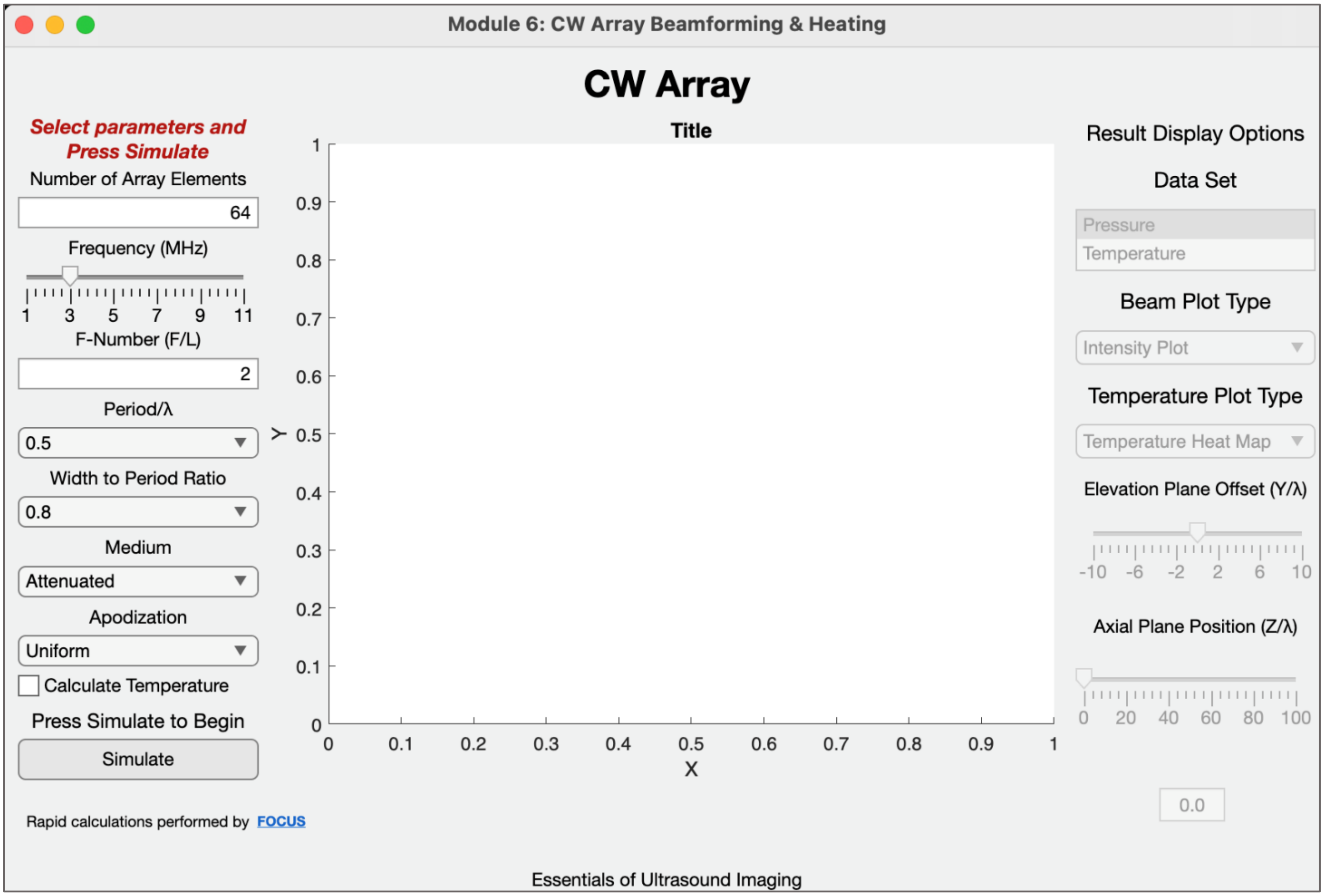

Figure 37: CW Array Simulator setup

This simulator has three types of controls: familiar input parameters, a choice of output variables, and many new display options. Several input controls in the left panel area are a combination of different inputs from the Field and Directivity simulators. A new output option is the capability to model steady-state heat in absorbing media generated by ultrasound in addition to the pressure field. For display, the conventional beam display options, such as those used in the Field Simulator are available along with new ones that provide field viewing options in planes other than the x-z plane in order to appreciate the three-dimensional nature of the field.

For detailed information on this simulator module, refer to Section 6.4.2: Continuous Wave Array Simulator for 3D Beams in the course textbook, Essentials of Ultrasound Imaging.

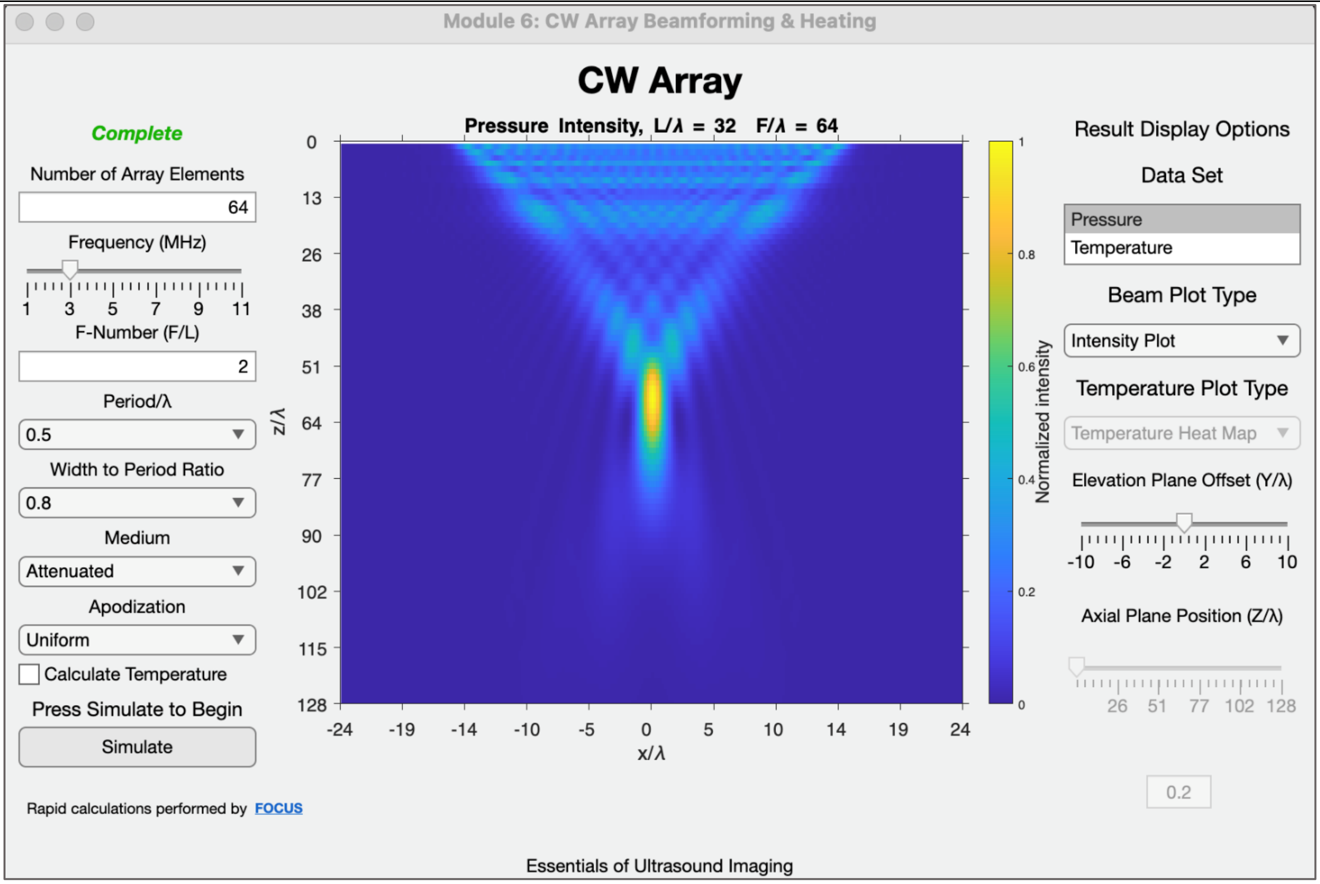

Figure 38: CW Array 3D simulator in Pressure mode Displaying an Intensity Plot

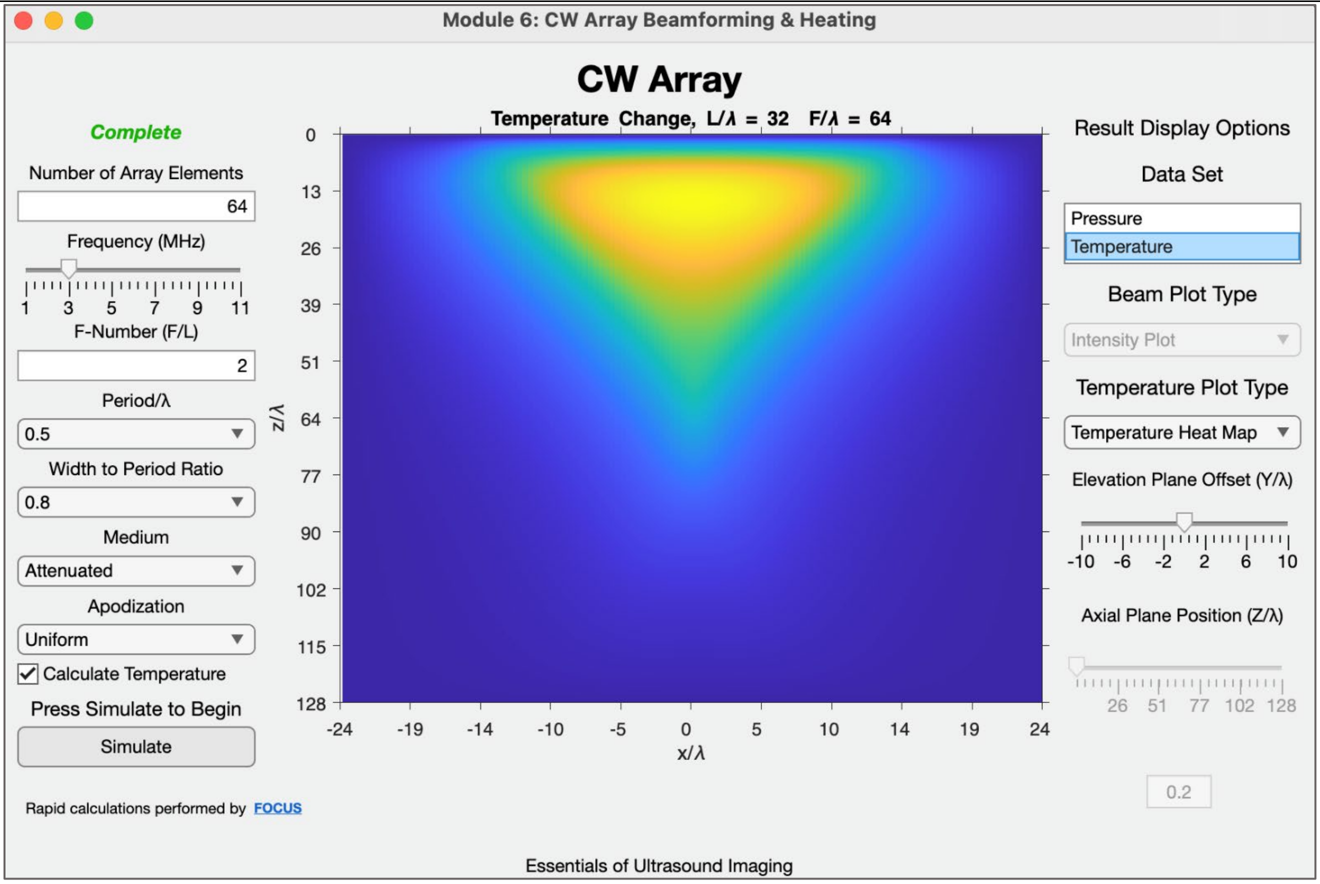

Figure 39: CW Array Simulator -Temperature Mode Displaying Temperature Heat Map

The **Continuous Wave Array** panel on the left side of the GUI allows the user to define an array operating at a continuous wave frequency and to select a medium to include the effects of absorption and heating. The **Result Display Options** panel to the right of the GUI allows the user to select the pressure dataset or temperature dataset and the corresponding output display plots associated with the selection. If only pressure fields are desired, make sure that the Calculate Temperature Box is not checked to minimize computation time and Pressure must be selected as the output display parameter in the Data Set panel (gray highlight). For temperature calculations, the Calculate Temperature box must be checked, and Temperature must be selected as the output display parameter in the Data Set panel. Note that an absorbing (not lossless) medium must be selected for heating to occur. When Temperature is selected, both heating and field calculations are initiated, and it is possible to toggle between Pressure and Temperature displays through the Data Set panel.

Note: The plots are rendered normalized to the maximum value on the color bar; however, the maximum values change based on whether the field is attenuated or not.

To familiarize yourself with the extensive capabilities of this simulator, the following walkthrough is suggested:

1. Familiarize yourself with the input options on the left side of the GUI. Note that when a medium other than lossless is selected, as it must be for any temperature calculation, the associated characteristics include the speed of sound, absorption, and thermal characteristics.
2. On the left side of the GUI, the user can set the following input acoustic parameters: number of array elements, frequency of the continuous wave, F-number (F/L) value, periods per wavelength value, width-to-period ratio, medium type, and apodization type. For this walkthrough, use the default values.

3. Check the Calculate Temperature checkbox for the initial default calculation that includes both pressure and temperature.
4. Click the Simulate button to initiate computation, initially through the use of default parameters.
5. Once the simulation is complete, the Pressure option is preselected from the default Dataset menu.
6. A default intensity display option appears in the output display window. The Beamplot Type dropdown menu offers the usual options of beamplot, contour, surface, and intensity options all in the x-z imaging plane where y=0 (similar to a B-mode image).
7. Use the Elevation Plane Offset (Y/λ) slider to move the field to parallel x-z planes for different offsets (different positions of the y-axis). This movement provides insights into the three-dimensional aspects of the beam.
8. Also available in the Beamplot Type dropdown menu are two new choices: Axial Plane Intensity and Axial Plane Surface to reveal the 3D nature of the beam. The Axial Plane Intensity option provides a C-mode image of the field in a plane transverse to the z-axis. The position of this transverse plane is governed by the slider, Axial Plane Position (Z/λ). The initial position is close to the transducer, so the user should see the approximate shape of the transducer. As Z/λ is increased, the field evolves—becoming narrower at the focal length F/λ and wider beyond it.
9. For a different display of the axial field, select the Axial Plane Surface plot option and adjust the Elevation Plane Offset slider to view a different representation of the field.
10. For heating options, select the Temperature option from the Dataset menu. Before doing so, select the Intensity plot option for Pressure.
11. From the Temperature Plot dropdown menu, choose Temperature Heat Map (this is the default option).
12. Compare the heat pattern to the pressure intensity map by toggling between the Pressure option (shown in Figure 38) and the Temperature option (shown in Figure 39) in the Dataset menu.
13. Choosing the Temperature option opens up a new set of plot options under the Temperature Plot Type dropdown menu.
14. Both the Temperature Heat Map and the Temperature Surface Plot have the x-z plane motion privileges from the Elevation Plane Offset (Y/λ) slider. A nice feature of the surface plot is a quantitative map of the temperature elevation.
15. In addition, users can view the index of the color in the Heat Map (or the pressure Intensity field plots) by using the MATLAB Data tool and then selecting a point in the temperature plot. Note that the Data Tips tool indicates the color index and not the actual temperature.
16. Among the Temperature Plot types are the Axial Plane Heat Map and the Axial Plane Temperature Surface which function in the same way as the corresponding Pressure Axial Plane plots (the positions of which are governed by the slider, Axial Plane Position (Z/λ)).

Note: If the user modifies any of the input parameters, they should click the Simulate button again to simulate the program with the modified parameters before viewing the desired plots.

Table 20: CW Array Simulator - UI Controls and Description

UI Control	Description
Number of Array Elements	Enter the number of array elements (between 1 and 128).
Center Frequency (MHz)	Set the frequency of the continuous wave using the slider.
F-Number (F/L)	Set the F-Number value—it is the ratio of focal length F to aperture L.
Period/λ	unitless
Width to Period Ratio	Using the Width to Period dropdown menu, change the spacing between elements and the relative size of the element to spacing.

<table>
<tr><th colspan="2">UI Control</th><th>Description</th></tr>
<tr><td colspan="2">Medium</td><td>From the Medium menu, select a medium. Here y=1.
<table><tr><th>Medium Type</th><th>Attenuation α(dB/cm/MHz)</th></tr><tr><td>Lossless</td><td>0</td></tr><tr><td>Attenuated</td><td>1</td></tr><tr><td>Liver</td><td>0.45</td></tr><tr><td>Muscle</td><td>0.57</td></tr><tr><td>Fat</td><td>0.6</td></tr></table></td></tr>
<tr><td colspan="2">Apodization</td><td>Apodization dropdown menu: Uniform, Bartlett, Chebyshev, Hamming, Hann, and Triangle. Each of the apodization types applies different mathematical functions to the element amplitudes along the aperture.</td></tr>
<tr><td colspan="2">Dataset</td><td>Select either the Pressure dataset or Temperature dataset to view the corresponding temperature plots or pressure plots.</td></tr>
<tr><td colspan="2">Axial Position in Wavelengths</td><td>Specify the location of the axial plane perpendicular to the z-axis (a slice through the 3D field) using the Axial Position in Wavelengths slider. The beam changes as a function of the axial position—this can be observed by adjusting the Z/λ distance from the aperture by the slider.</td></tr>
<tr><td colspan="2">Elevation in Wavelengths</td><td>Elevation offset as y/λ</td></tr>
<tr><td rowspan="6">Beamplot Type</td><td>Pressure Beam Plot</td><td>Select the Pressure Beam Plot (a stacked or waterfall-type plot) to visualize the pressure distribution of a beam as it propagates through a medium.</td></tr>
<tr><td>Pressure Surface Plot</td><td>Select the Pressure Surface Plot to visualize the distribution of pressure levels in a two-dimensional plane.</td></tr>
<tr><td>dB Contour Plot</td><td>Select the dB Contour Plot to display contour lines representing equal levels of decibel (dB) values across a two-dimensional surface. This plot helps analyze the distribution of signal strength or intensity in a given area and shows what the contours are at -6dB, -10dB, and -20dB levels.</td></tr>
<tr><td>Intensity Plot</td><td>Select the Intensity Plot to visualize a color intensity map that shows the distribution of intensity levels across a slice of the beam laterally with depth and across the array.</td></tr>
<tr><td>Axial Plane Intensity</td><td>Select the Axial Plane Intensity Plot to display a slice through the 3D field at the location as specified by the Axial Plane Position slider (Z/λ).</td></tr>
<tr><td>Axial Plane surface</td><td>Select the Axial Plane Surface Plot to display the absolute value of normalized intensity in a plane determined by the Axial Plane Position (Z/λ) slider.</td></tr>
<tr><td colspan="2">Calculate Temperature</td><td>Check the checkbox to view the steady-state temperature plot.</td></tr>
<tr><td colspan="2">Simulate</td><td>After providing all the inputs, select the Simulate button to simulate the desired plot.</td></tr>
<tr><td rowspan="3">Temperature Plot Type</td><td>Temperature Heat Map</td><td>Displays temperature rise as a color map in an x-z plane whose position is determined by the Elevation Plane Offset (Y/l) slider.</td></tr>
<tr><td>Temperature Surface Plot</td><td>Displays a quantitative Temperature Surface plot t in an x-z plane whose position is determined by the Elevation Plane Offset (Y/l) slider.</td></tr>
<tr><td>Axial Plane Heat Map</td><td>Displays a color map of temperature in a transverse plane determined by the Axial Plane Position (Z/l) slider.</td></tr>
</table>

UI Control		Description
	Axial Plane Temperature Surface	Displays a quantitative Temperature Surface plot determined by the Axial Plane Position (Z/l) slider.

Plane Wave Compounding Simulator

The Plane Wave Compounding simulator demonstrates how a beam pattern narrows by combining multiple plane waves steered at different angles. This simulator offers a superset of unfocused steered beams generated by the CW Array Simulator; therefore, the run time is proportional to the number of planes selected. The left input panel is very similar to that of the CW Array Simulator.

For detailed information on this simulator module, refer to Section 6.6.2: Plane Wave Compounding in the course textbook, Essentials of Ultrasound Imaging.

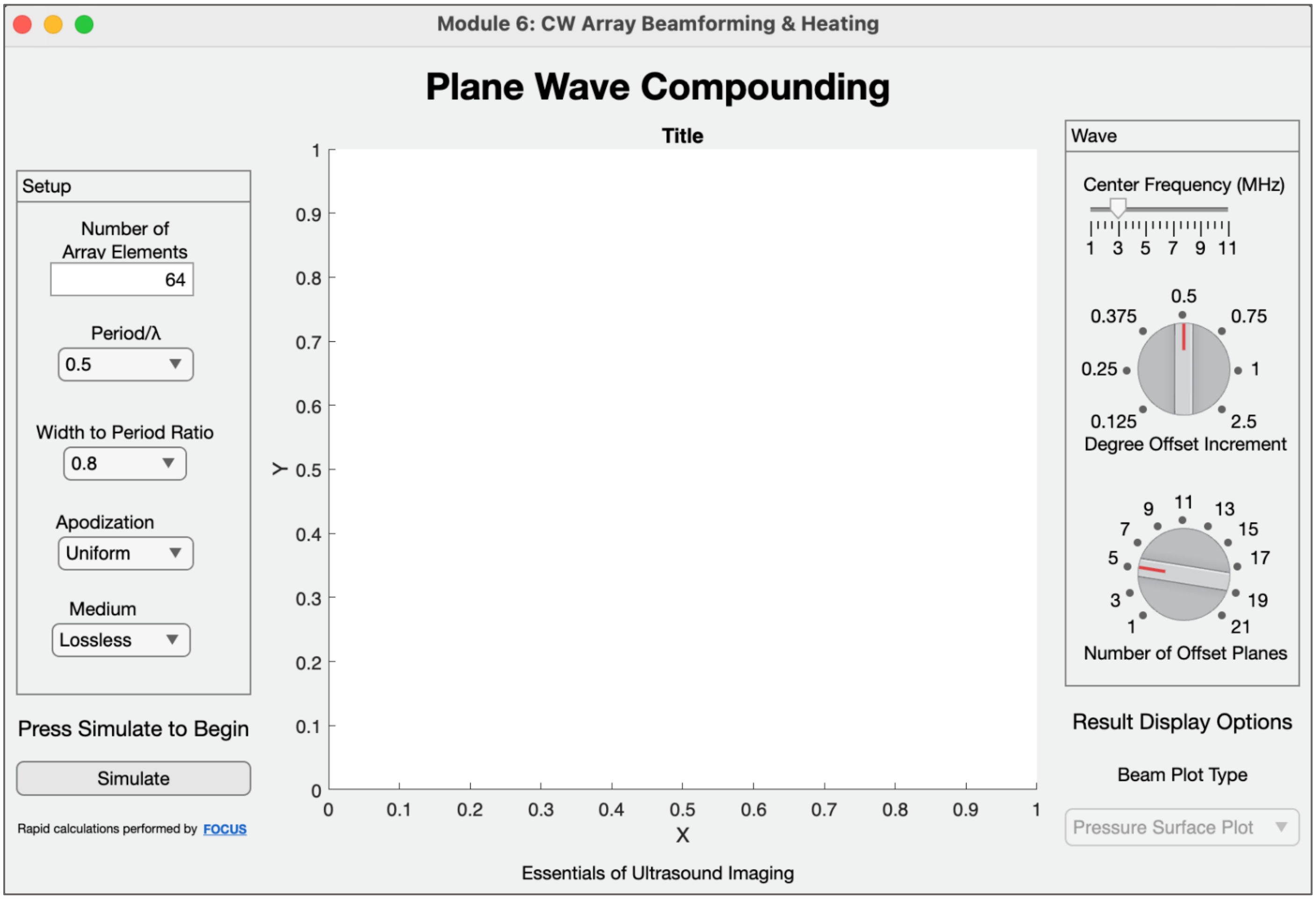

Figure 40: Plane Wave Compounding Simulator GUI

The Setup panel on the left side of the GUI allows users to define array element input parameters as well as the propagation medium. The Wave panel on the right side of the GUI allows users to specify plane wave input parameters: angular increment and number of planes. Note that aside from a plane wave transmitted at zero degrees, plane waves are generated in symmetric pairs at +θ and -θ angles. The Result Display Options panel on the lower right of the GUI provides beam display options for the combined acoustic field in the x-z plane. A typical sequence of operations through this simulator is as follows:

1. Define the input array parameters and medium—the number of array elements, periods per wavelength, width-to-period ratio, apodization type, and medium type. Note that the beam is unfocused. As before, initially, use the default parameters to understand the operation of the simulator.
2. Define the plane wave parameters, including the frequency, the number of plane waves, and the angular increment between the plane waves. Again, begin with default parameters.

3. Click the Simulate button to start the simulation.
4. Once the calculations finish and ***Complete*** is displayed at the top of the setup panel, use the Beam Plot Type dropdown menu to select the preferred output plot—Pressure Beam Plot, Pressure Surface Plot (default), dB Contour plot, or Intensity plot.
5. Note the Pressure Surface Plot can be rotated in 3D (by clicking inside the plot and dragging) to see a different orientation of the resultant field.
   Note: If any of the input parameters are changed, the user must click the Simulate button again to update the simulation results as prompted by the ***Please re-compute*** indication in the upper left corner of the GUI.

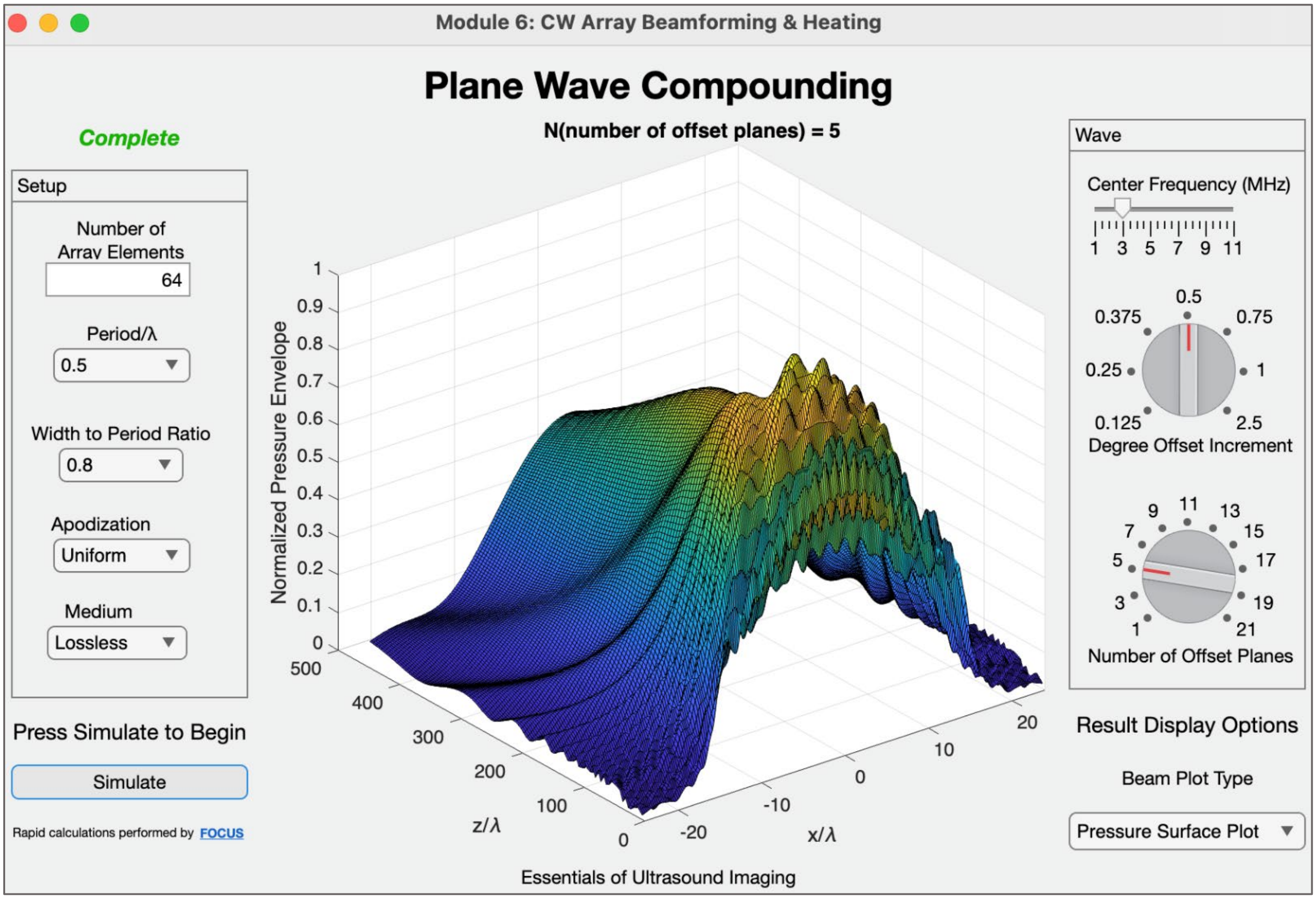

Figure 41: Plane Wave Compounding GUI - Pressure Surface Plot

Table 21: Plane Wave Compounding Simulator - UI Controls and Description

<table>
<tr><th colspan="2">UI Control</th><th>Description</th></tr>
<tr><td colspan="2">Number of Array Elements</td><td>Enter the number of array elements, between 1 and 128.</td></tr>
<tr><td colspan="2">Period/λ</td><td>Set the value using the dropdown menu. This value is unitless.</td></tr>
<tr><td colspan="2">Width to Period Ratio</td><td>Using the Width to Period dropdown menu, change the spacing between elements and the relative size of the element to spacing.</td></tr>
<tr><td rowspan="6">Apodization</td><td>Uniform</td><td rowspan="6">From the Apodization dropdown menu, select an Apodization option. Each of the apodization types applies different mathematical functions to smoothly decrease pressure amplitude towards the ends of the aperture with varying levels of beam sidelobe suppression and transition characteristics.</td></tr>
<tr><td>Bartlett</td></tr>
<tr><td>Chebyshev</td></tr>
<tr><td>Hamming</td></tr>
<tr><td>Hann</td></tr>
<tr><td>Triangle</td></tr>
<tr><td colspan="2">Medium</td><td>From the Medium menu, select a medium.
<table><tr><th>Medium Type</th><th>Attenuation α(dB/cm/MHz)</th><th>Speed of Sound (m/s)</th></tr><tr><td>Lossless</td><td>0</td><td>1500</td></tr><tr><td>Attenuated</td><td>1</td><td>1500</td></tr><tr><td>Muscle</td><td>0.57</td><td>1578</td></tr><tr><td>Fat</td><td>0.6</td><td>1580</td></tr><tr><td>Liver</td><td>0.45</td><td>1430</td></tr></table></td></tr>
<tr><td colspan="2">Center Frequency (MHz)</td><td>Adjust the slider to define the center frequency of the wave.</td></tr>
<tr><td colspan="2">Degree Offset Increment</td><td>angular increment in degrees</td></tr>
<tr><td colspan="2">Number of Offset Planes</td><td>plane 1 is at zero degrees; the others are symmetric pairs.</td></tr>
<tr><td rowspan="4">Beamplot Type</td><td>Pressure Beam Plot</td><td>Select the Pressure Beam Plot (a waterfall-type plot) to visualize the pressure distribution of a beam as it propagates through a medium.</td></tr>
<tr><td>Pressure Surface Plot</td><td>Select the Pressure Surface Plot to visualize the distribution of pressure levels in a two-dimensional plane.</td></tr>
<tr><td>dB Contour Plot</td><td>Select the dB Contour Plot to display contour lines representing equal levels of decibel (dB) values across a two-dimensional surface. This plot helps analyze the distribution of signal strength or intensity in a given area and shows what the contours are at -6dB, -10dB, -20dB, -40dB, and -60dB levels.</td></tr>
<tr><td>Intensity Plot</td><td>Select the Intensity Plot to visualize a color intensity map that shows the distribution of intensity levels across a slice of the beam laterally with depth and across the array.</td></tr>
<tr><td colspan="2">Simulate</td><td>After providing all the inputs, select the Simulate button to simulate the desired plot.</td></tr>
</table>

Module 7: Pulsed Phased Array Beamforming

Pulsed Array Simulator

The Pulsed Array simulator adds the dimension of time to the beamforming calculations and displays many features of an acoustic field generated by a phased array using different waveform excitations.

The Excitation Signal offers two choices with adjustments. The Medium options are similar to those used in the Absorption Filter simulator. The Transducer Array panels have similar input variable offerings to those seen in the CW Array simulator with the addition of steering. (Note that the aperture length is L=Np, the number of elements times the element period.)

The output variables are accessed in the output panel on the lower left corner of the GUI, arranged in different tabs—the Pressure Animation tab, the Pressure Waveform tab, the Lateral Beamplot tab, the Multiple Beamplots tab, and the Excitation Signal tab. Each of these tabs offers one or more display options for various outputs. These are independent and can be computed in any order.

An important aspect of this simulator is that it produces a snapshot of a pulsed beamformed wavefront, the position of which is defined by a propagation axis delay time, $t=|\mathbf{r}|/c$, or distance $|\mathbf{r}|$. Specifically, for a steered beam, the direction is defined by a vector, **r**, along which the focal distance has cartesian components F_x and F_z. For an unsteered beam, $F_x=0$ and $F=F_z$.

For detailed information on this simulator module, refer to Section 7.2.2: Pulsed Array Simulator in the course textbook, Essentials of Ultrasound Imaging.

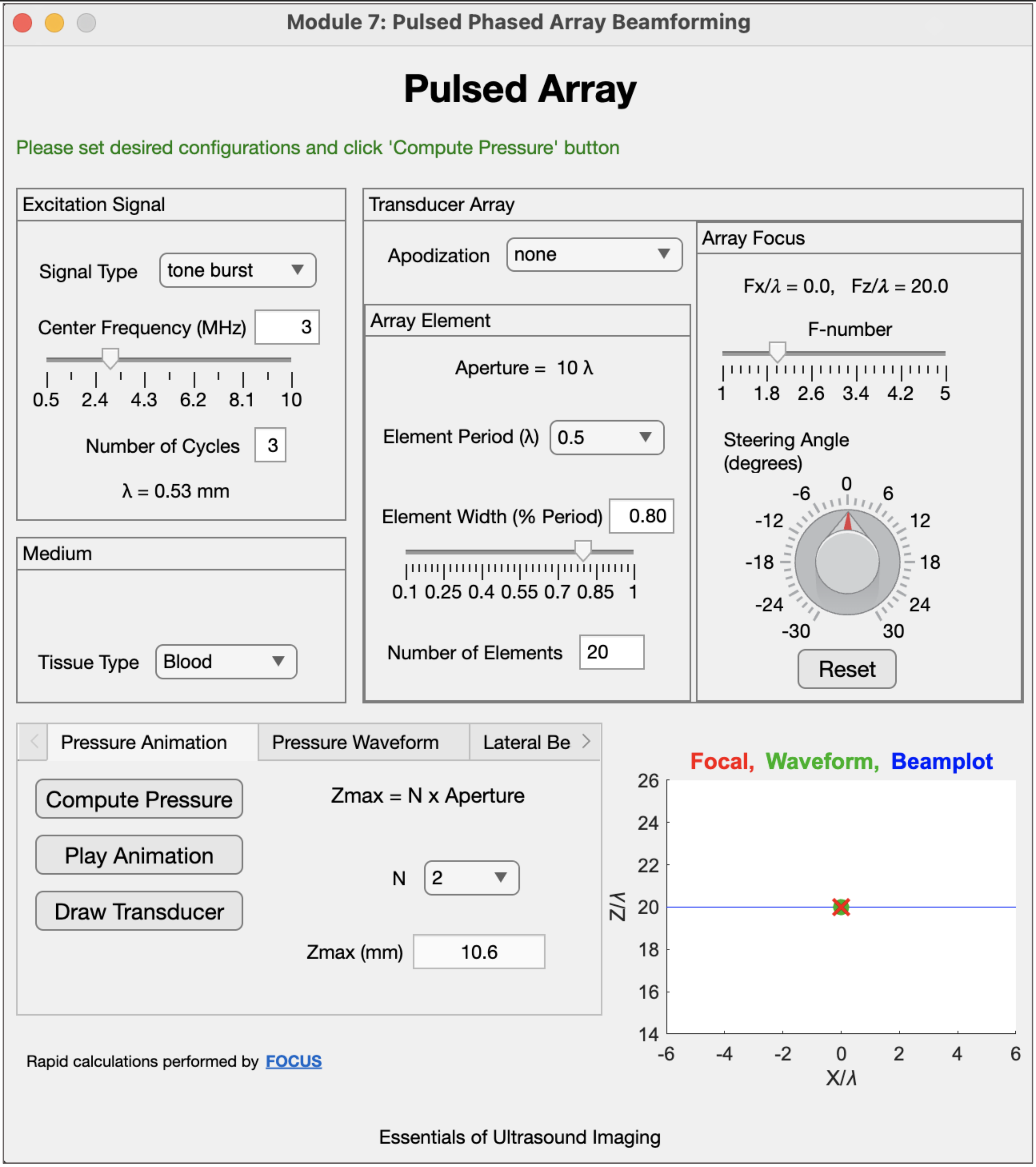

Figure 42: Pulsed Array Simulator GUI

The following walkthrough describes the extensive features of the Pulsed Array Simulator:

1. From the Signal Type dropdown menu in the Excitation Signal panel, select a signal type. The default signal type is set to a short tone burst. Note that this waveform represents the result of an electrical

excitation signal combined (convolved) with the one-way transducer electro-acoustic element impulse response. For more details, refer to Table 22.

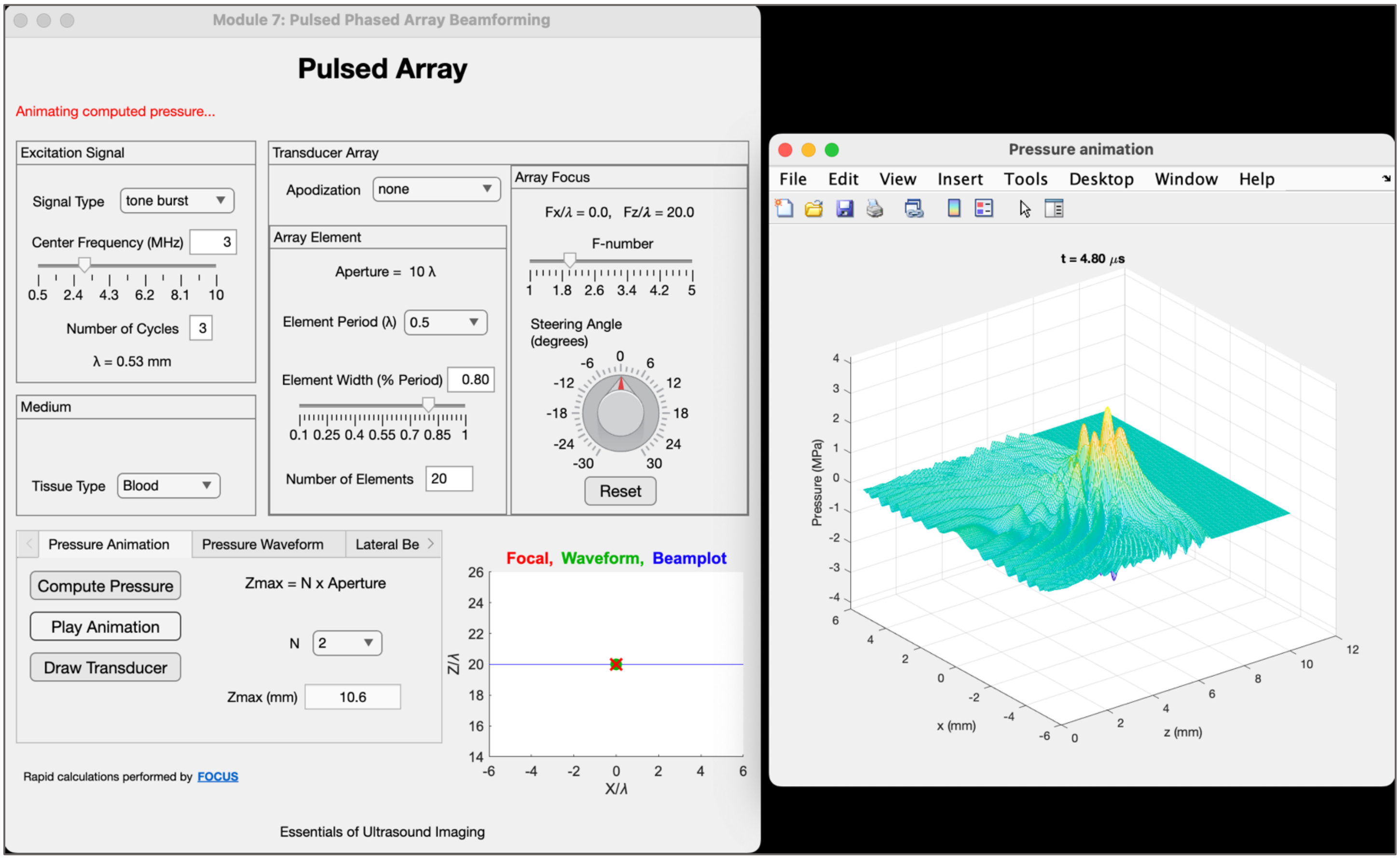

Figure 43: Pulsed Array Simulator GUI: Pressure Animation Example

2. From the Tissue Type dropdown menu in the Medium panel, select a tissue type. The default tissue type is set to blood. Waveforms and lateral beam plots are automatically generated for both lossless and selected medium cases. Once a medium is selected, the wavelength value is displayed in the Excitation Signal panel.
3. Note that the default parameter values in the Transducer Array panel are set for a relatively short array aperture default value of 10 λ and the default steering angle is set to zero degrees. During the initial walkthrough, use the default settings provided and observe the results.
4. To see the transducer layout, click the Draw Transducer button to display a plot of the array elements with apodization shading in a popup window (not shown here). For the default unapodized setting, there is no shading.
5. Once the array and medium input parameters are selected, click the Compute Pressure button to initiate the computation process. Once the computation is complete, a verification message (completed computation verification) appears in the top left of the GUI. Many options are available for viewing the acoustic field and its characteristics—these options can be selected using the tabs in the lower left panel.
6. Explore various output options available on the lower left of the GUI using the guidelines summarized below:
   - During the initial walkthrough of the program using default settings, select the **Pressure Animation** pane to display simulator calculations as a series of beamformed wavefront snapshots in an animation with an updated propagation delay time.

a. Specify the scaled maximum propagation distance Zmax by selecting an N value from the dropdown menu. (The Zmax value is calculated by multiplying the parameter N by the aperture length).
b. Click the Play Animation button to visualize an animation of the selected pressure wavefront. The delay time of the wavefront is shown above the plot during propagation. Refer to Figure 43.
c. To repeat the animations, click the Play Animation button again.

All subsequent tab calculations capture aspects of a specific selected wavefront frozen at a particular delay time or equivalently, a propagation distance, z, or in the case of a steered beam, the distance along the propagation axis of the beam.

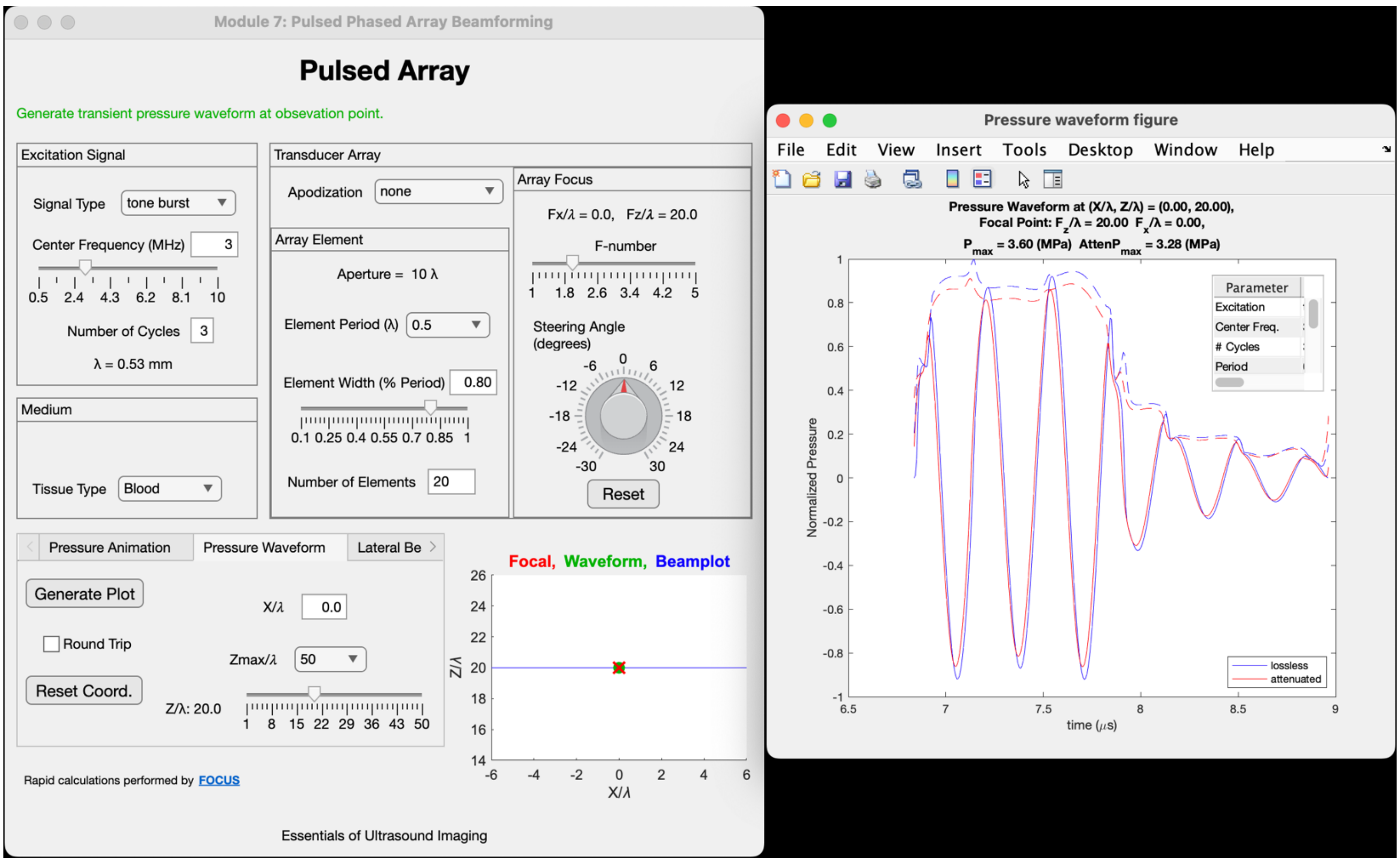

Figure 44: Pulsed Array Simulator GUI: Pressure Waveform Example

- Under the **Pressure Waveform** tab, the default location is on the propagation axis at the focal distance. In this case, the location is set for X/λ =0 and z=F, as indicated graphically in the plot at the lower right corner of the GUI. The Z/λ slider allows waveforms to be visualized at other distances; the green waveform dot in the plot tracks the selected Z/λ slider position. Similarly, off-axis positions are controlled by the X/λ edit window—it is recommended to choose small values close to the propagation axis, as the beam is narrow; the green dot tracks this position accordingly. Round-trip waveforms can be displayed by checking the round-trip box. To display a waveform for the default conditions of this walkthrough, click the Generate Plot button. Two waveforms are displayed in the popup window: one for a lossless medium and the other for a selected absorbing medium. In addition, the corresponding envelopes and settings for the plot are also shown in the title and scrollable plot inset. See Figure 44.

- The **Lateral Beamplot** tab has many of the same options as the Pressure Waveform tab: the Z/λ slider for the position of the beamplot, and a Round-Trip check box with the default position reverting to the selected Focal length as indicated by a blue line in the position plot to the right. By pressing the Generate Plot button, a popup window displays two beam plots: one plot for a lossless medium and the other plot for a selected absorbing medium. In addition, the settings for the plot are also shown in the title and scrollable plot inset. As before, obtain additional quantitative information for both beam plots and waveforms using the Data Tips tool. See Figure 45.
- The **Multiple Beamplots** tab offers the usual Transmit Field Plot Type options; however, there is an important difference—the beamformed wavefront at a selected distance (as determined by the Z/λ slider) can be visualized; the default wavefront is at the focal length distance. Options to enable absorption (by sliding the Absorption slider to the On position) and to select the maximum distance dropdown window of the display are available. Pressing the Generate Plot button creates a popup window with the wavefront display; here the default option is a surface plot, which depicts the extent of the frozen wavefront.
- The **Excitation Signal** tab provides a way of showing the excitation waveform through the Generate Plot button.

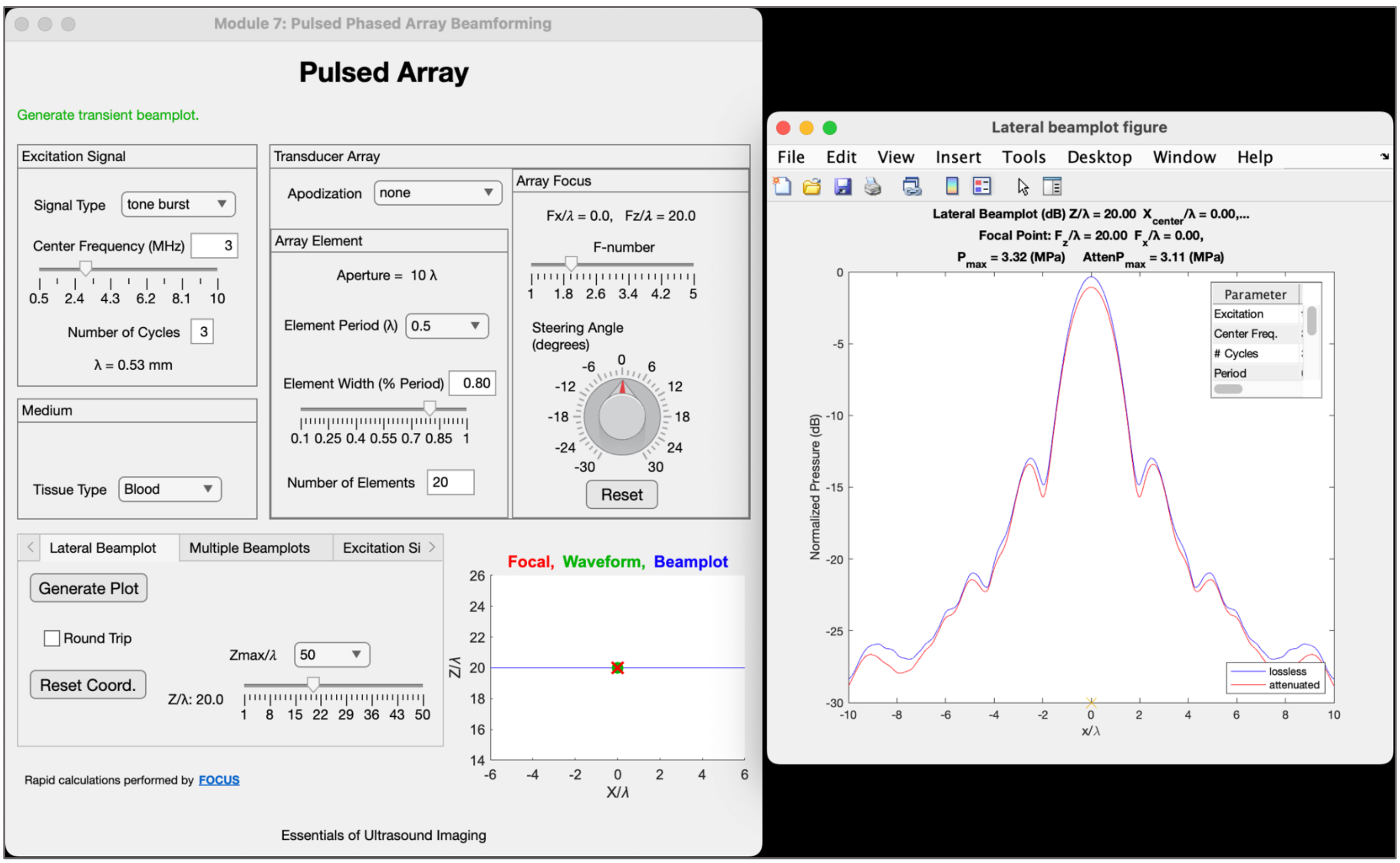

Figure 45: Pulsed Array Simulator GUI: Lateral Beamplot Example

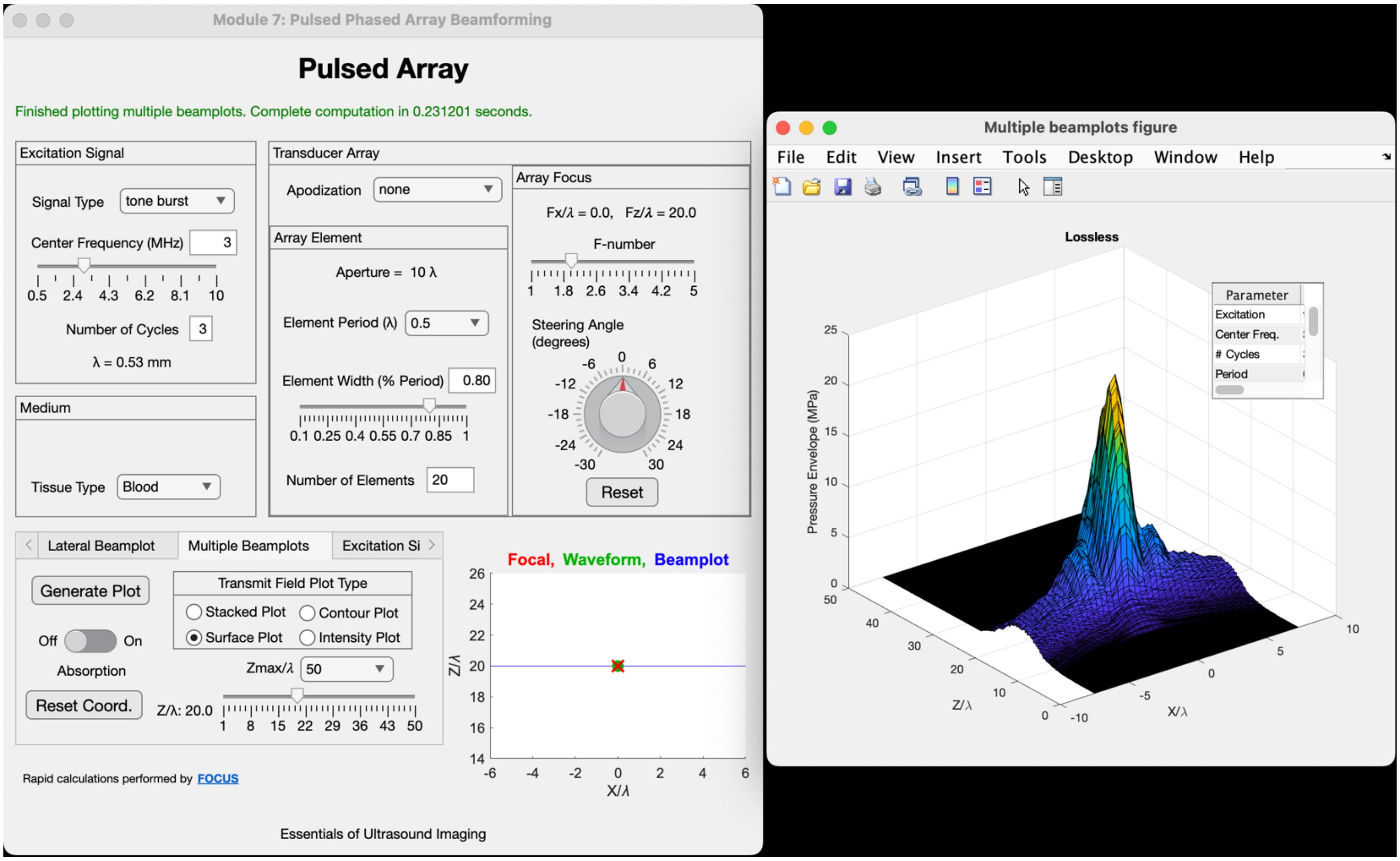

Figure 46: Pulsed Array Simulator GUI: Multiple Beamplots Example

Note that the displays of different field characteristics in the different output tabs may be performed in any order.

Table 22: Pulsed Array Simulator - UI Controls and Descriptions

UI Control		Description
Excitation Signal	Signal Type	Select the excitation signal type from the dropdown menu options—either Tone Burst, or Hanning Pulse.
	Center Frequency (MHz.)	Select the center frequency of the excitation signal.
	Number of Cycles	Enter the number of cycles of the excitation signal.
	The wavelength λ of the excitation signal is displayed based on the input parameter selection.	
Apodization		Apodization dropdown menu: none, Bartlett, Chebyshev, Hamming, Hann, and Triangle. Each of the apodization types applies different mathematical functions to the element amplitudes along the aperture.
Array Element	Element Period (λ)	Select the element period value expressed in wavelengths from the dropdown menu.

<table>
<tr><th colspan="2">UI Control</th><th>Description</th></tr>
<tr><td rowspan="3"></td><td>Element Width (normalized)</td><td>Adjust the element width to period ratio using the slider. This value is set to 0.8 usually but can be changed if desired.</td></tr>
<tr><td>Number of Elements</td><td>Enter the number of array elements.</td></tr>
<tr><td colspan="2">The Aperture value (the width of the entire array is the product of the period and the number of elements) is displayed.</td></tr>
<tr><td rowspan="3">Array Focus</td><td>F-number</td><td>Set the transmit focal length value of the array using the F-number slider. The array will focus on a shorter or longer distance depending on the F-number choice. The focal depth in wavelengths is displayed.</td></tr>
<tr><td>Steering Angle</td><td>Set the steering angle of the transducer array using the Steering Angle knob.</td></tr>
<tr><td>Reset</td><td>Click the Reset button to reset all the Array Focus parameters to their defaults.</td></tr>
<tr><td>Medium</td><td>Tissue Type</td><td><table><tr><th>Tissue Type</th><th>Attenuation α(dB MHz-y cm-1)</th><th>Exponent y (no units)</th></tr><tr><td>Blood</td><td>0.14</td><td>1.21</td></tr><tr><td>Bone</td><td>3.54</td><td>0.9</td></tr><tr><td>Brain</td><td>0.58</td><td>1.3</td></tr><tr><td>Breast</td><td>0.75</td><td>1.5</td></tr><tr><td>Kidney</td><td>0.24</td><td>1.02</td></tr><tr><td>Spleen</td><td>0.4</td><td>1.30</td></tr><tr><td>Water</td><td>2.17E-03</td><td>2.0</td></tr><tr><td>Phantom</td><td>0.43</td><td>1.83</td></tr></table></td></tr>
<tr><td rowspan="3">Pressure Animation</td><td>Compute Pressure</td><td>Click the Compute Pressure button to compute the acoustic pressure throughout the time chosen for the simulation, as defined through the choice of Max. F-number.
Note: Any time a parameter is changed in any input panel, the Compute Pressure button must be clicked again to update the simulation results.</td></tr>
<tr><td>Play Animation</td><td>Click the Play Animation button to view the pressure animation of the selected waveform.
In the animation, the wavefront propagates as a sequence of stop-action frames. The acoustic field is computed at discrete elapsed times in the region where the wave packet is located (and is zero everywhere else), each at a freeze-frame of the wave packet at the selected time. In that region, the propagated signal is computed over a fine time grid.</td></tr>
<tr><td>Draw Transducer</td><td>Select the Draw Transducer button to visualize the transducer array. The user can change the transducer parameters such as Apodization and study the effect on the corresponding transducer array plots.</td></tr>
</table>

UI Control		Description
	Max. F-number	Set the maximum computational grid distance using Max. F-number dropdown menu.
Pressure Waveform	X/λ	Using this slider, view the waveforms of the main beam axis. Note that the X/λ value chosen should lie within the extent of the values displayed on the scatter plot.
	Z/λ	Set the slider to a desired field probing distance at which waveforms are calculated. The default position of this slider is at the default focal distance in wavelengths such that the Focal length icon (red X) and Waveform icon (green circle) on the scatter plot (shown in the bottom right corner of the GUI) coincide.
	Reset Coord.	Click the Reset Coord. button to reset the settings (X/λ and Z/λ)back to their default values.
	Round Trip	Click the Round-Trip button to display a pulse-echo signal waveform plot upon selecting the Generate Plot button.
	Generate Plot	Click the Generate Plot button to generate the pressure waveform plot.
Lateral Beamplot	Reset Coord.	Click the Reset Coord. button to reset the setting (Z/λ) back to its default value.
	Z/λ	Set the slider to a desired field display distance at which a beam profile is plotted.
	Generate Plot	Click the Generate Plot button to view a line profile through the beam. The blue line indicated in the scatter plot represents the position of the line profile through the beam.
Multiple Beamplots	Plot Type	Linear Field: Creates a waterfall array (stacked beamplots) of lateral beam plots spaced at equal intervals along the z(propagating) axis with distances increasing in an upward direction. The aperture is diagrammed at the bottom. Linear Surface: Creates a surface plot of the field on a linear scale. The aperture is on the right side of the plot at Z/λ=0. Contour: Creates a contour plot with -6 dB, -10 dB, -20 dB contours. This plot provides a quantitative interpretation of the field structure. The aperture is at the top. Intensity: Select Intensity to get a map of the field in a continuous color representation. The aperture is at the top. This selection adds the Axial-Lateral Profile option.
	Absorption	Slide the radio button to the right to include the effects of absorption in the output calculation. Slide the radio button to the left to exclude absorption effects from the output calculation.
	Max. Z/λ	Adjust the slider to determine the maximum distance used for generating multiple beam plots. By adjusting the distance, the acoustic field in the output plot is computed when the pulse reaches

UI Control		Description
		near the selected position, similar to freezing a frame of wavefront at that specific distance for analysis and observation.
	Generate Plot	After selecting the plot type, Max. Z/λ, Absorption option, click the Generate Plot button to obtain a global spatial view for the selected transmit waveform.
Excitation Signal	Generate Plot	Click the Generate Plot button to visualize the excitation signal emitted by the array elements based on specified parameters in the Excitation signal panel. Note: In this computation, this signal is to be viewed as a combination of the excitation convolved with the one-way transducer response for computational simplification. Therefore, it can be viewed as the particle velocity waveform, with an amplitude of 1, at the surface of the transmitting array element. Similarly, the echo signal is a delayed and summed combination of the pulse-echo waveforms arriving at the elements from a flat mirror target at the observation point.

Module 8: Ultrasound Imaging Systems and Display

Scatter Image Simulator

The Scatter Image simulator shows how an arrangement of point scatterers in different media appear when imaged by a realistic ultrasound phased array. In this simulator, the user can define array parameters, explore the arrangement of scatterers in different selectable media, and adjust B-mode image controls.

For detailed information on this simulator module, refer to Section 8.4.2: Scatter Image Simulator in the course textbook, Essentials of Ultrasound Imaging.

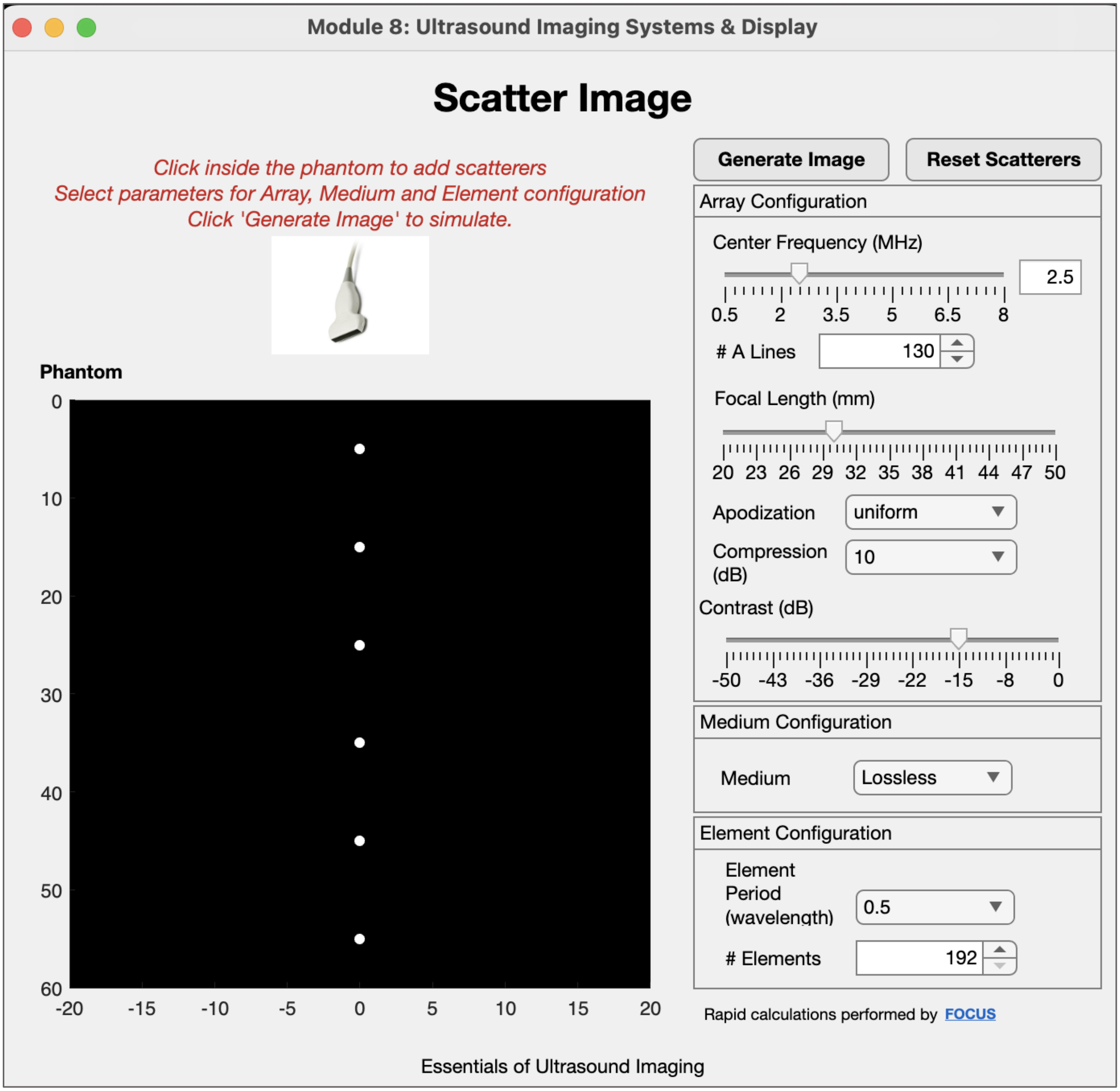

Figure 47: Scatter Image Simulator

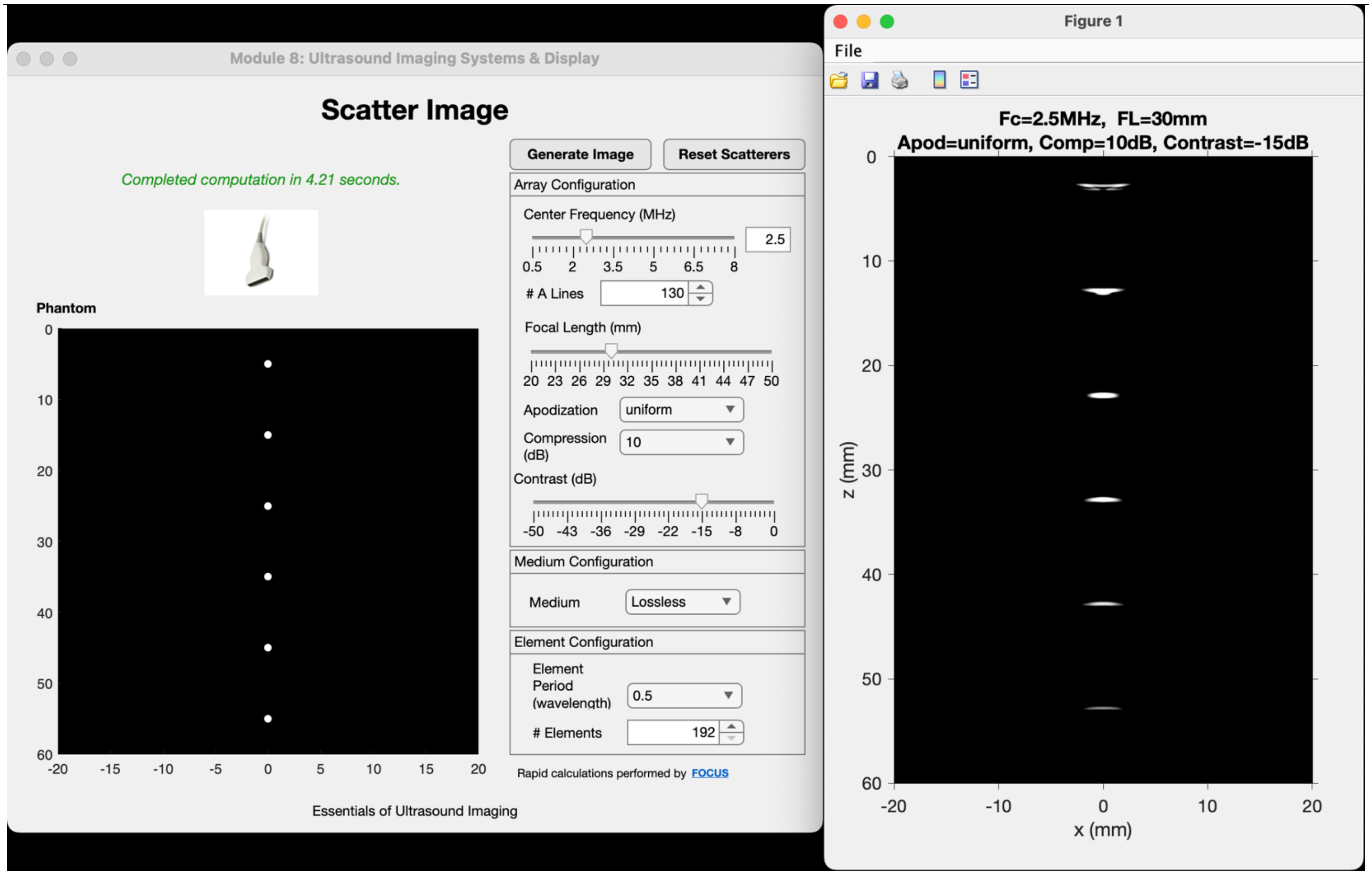

Figure 48: Scatter Image Simulator: B-mode Image of Scatterers

An introductory tour of the Scatter Imaging simulator employs default parameters. Users can familiarize themselves with the tool using this default arrangement.

A typical sequence of operations through this simulator is as follows –

1. Note that the simulator initially displays a map of a line of six-point ideal point scatterers spaced 1 cm apart.
   Add more scatterers if desired by clicking at the desired locations anywhere within the image window.
2. Define the transducer array parameters-
   - From the Array Configuration panel, define the center frequency, focal length, and apodization.
   - From the Element Configuration panel, define the element period in wavelengths and number of elements.
3. Select a medium from the Medium dropdown menu in the Medium Configuration panel.
4. Finally, select the image processing parameters—such as the number of A-lines in the final B-mode image, compression, and contrast controls—from the Array Configuration panel.
5. Click the Generate Image button to view the resulting B-mode image, which appears in a popup window. **Note**: The appearance of each scatterer depends on the point spread function at the location of that point.

Table 23: Scatter Image Simulator - UI Controls and Description

UI Control	Description
Center Frequency (MHz.)	Adjust the center frequency of the array using the slider. Note that increasing the frequency will decrease the width of the image because the

<table>
<tr><th colspan="2">UI Control</th><th>Description</th></tr>
<tr><td colspan="2"></td><td>array length is proportional to the wavelength; a linear array typically creates an image of the same width as the array. Some scatterers at the edge of the map may not be visible at higher frequencies.</td></tr>
<tr><td colspan="2">A-Lines</td><td>Define the number of A-lines in the ultrasound image of the phantom.
A-lines are focused beamformed vertical lines from which the overall B-mode image is formed. The greater the number of A-lines, the more time it takes to compute. Note the maximum number of image lines possible is the number of elements. The overall width of the image is approximately Nlines * element period.</td></tr>
<tr><td colspan="2">Focal Length</td><td>Define the focal length of the transducer array.</td></tr>
<tr><td colspan="2">Apodization</td><td>Apodization dropdown menu: Uniform, Bartlett, Chebyshev, Hamming, Hann, and Triangle. Each of the apodization types applies different mathematical functions to the element amplitudes along the aperture.</td></tr>
<tr><td colspan="2">Compression</td><td rowspan="2">Adjust the compression slider and the contrast slider simultaneously to optimize the image quality.</td></tr>
<tr><td colspan="2">Contrast (in dB)</td></tr>
<tr><td colspan="2">Medium</td><td>Select a medium from the dropdown menu. Note that each of the media in the menu has distinct sound speed and attenuation values.
<table>
<tr><th>Tissue Type</th><th>Attenuation α(dB MHz-y cm-1)</th><th>Exponent y (no units)</th></tr>
<tr><td>Blood</td><td>0.14</td><td>1.21</td></tr>
<tr><td>Bone</td><td>3.54</td><td>0.9</td></tr>
<tr><td>Brain</td><td>0.58</td><td>1.3</td></tr>
<tr><td>Breast</td><td>0.75</td><td>1.5</td></tr>
<tr><td>Kidney</td><td>0.24</td><td>1.02</td></tr>
<tr><td>Spleen</td><td>0.4</td><td>1.30</td></tr>
<tr><td>Water</td><td>2.17E-03</td><td>2.0</td></tr>
<tr><td>Phantom</td><td>0.43</td><td>1.83</td></tr>
</table></td></tr>
<tr><td rowspan="2">Array Element</td><td>Element Period (λ)</td><td>Select the element period value from the dropdown menu. Element period is the spacing between the array elements.</td></tr>
<tr><td>Number of Elements</td><td>Enter the number of array elements, choosing a value between 192 and 300.</td></tr>
<tr><td colspan="2">Generate Image</td><td>Click the Generate Image button to view the B-mode intensity plot.</td></tr>
<tr><td colspan="2">Reset Scatters</td><td>Click the Reset Scatters button to reset the scatters to the initial setup. By default, the scatterers are spaced inline at 1 cm. intervals in depth.</td></tr>
</table>

Multifocus Simulator

The Multifocus simulator allows users to compare a B-mode intensity image obtained from the multi-focus approach to that of a single-focus approach. In the Multifocus approach, the image is split into horizontal zones, each with a specific transmit focal point. These individual highest-resolution images for each zone are combined to cover the entire field of view. This simulator offers many customizable input options such as image parameters, array parameters, and the speed of sound in the beamformer.

For detailed information on this simulator module, refer to Section 8.4.3: Multifocus Simulator in the course textbook, Essentials of Ultrasound Imaging.

An introductory tour of the capabilities of the Scatter Imaging simulator employs default parameters. Note that upon startup, this simulator computes the images using these default settings. Users can familiarize themselves with the tool using this default arrangement.

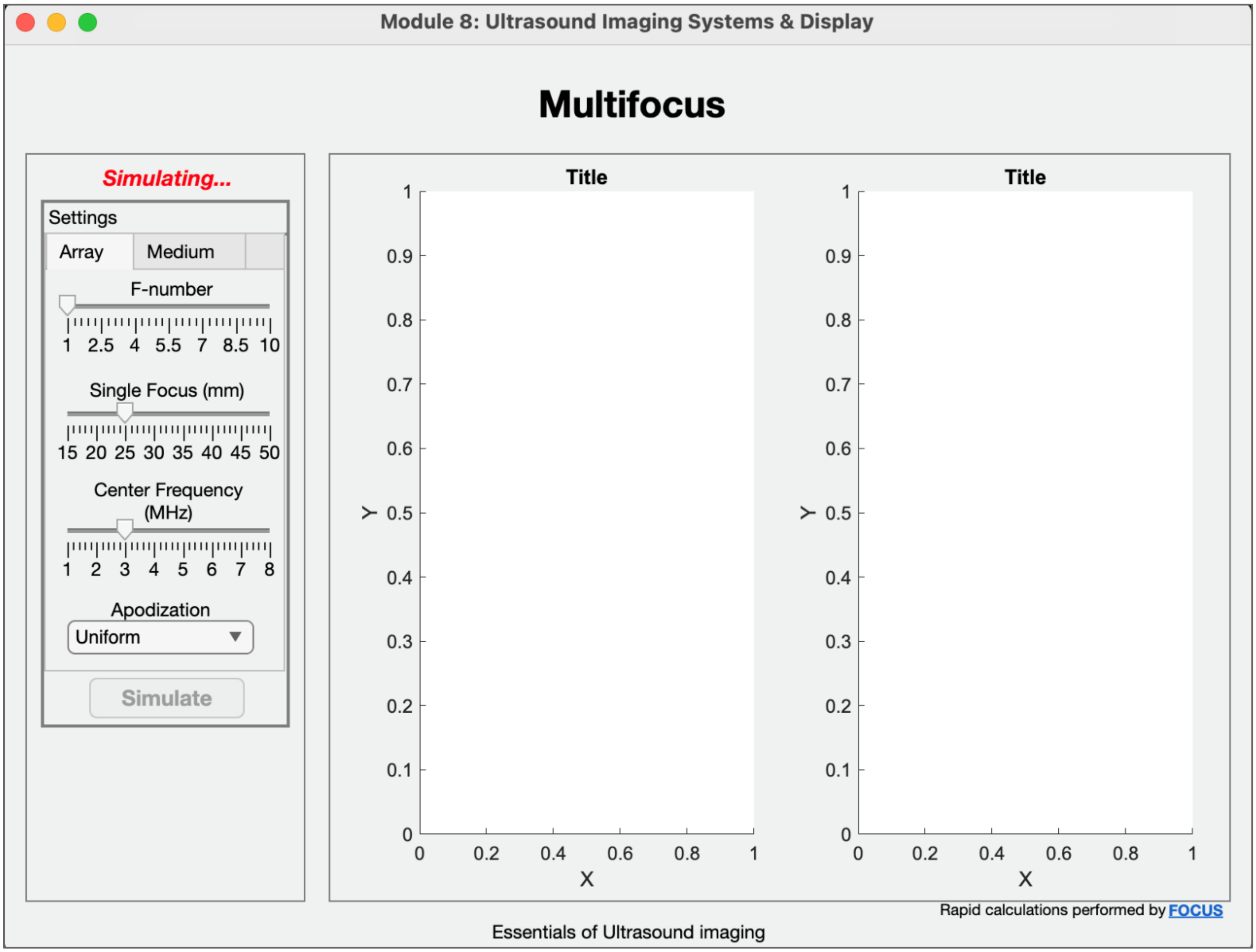

Figure 49: Multifocus Simulator: Default Settings

Use the following workflow to change the default settings and explore the simulator options:

1. Define the pulsed array input parameters (F-number, single focus depth, center frequency, and apodization) from the Array tab in the Settings panel. Bear in mind that the point targets to be imaged are located at 1 cm intervals at depths from 1 to 5 cm.

2. Select the medium, contrast, and compression from the Medium tab in the Settings panel. Note the sound speed on the slider is set automatically by the choice of selected input medium but it can be overridden by moving the slider to adjust array focusing delays for exploration of sound speed mismatch artifacts. Display controls (contrast and compression) adjust the appearance of the image.
3. Once satisfied with the input parameter values, click the Simulate button to visualize single-focus and multi-focus B-mode intensity images.

Note: If the user changes any of the input parameters, the Simulate button must be clicked again once all desired changes are made to update the images; this is also true when adjusting Contrast and Compression.

Single Focus plot:

displays on the left an image of the point scatterers based on the single focus location and other input parameter settings. Note identical array focusing is assumed on transmit and receive.

Multiple Focal Position plot:

displays on the right an image of the point scatterers based on multiple foci, each of which is positioned on the target locations on both transmit and receive.

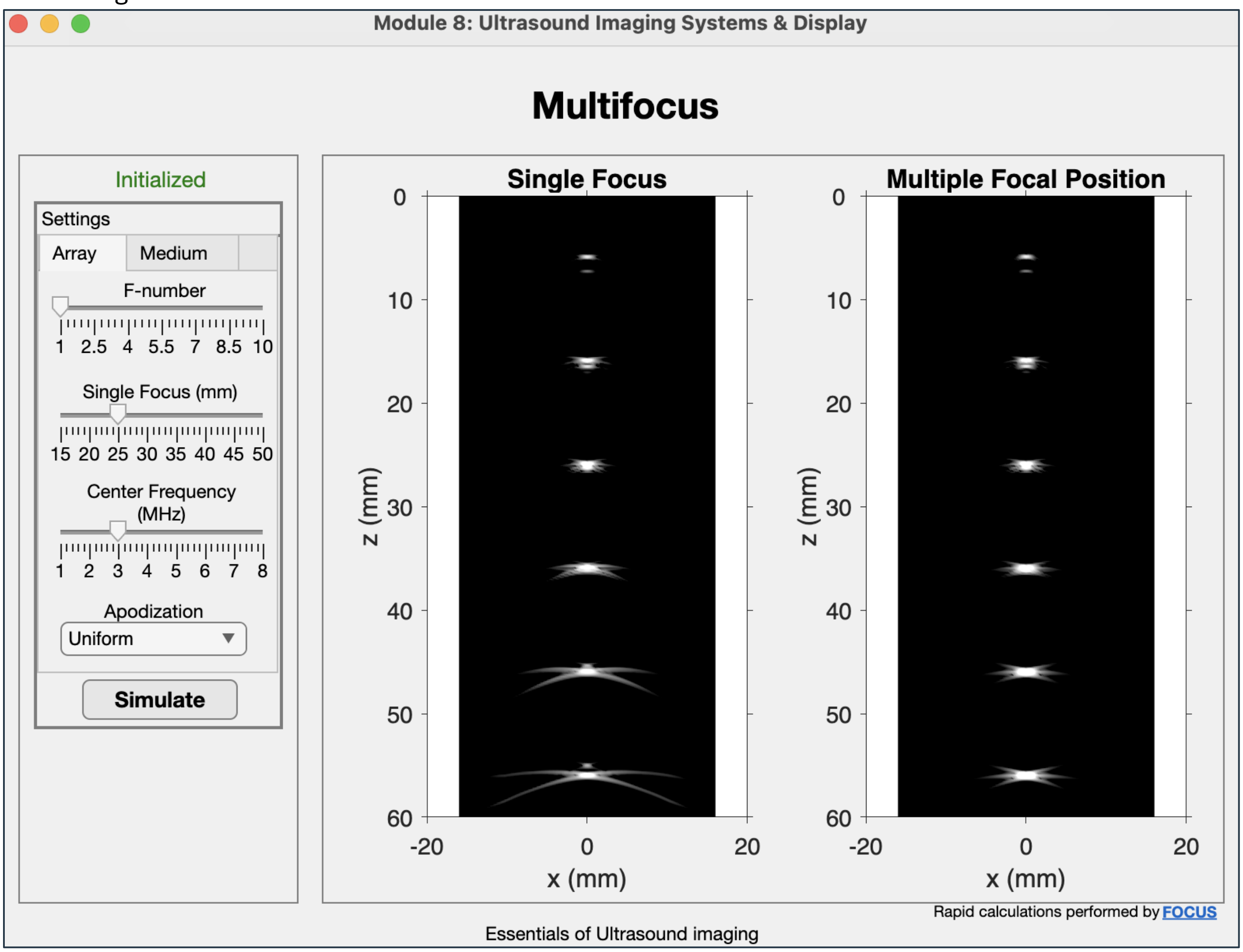

Figure 50: Multifocus Simulator: Array Tab Settings

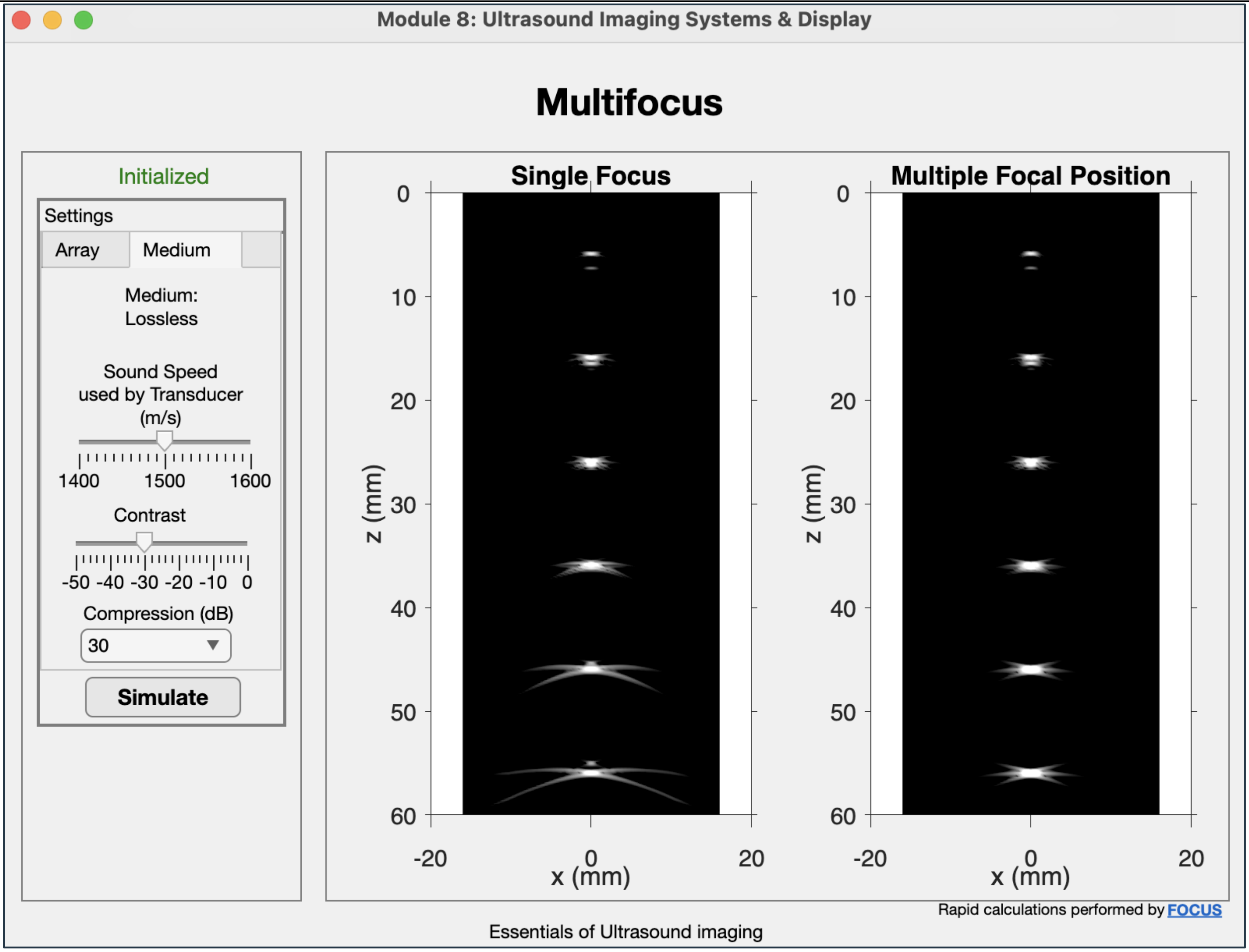

Figure 51: Multifocus Simulator - Medium Tab Settings

Table 24 describes the GUI controls in the Multifocus simulator.

Table 24: Multifocus Simulator GUI

UI Control	Description
F-number	Adjust the F-number of the array using the slider.
Single Focus	Using the Single Focus position slider, adjust the focal depth of the transducer array.
Center Frequency (MHz.)	Define the center frequency of the transducer array using the slider. Note that increasing the frequency will decrease the width of the image because the array length is specified as a fixed number of wavelengths, and a linear array typically creates an image of the same width as the physical length of the array.
Apodization	Select an Apodization type from the dropdown menu. Each of the apodization types applies different mathematical functions to the element amplitudes along the aperture.
Medium	The default option for the medium is a lossless medium.

UI Control	Description
Sound Speed used by the Transducer (m/s)	Define the sound speed used in image reconstruction (receive beamforming) using the slider. The Sound Speed slider position defaults to the sound speed of the selected medium. However, the user has the option to change the sound speed used in reconstruction to see the effect on focusing—when the sound speed used in reconstruction matches the default sound speed value of the selected medium, the focus is optimal.
Contrast	Adjust the compression dropdown menu and the contrast slider simultaneously to optimize the image quality.
Compression	
Simulate	Click the Simulate button to visualize single-focus and Multifocus B-mode intensity images.

TGC Simulator

The TGC simulator demonstrates how the Time Gain Compensation (TGC) controls compensate for increasing absorption with depth. The simulator offers six independent TGC slider controls that increase signal gain in a horizontal strip centered at a designated depth. Additional image adjustments (contrast and compression) are also available. *For detailed information on this simulator module, refer to Section 8.5.3: Time Gain Compensation Simulator in the course textbook, Essentials of Ultrasound Imaging.*

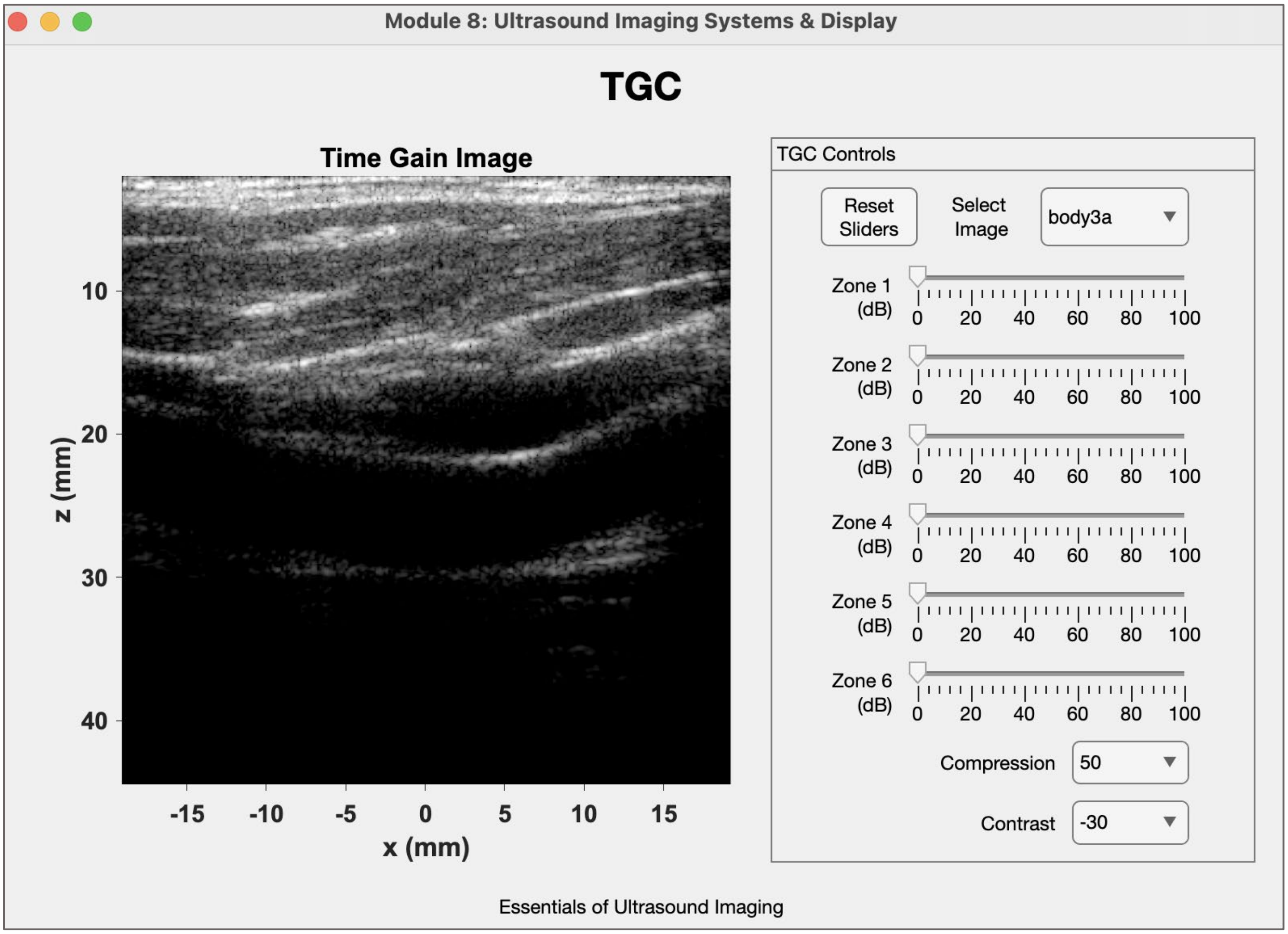

Figure 52: TGC Simulator GUI

Users can familiarize themselves with the tool using the default image.

Use the following workflow to change the default settings and explore the simulator options:

1. Select an image from the Select Image dropdown menu.
2. Equalize the image by adjusting each of the zone sliders to obtain a nearly continuous background brightness level across different depths.
3. Adjust the image controls to change compression and contrast values, if needed. Typically, most of the desired changes are obtained using the TGC controls without resorting to the image controls.

Table 25: TGC Simulator - UI Controls and Description

UI Control	Description
Select Image	From the Select Image dropdown menu, choose an image.
Zone 1 (dB)	Adjust the TGC setting of Zone 1 using the slider.
Zone 2 (dB)	Adjust the TGC setting of Zone 2 using the slider.
Zone 3 (dB)	Adjust the TGC setting of Zone 3 using the slider.

UI Control	Description
Zone 4 (dB)	Adjust the TGC setting of Zone 4 using the slider.
Zone 5 (dB)	Adjust the TGC setting of Zone 5 using the slider.
Zone 6 (dB)	Adjust the TGC setting of Zone 6 using the slider.
Compression	Change the overall depth-independent Compression value using the dropdown menu. Units (dB).
Contrast	Change the overall depth-independent Contrast value using the dropdown menu. Units (dB).

Speckle Simulator

The Speckle simulator provides B-mode images of the same phantom targets with a speckled background taken at four different frequencies. Users can generate a line profile within the image to study pixel intensity variation along the line profile and infer image properties such as contrast and resolution at different frequencies.

For detailed information on a similar simulator module, refer to Section 8.6.3: Speckle Simulator in the course textbook, Essentials of Ultrasound Imaging.

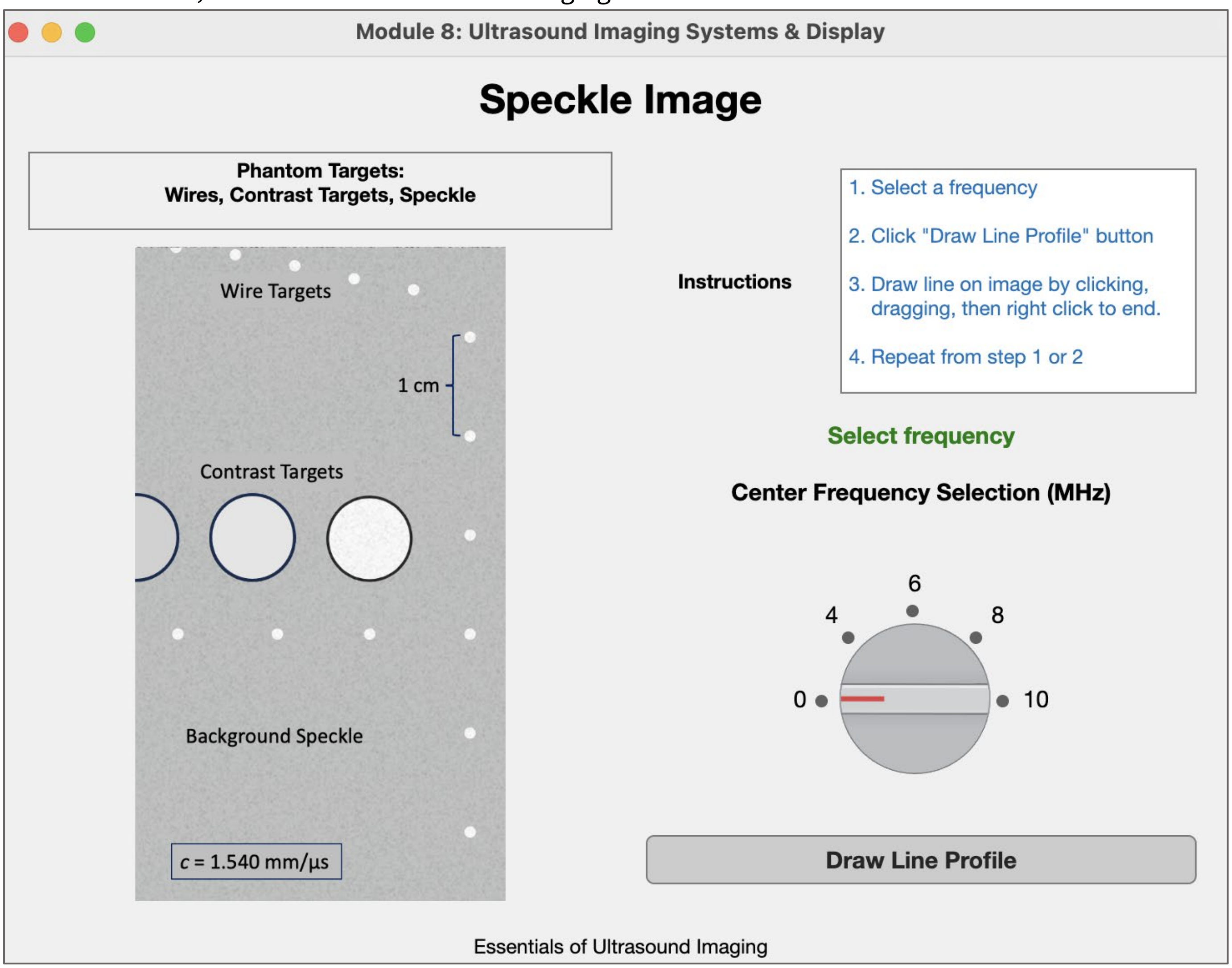

Figure 53: Speckle Simulator GUI

Use the following workflow to explore the capabilities of this simulator:

1. Rotate the Center Frequency Selection knob from the 0 setting to the desired frequency. Upon selecting a frequency, a pop-up window displays the image of the phantom at the selected frequency. To begin, set the frequency at 6 MHz
2. Compare the image with the schematic drawing of the phantom targets within the GUI. Three types of backscattering targets are identifiable: wires (point targets), cylinders (circular regions) of varying densities of scatterers demonstrating different contrasts with respect to the background, and a background of fine-grained speckle.
3. To obtain more detailed data from the image-
    a. Click the Draw Line Profile button. A pop-up window with the B-mode image of the phantom map appears along with a cursor.
    b. Place the cursor at a desired location in the image and click once to establish the starting point.
    c. Move the cursor to a desired endpoint and right-click to draw the line (a thin-dashed line will appear to assist in alignment before the endpoint is chosen).
    d. Upon drawing a profile line, a two-dimensional plot depicting the variation in pixel intensity along the line appears. The x-axis indicates the linear coordinates along the line and the y-axis indicates the pixel intensity. This line through the image reveals quantitative information about the image and provides the maximum, minimum, and mean pixel intensity values along the line. By experimenting with the length and placement of such profiles, measurements of resolution, contrast, and scattering properties and levels can be obtained.
    Note: MATLAB Data Tips cursor can be used to find values of individual points along the line.
4. By rotating the frequency knob to another frequency setting, another popup image at another frequency appears, and new profiles can be obtained.
5. Compare the images of the phantom at different frequencies.

Video Simulator

The Video simulator simulates ultrasound videos of moving point targets viewed at different selectable frame rates. *For detailed information on this simulator module, refer to Section 8.8.3: Ultrasound Video Simulator in the course textbook, Essentials of Ultrasound Imaging.*

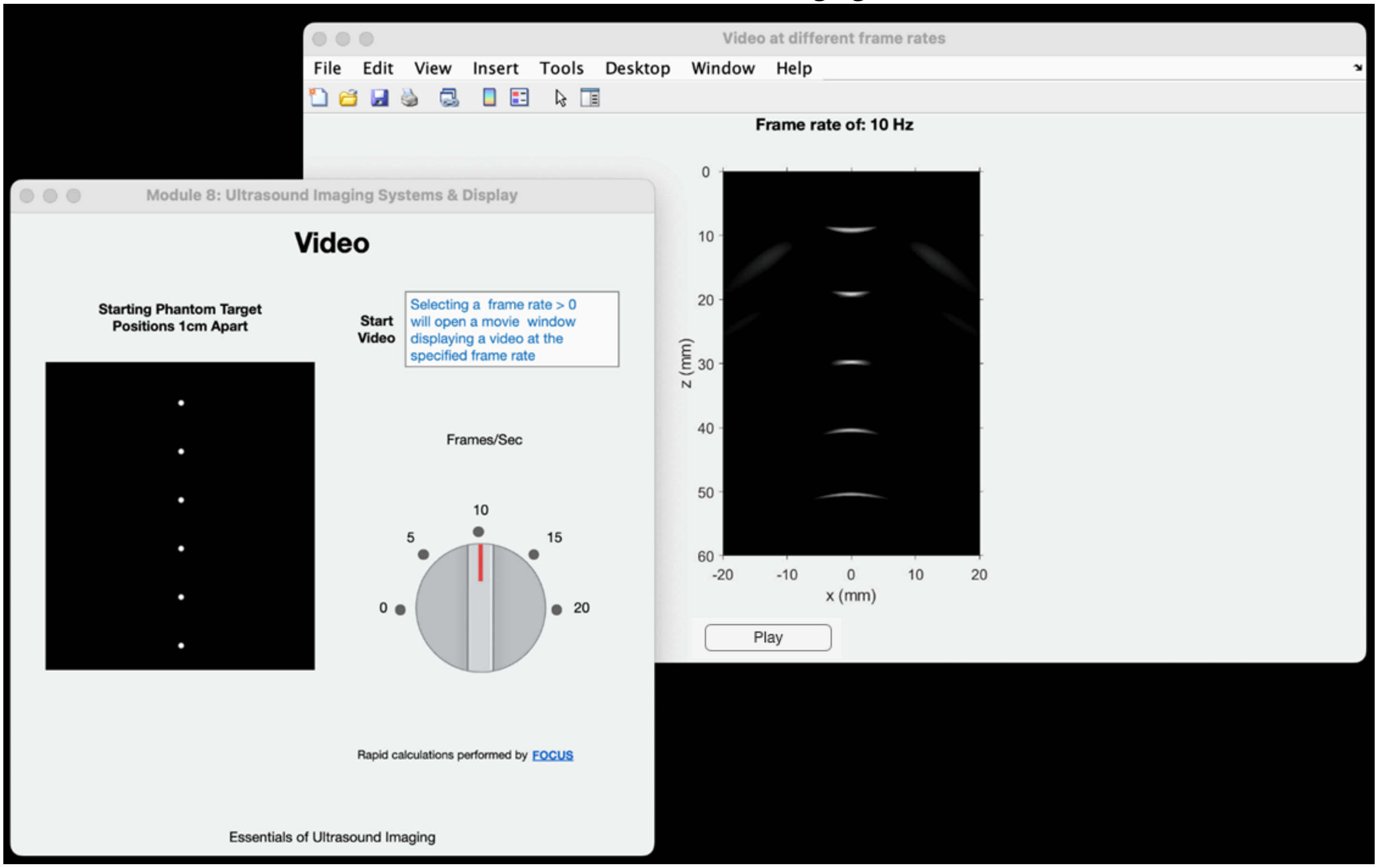

Figure 54: Video Simulator GUI

To generate an ultrasound video:

1. Observe the initial positions of the ideal point targets to be imaged in the GUI window. The default frame rate is zero (no video).
2. Select a frame rate (greater than 1) using the Frame Rate/Sec knob.
3. Observe that a movie window pops up, displaying a video at the specified frame rate. Click the play button to start the video.

Module 9: Doppler Imaging

Doppler Simulator

The Doppler simulator replicates the real-time imaging of flow using specific sets of parameters, presenting a cine loop of Doppler acquisition. The goal is to present the appearance of Color Doppler flow as acquisition parameters are varied for various flow geometries and velocities.

For detailed information on this simulator module, refer to Section 9.9.3: The Color Flow Doppler Simulator in the course textbook, Essentials of Ultrasound Imaging.

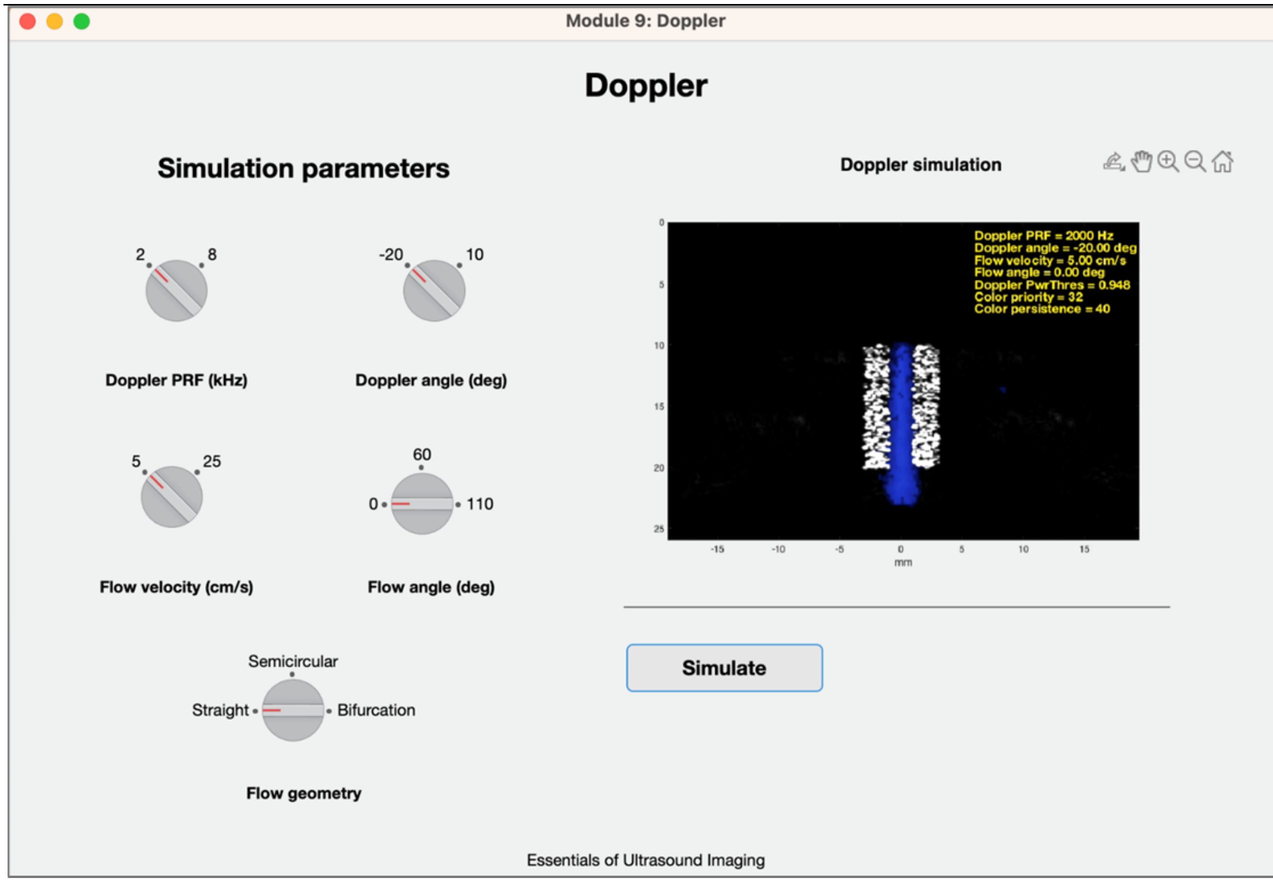

Figure 55: Doppler Simulator GUI

The Simulator parameter controls on the left side of the GUI allow users to select specific values for the Doppler acquisition, flow, and flow geometry. The Doppler simulation is displayed on the right side of the GUI, and the image region includes annotations for all of the parameters used in the chosen simulation. In the displayed flow, the blue color corresponds to the upward flow and the red color corresponds to the downward flow.

The simulation is for constant flow with a parabolic flow velocity profile across the diameter of the lumen inside a vessel made of "tissue walls" (grayscale speckle). Without flow, the lumen appears dark (black) because of the lack of strong scatterers. The Doppler flow estimates are computed throughout the region, and occasionally appear outside the confines of the model lumen and wall scatterer field; this artifact should be ignored for this simulator. Once the input parameters have been selected, click the Simulate button to simulate the actual imaging of the flow through the selected flow geometry model.

Table 26: Doppler Simulator - UI Controls and Description

UI Control		Description
Doppler PRF (kHz.)		Define the Doppler PRF value by adjusting the knob—this parameter controls the acquisition.
Doppler Angle (deg.)		Define the Doppler angle value by adjusting the knob—this parameter controls the acquisition.
Flow Velocity (cm/s)		Define the flow velocity by adjusting the knob—this parameter controls the flow.
Flow Angle (deg.)		Define the flow angle by adjusting the knob—this parameter changes the orientation of the flow geometry model; thereby, controlling the flow.
Flow Geometry	Straight	By selecting the Straight geometry, create a straight flow model.
	Semicircular	By selecting the Semicircular geometry, create a semicircular flow model.

UI Control		Description
	Bifurcation	By selecting a Bifurcation geometry, create a flow model that demonstrates flow through a bifurcation—it is a crude approximation of how the flow changes angles.
Simulate		Click the Simulate button to simulate the actual imaging of the flow through the select flow geometry model. Note that the loop cannot be interrupted or paused; replaying it requires pressing the Simulate button again, after the loop has stopped.

Acknowledgments

These simulators were conceived by Thomas L. Szabo and put in graphical user interface form using MATLAB App Designer by his team of graduate students at Boston University sponsored by a grant from Verasonics. The simulators were further refined with the help of Peter Kaczkowski during the writing of the companion book. Finally, the simulators were put in final form and further improved by a team of software experts at Verasonics.

Key parts of some of the simulators rely on the fast FOCUS beamforming software created by Professor Robert McGough and his team at Michigan State University (https://www.egr.msu.edu/~fultras-web/).

Limitations of the Simulator Software

The simulator software may not run optimally on systems based on Apple silicon (M-series processors) architecture. If unexpected behavior occurs while running the simulator GUI on these systems, the user should close the simulator window and reopen it. While this is not a guaranteed fix, it may temporarily resolve the issue. Currently, there are no guidelines offered for troubleshooting problems specific to the systems based on Apple silicon (M-series processors) architecture. However, these concerns are being addressed and will be resolved in an upcoming software update.