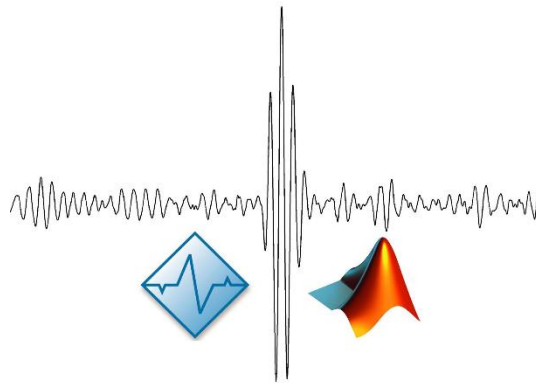


# TELEMED RF data tools for the research in the MATLAB environment



## User Manual



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## Introduction

Majority of the commercial ultrasound machines are closed for the researchers and do not provide access to raw RF signals. These signals carry valuable information about acoustic wave and tissue interaction and it could be employed for the developments of new diagnostic methods. The user manual describes the research package implemented in the MATLAB® (MathWorks, Inc., Natick, Massachusetts) environment which allows to off-line analyze the raw radiofrequency (RF) data acquired by new generation TELEMED ultrasound scanner **ArtUs**.

The research package contains few graphical user interfaces which allow to import and review annotated RF data and collection of scripts illustrating conventional RF signal processing steps such as filtering or logarithmic compression, which are typically used in the B mode image formation engine.

Please note that in this manual presented software screenshots may look slightly different than actual software user interface, because user interface can be customized and depends on the chosen options.

# 1. ArtUs RF Data Control

The native C++ SDK sample **ArtUs RF Data Control** should be used for the beamformed RF data capture, and recording into the data files. The sample allows to control few parameters of ultrasound scanner **ArtUs** and to define dimensions of RF data stream. For the explicit description of the sample we refer to [1]. The front panel of the demo sample is presented in the Fig. below. The RF window (11) defines the amount of RF data to be transferred and the relative position of the RF output window in the image frame (10). For the convenience in the user manual RF window data and the main acquisition parameters sometimes will be called sub-frame. The sample allows to record RF window data to the file (6). The front panel and main controls of ArtUs RF Data Control sample are presented below:

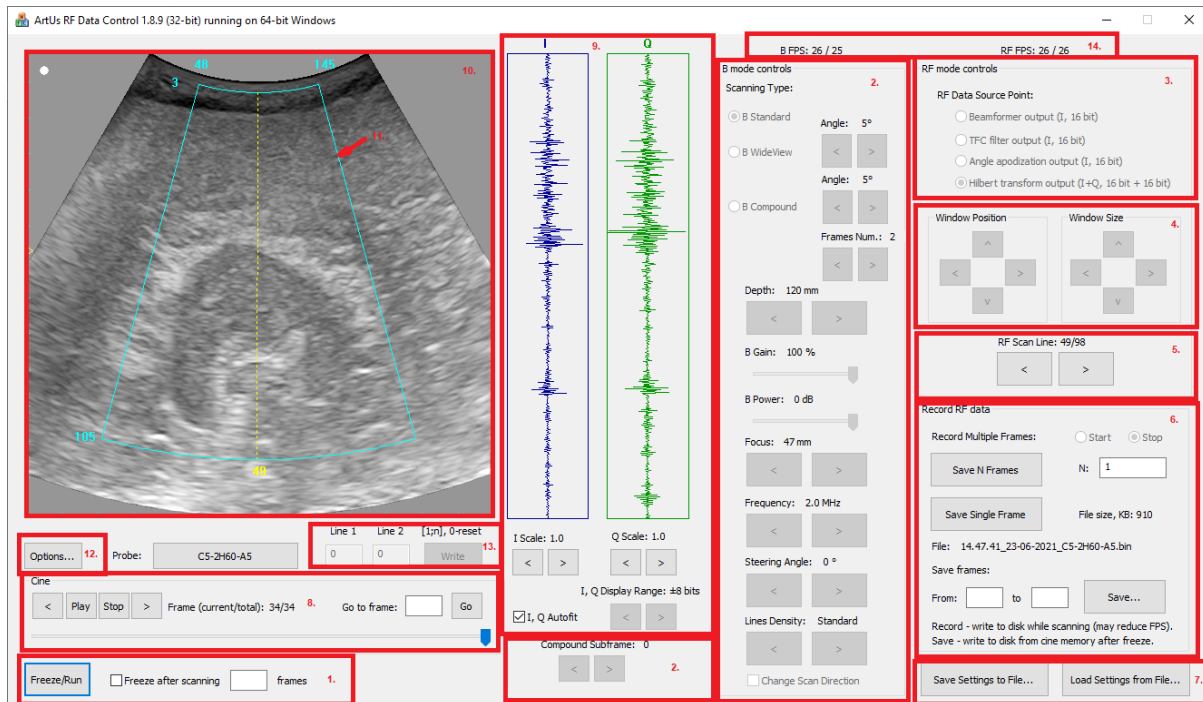


Fig. Front panel of ArtUs RF Data Control demo

Num	Component	Description
1	Main scanning controls	Controls starts ( <b>Run</b> ) and stops ( <b>Freeze</b> ) ultrasound scanning.
2	B mode controls	Allows to select scanning type ( <b>B Standard</b> , <b>B WideView</b> ), to adjust scanning depth ( <b>Depth</b> , mm), digital amplification of the image data ( <b>B Gain</b> , %), power of transmitted ultrasound signal ( <b>B Power</b> , dB), focal depth ( <b>Focus</b> ), scanning frequency ( <b>Frequency</b> ), steering angle ( <b>Steering Angle</b> ) and lines density ( <b>Lines Density</b> ).
3	RF Data Source Point	RF data is received as an array of 16-bit integers. This option allows to select the point of the beamformer from which RF data will be received. For ArtUs ultrasound scanner the following RF data types are available: <ul style="list-style-type: none"> <li>• Beamformer output (<i>I</i>, 16 bit),</li> <li>• TFC (time-frequency control) filter output (<i>I</i>, 16 bit),</li> <li>• Angle apodization output (<i>I</i>, 16 bit),</li> <li>• Hilbert transform output (<i>I+Q</i>, 16 bit + 16 bit).</li> </ul> For the further details related to these data types we refer to [1].
4	RF window Position and Size	The position and size of RF window could be adjusted by the controls. There is a trade-off between RF window size and scanning speed (fps).

5	<b>RF Scan Line</b>	These controls allow to select RF scanning line which will be displayed on screen.
6	<b>Record RF data</b>	RF data recording into (*.bin) file from the selected data source point and RF window (11). Preselected number of frames (N) is recorded into the file (default value – 100). The position and size of RF window can be adjusted by the controls. The file size could be controlled by observing indications of the counter (size in MB). There is an option to record single RF frame (button <b>Record Single Frame</b> ) which could be selected from cine loop. The RF frames could be recorded by pressing Start/Stop radio buttons as well. Recording of RF data while scanning may result into reduced FPS (depends on the disk). There is an option to save RF data from Cine buffer after scanning when freeze button is pressed. Such writing ensures that all collected RF data will be recorded without missing frames and reduction of FPS.
7	<b>Save/Load settings</b>	Allows to save current scanning and RF window settings to file, which could be loaded and settings reset.
8	<b>Cine</b>	Cine loop options. Allows to play recorded sequence and to watch it frame by frame.
9	<b>RF data plot</b>	Displays the RF data of the single selected line (dashed yellow line superimposed on the B mode image marks the scanline position). Controls (I Scale, Q Scale) allows to adjust the scale of shown RF signal. The displayed RF signals are scaled by both axes in order to obtain well visible waveforms.
10	<b>Main B mode imaging window</b>	Displays full grayscale B mode images and the superimposed boundary lines of adjustable RF window.
11	<b>RF window</b>	The contour (solid light blue lines) outlines the external boundaries of the RF window. The scanning line numbers and imaging depth are displayed close to the border.
12	<b>Options</b>	Options allows to adjust size of acquired Cine in MB. Maximum allowed size 1200 MB. Takes effect after software restart.
13	<b>Two scanning lines mode</b>	This mode scans only two selected (Line1, Line2) scanning lines and allows to achieve much higher FPS.
14	<b>FPS indicators</b>	There are FPS indicators B FPS: X / Y and RF FPS: X / Y where: X – screen rendering speed, depends on PC performance Y – true scanning speed.

### Structure of the RF data file

The collected RF data and the main acquisition parameters needed for off-line analysis and imaging could be recorded into binary files (\*.bin). The filename contains acquisition time and date information, and the probe type code (**HH.MM.SS\_DD-MM-YYYY\_probe\_code.bin**, i.e. “16.34.00\_27-10-2017\_L18-10H30-A4.bin”). The **ArtUs** RF Data Control SDK allows to record the RF data files of unlimited size (limited only by the capacity of the HDD).

Each recorded RF data sub-frame contains header information and beamformed RF data from the corresponding RF window. The position and size of the window could be adjusted during scanning, and therefore the header of acquisition information is written to file for each sub-frame in a recorded sequence. Please note that smaller window size allows to achieve higher frame rates. The file structure for single sub-frame is defined as follows:

Contents of the file	Data type	Number of elements (bytes)	Description
<i>RF file type</i>	char	1 (6 bytes)	RF file version is written only in the beginning of the file not before each frame (currently <b>RF0003</b> ).
<i>number_of_frames</i>	int32	1 (4 bytes)	Number of RF frames recorded into file
<i>header_size</i>	int32	1 (4 bytes)	Size of header in bytes
<i>frame_size</i>	int32	1 (4 bytes)	Size of RF frame in bytes
<i>source_ID</i>	int32	1 (4 bytes)	RF data source ID: 1 – Beamformer output, 2 – TFC filter output, 3 – Angle apodization output, 4 – Hilbert transform output
<i>tx_frequency</i>	int32	1 (4 bytes)	US wave transmission frequency, in Hz.
<i>frame_rate</i>	int32	1 (4 bytes)	The actual number of frames per second, since streaming started, depends on the used scanning probe and size of RF window. Frame rate is multiplied by 100.
<i>Length_of_RF_row</i>	int32	1 (4 bytes)	Number of RF signal samples in a single scanning row.
<i>Number_of_RF_rows</i>	int32	1 (4 bytes)	Number of RF scanning lines in a predefined RF window.
<i>Sampling_period_ns</i>	int32	1 (4 bytes)	Sampling period – defines the digitization resolution, in nanoseconds (ns). For the ArtUs system - 25 ns ~ 40 MHz sampling for depths up to 8192 samples, and 50 ns (20 MHz) for greater depths.
<i>Sample size</i>	int32	1 (4 bytes)	Number of BIT's, at present 16/32 BIT for the RF data
<i>start_depth</i>	int32	1 (4 bytes)	Scanning start depth in mm (offset for each beam) used for imaging of the scanning window in absolute coordinate system
<i>Start_point_position_and_orientation</i>	int32	3 × Number_of_RF_rows (3 × Number_of_RF_rows × 4 bytes)	<p>Start position coordinates and orientation angle of each beam are originally recorded in triplets (beam_x<sub>i</sub>, beam_y<sub>i</sub>, angle<sub>i</sub>, where <i>i</i>-th scanning beam) for each scanning beam beginning from left side of the sector.</p> <ul style="list-style-type: none"> <li>• angle – specifies the angle of the ultrasonic beam's direction (in radians multiplied by 1000000). The angle is given relative to the perpendicular to the center of the probe's surface (angle = 0 for linear array probes); in case of compound scanning mode (B compound) the parameter returns angle of beams for each compounded sub-frame (number of compounded sub-frames could be adjusted by Frames Num. control);</li> <li>• beam_x - start x coordinates of each beam, (in μm);</li> <li>• beam_y - start y coordinates of each beam, (in μm).</li> </ul>
<i>time_stamps</i>	uint32	Number_of_RF_rows (Number_of_RF_rows × 4 bytes)	Time stamps for each ultrasound scanning line. Timestamp – time from the last start of scanning until the start of receiving of RF-data in present ultrasound line. One discrete of Timestamp = sampling period (25 ns for 40 MHz sampling clock of ArtUs). Maximum time for 32-bit timestamp is 28606043.625 μsec (28.605043625 sec), after that timestamp counter begins count from zero. Timestamps are in samples.

<i>frame</i>	<i>int16</i>	Number_of_RF_rows × Length_of_RF_row (Number_of_RF_rows × Length_of_RF_row × 2 bytes) for <i>source_ID</i> =1, 2, 3; and 2 × Number_of_RF_rows × Length_of_RF_row (2 × Number_of_RF_rows × Length_of_RF_row × 2 bytes) for <i>source_ID</i> =4	Single sub-frame RF data in 1D vector format (int16);
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Structure of the file:

*Source\_ID*=1, 2, 3

4 bytes	4 bytes	4bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	3 × Number_of_RF_rows × 4 bytes	Number_of_RF_rows × 4 bytes	Number_of_RF_rows × Length_of_RF_row × 2 bytes
<i>number_of_frames</i>	<i>header_size</i>	<i>frame_size</i>	<i>source_ID</i>	<i>tx_freq</i>	<i>frame_rate</i>	<i>Length_of_RF_row</i>	<i>Number_of_RF_rows</i>	<i>Sampling_period_ns</i>	<i>Sample_size</i>	<i>start_depth</i>	<i>Start_point_position_and_orientation</i>	<i>time_stamps</i>	<i>frame</i>

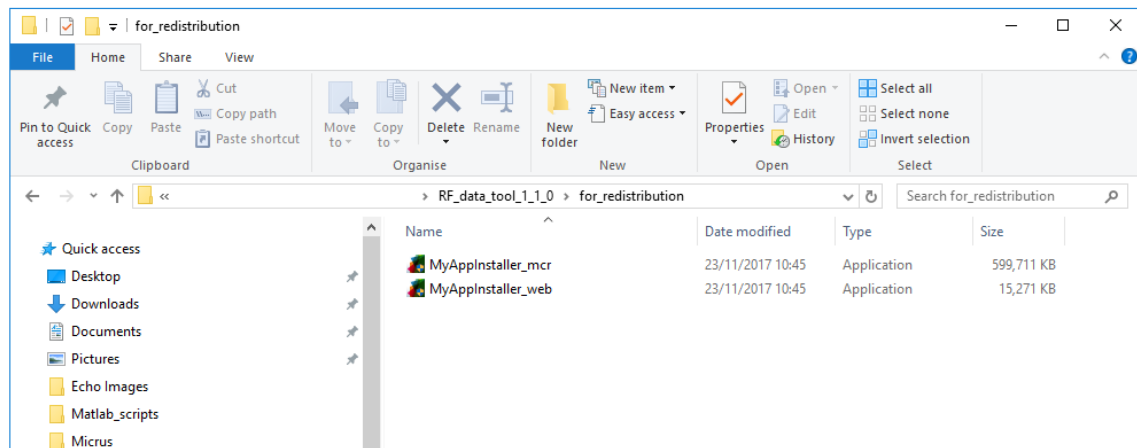
*Source\_ID*=4 (Hilbert transform output)

4 bytes	4 bytes	4bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	4 bytes	3 × Number_of_RF_rows × 4 bytes	Number_of_RF_rows × 4 bytes	2 × Number_of_RF_rows × Length_of_RF_row × 2 bytes	
number_of_frames	header_size	frame_size	source_ID	tx_freq	frame_rate	Length_of_RF_row	Number_of_RF_rows	Sampling_period_ns	Sample_size	start_depth	Start_point_position_and_orientation	time_stamps	I component	Q component

## 2. MATLAB RF data tool installation notes

The software package contains standalone compiled version of RF data tool graphical user interface (`RF_data_tool_1_0_1.exe`) and a collection of functions (M-files) including main file of the GUI (`RF_data_tool_1_0_1.m`). The directory `C:\.....\RF_data_tool_1_0_1` contains all the files necessary to install the RF data tool GUI on your system. Users can run GUI even without full MATLAB installation. It is enough to setup standalone MATLAB Runtime (mandatory shared libraries which allows execution of compiled programs). MATLAB compiler runtime could be installed using:

1) provided web installer `MyAppInstaller_web.exe`;



2) or the runtime could be downloaded from website. Please install version for 64-bit Windows: <https://se.mathworks.com/products/compiler/matlab-runtime.html>. The GUIs were compiled by using MATLAB R2016a.

Run the GUI by using `RF_data_tool_1_0_1.exe`, which could be found in directory `...for_testing`.

**Please note:** 1) the runtime allows to use GUI only, but aiming to use the scripts (`...\scripts`), modify and built your own applications full version of MATLAB should be installed; 2) this section explain installation notes for `RF_data_tool_1_0_1` as an example, but there are more GUIs in the package, but their instructions for installation are similar and therefore are not described again.



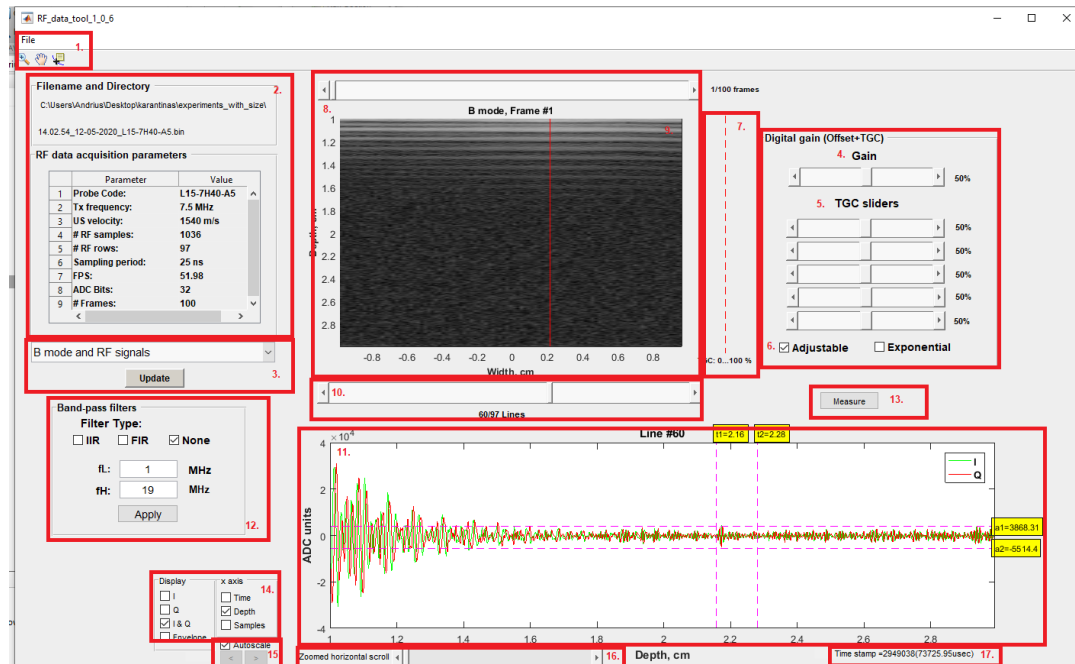
### 3. RF data tool graphical user interface structure

This section presents the MATLAB RF data tool graphical user interface main window and the available controls. GUI allows to import data files recorded by demo sample **ArtUs RF Data Control**.

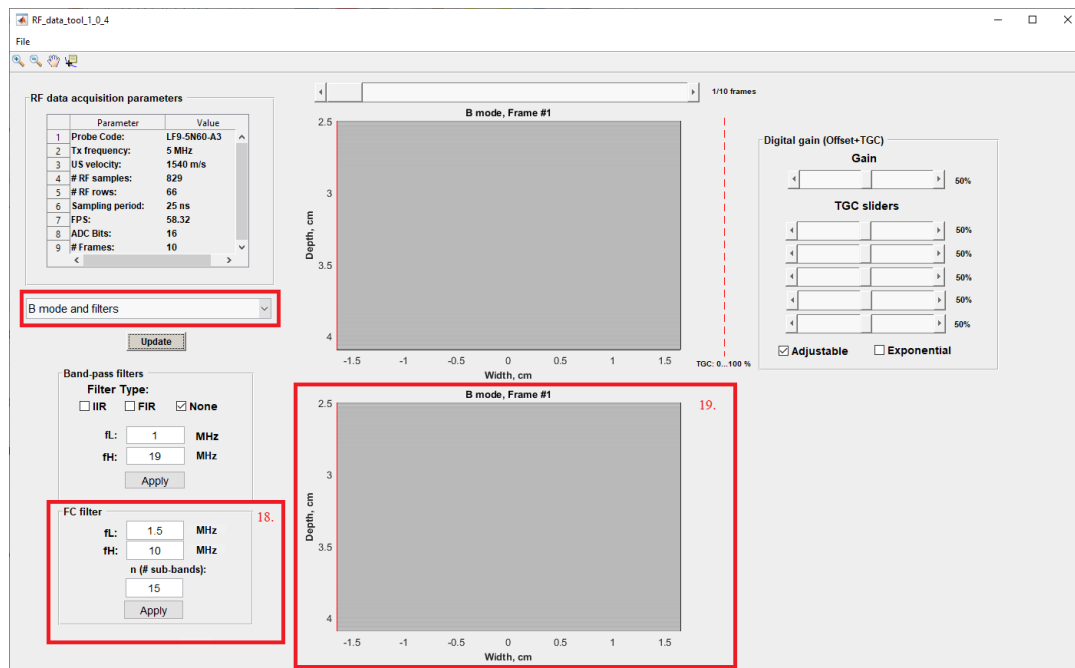
#### 3.1. Main window and controls

There are 4 GUI front panel display options dependent on popup-menu selection and specific controls for each menu option are described in the Table below:

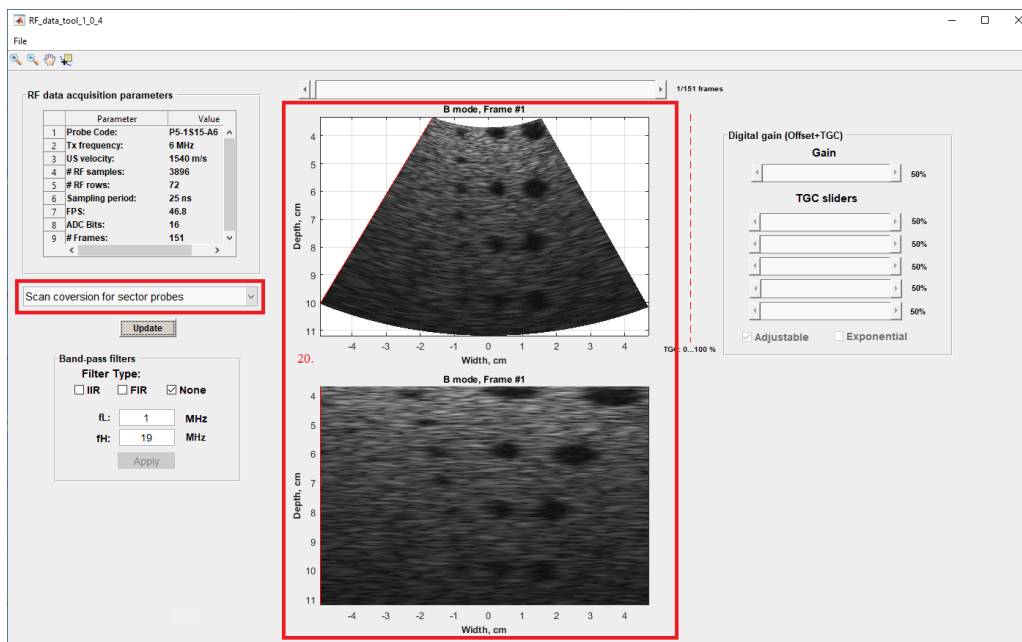
- **Popup-menu option: “B mode and RF signals”**



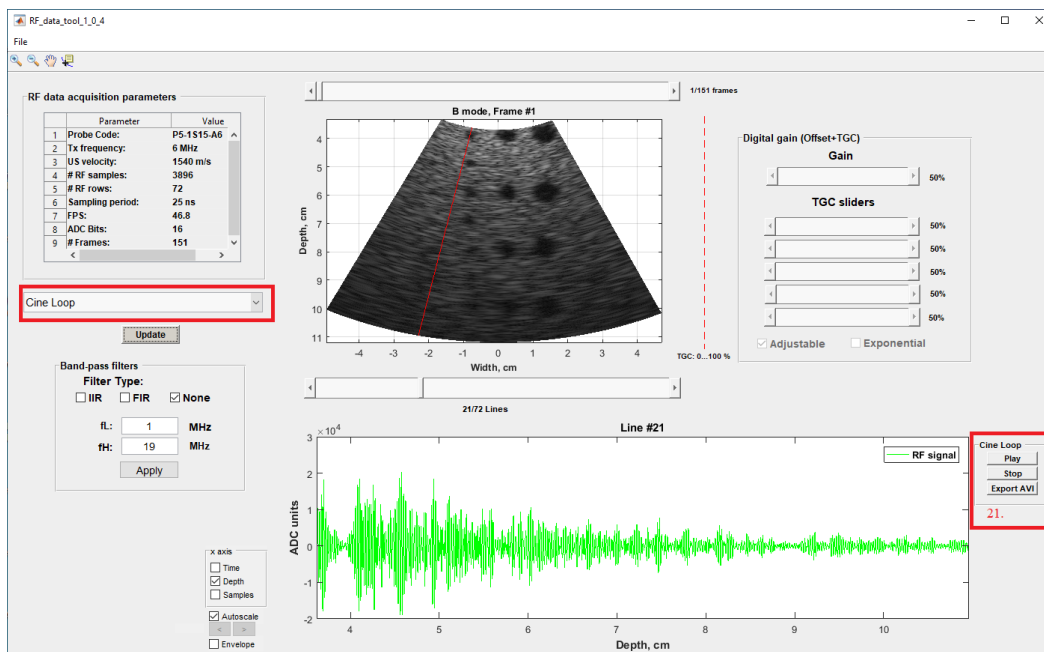
- **Popup-menu option: “B mode and filters”**



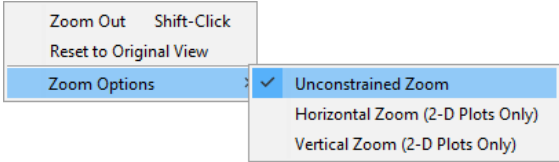




- Popup-menu option: “*Scan conversion for sector probes*”



- Popup-menu option: “*Cine Loop*”



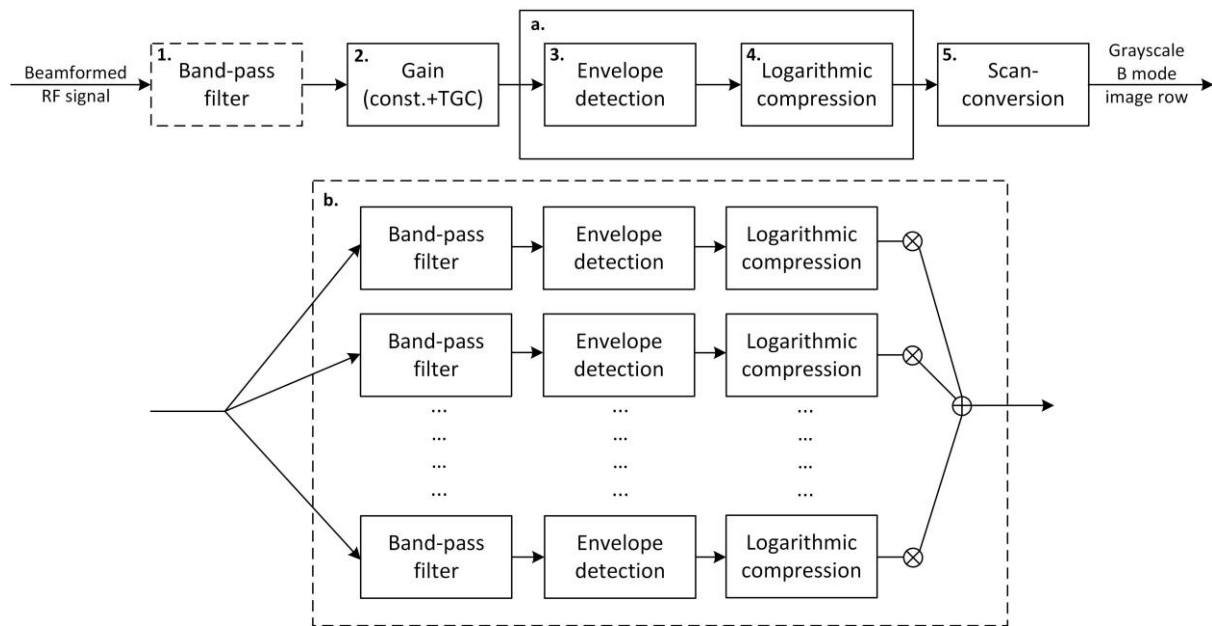
Num	Component	Description
1	File selection menu and Interactive display tools	<p>There are two <b>File</b> menu options:</p> <p>(i) File =&gt; Open... – allows to select file (RF data record) to be loaded into MATLAB workspace from the desired directory, and</p> <p>(ii) File =&gt; Close (closes RF data tool GUI).</p> <p>The controls which allow to interactively control the plotted data in figure axes:</p> <ul style="list-style-type: none"> <li>Zoom in </li> <li>Zoom out </li> </ul> <p>There are few Zoom Options:</p> <ul style="list-style-type: none"> <li>Unconstrained Zoom – default zoom,</li> <li>Horizontal Zoom (2-D Plots Only) – zoom changes only in horizontal direction,</li> <li>Vertical Zoom (2-D Plots Only) – zoom changes only in vertical direction,</li> <li>Reset to Original View – changes magnification to initial scale.</li> </ul>  <ul style="list-style-type: none"> <li>Pan  – turns on mouse-based panning for axes in the current figure</li> <li>Data Cursor  – enable you to read data directly from a graph by displaying the values of points you select on plotted lines</li> </ul>
2	RF data acquisition parameters and Filename and Directory	<p>Shows Filename and Directory of uploaded RF data file;</p> <p>The <b>RF data acquisition parameters</b> information panel presents main RF signal acquisition parameters:</p> <ul style="list-style-type: none"> <li><b>Probe code</b> – describes transducer type, bandwidth, width of array and code of manufacturer (i.e. L18-10H30-A4: L – linear array, bandwidth 18 – 10 MHz, width of array 30 mm, manufacturer no.: A4,</li> <li><b>Tx frequency</b> – transmission frequency in MHz,</li> <li><b>Speed of Sound</b> – ultrasound velocity, 1540 m/s (used for calculations of geometry),</li> <li><b># RF samples</b> – number of RF samples in single row,</li> <li><b># RF rows</b> – number of scanning rows in RF window,</li> <li><b>Sampling period</b> – RF signal digitization period,</li> <li><b>B mode FPS</b> – scanning speed frames/second (of B mode),</li> <li><b>RF FPS (calc.)</b> – scanning speed frames/second of scanner (Note: it is calculated on the basis of time stamps (not recorded into header of the file) and there will be no value for the first frame (shown NaN) and it may vary if some frames are missing or due to time stamps clock filling),</li> <li><b>Sample size</b> – RF signal digitization resolution in bits,</li> <li><b># Frames</b> – number of recorded frames (RF windows).</li> </ul>
3	Popup-menu	<p>Different options for RF data processing and B mode visualization:</p> <ul style="list-style-type: none"> <li><b>B mode and RF signals</b> – the purpose of first page is to present acquired data. RF signals and corresponding B mode images and the acquisition parameters can be reviewed by data analyst,</li> <li><b>B mode and filters</b> – second tab allows to adjust few optional digital RF data pre-processing filters and to observe how the filtering affects the B mode image,</li> </ul>

		<ul style="list-style-type: none"> <li>• <b>Scan conversion for sector probes</b> – demonstrates scan-converted B mode image and the image before scan conversion in rectangular coordinate system (option only for sector array probes),</li> <li>• <b>Cine Loop</b> – allows to review collected B mode sequence and data of single selected RF scanning line.</li> </ul> <p><b>Note:</b> user must confirm the selection by pressing “<b>Update</b>” button. The button stays inactive while the RF data file is loaded into MATLAB work space.</p>
4	<b>Digital gain control</b>	Slider adjusts the level of digital amplification of RF signals before envelope detection and logarithmic compression. The gain values are coded in percentage (0 ... 100 %). The scheme of the digital amplification (constant gain and time-gain compensation amplification proportion are explained below).
5	<b>TGC sliders</b>	The sliders (5 in total) allow to adjust the RF signal amplification at five different scanning depths (amplification intervals are equally spaced). The TGC values are coded in percentage (0 ... 100 %). The scheme of the digital amplification (constant gain and time-gain compensation amplification proportion are explained below).
6	<b>TGC curve type</b>	Option to select the time-gain compensation TGC curve type: (i) <b>Adjustable</b> – controlled by 5 sliders, (ii) <b>Exponential</b> – automatically applies exponential amplification which is opposite to theoretical frequency-dependent attenuation law (assumed attenuation coefficient $\alpha=0.47$ [dB/(cm*MHz)]).
7	<b>TGC curve visualization</b>	Visualization of TGC curve respective to scanning depth of the B mode sub-image.
8	<b>Recorded frame selection</b>	Slider allows to select RF frame in a recorded sequence for the analysis. The number of the selected frame is indicated in a B mode sub-image title.
9	<b>B mode image display</b>	Draws a pseudocolor plot of grayscale B mode image part captured in an RF window (scan-converted RF scanning lines from the adjustable RF data acquisition window) build from collected RF signals of the selected scanning sub-frame. Title of the figure indicates the number of the acquired frame (in presented example – Frame #2).
10	<b>RF scanning line selection</b>	Slider allows to select single RF scanning line which will be displayed in a separate plot below (see 9). The selected line (red solid) is marked together with B mode sub-image. The line selection could be done by left mouse button click as well.
11	<b>Plot RF line and envelope</b>	Figure displays the beamformed RF signal (black color) of the selected scanline (slider 7) and its envelope (red solid line). Title of the figure indicates the number of scanline in a RF window (in presented example – Row #42).
12	<b>Band-pass filters panel</b>	Panel for control of digital filters with adjustable pass-band (upper and lower frequencies of the pass-band, boundary values for the pass-band $f_L=0.5$ MHz and $f_H=19$ MHz). There are three filtering options (Checkboxes): (i) IIR – infinite impulse response, (ii) FIR – finite impulse response, (iii) None – turn-off the filtering option.
13	<b>Measure button</b>	Turns on 4 cursors for manual measurement of RF data time and amplitude values. Obtained values are shown in yellow labels. Button <b>Update</b> turns off measurement cursors.
14	<b>Display and x axis selection checkboxes</b>	It is optional what to display in axes: I, Q components or both together with envelope obtained through Hilbert’s transform. It is optional to select x-axis representation it could be in time ( $\mu s$ ), depth (cm) or in samples.

15	<b>Autoscale</b>	Checkboxes turns on/off autoscale and allows to select imaging range in bits.
16	<b>Zoomed horizontal scroll</b>	Allows scrolling through RF data after it is zoomed by using interactive display tools (Num 1).
17	<b>Time stamp</b>	Shows time stamp value for selected RF scanning line in samples and in ( $\mu$ s).
18	<b>FC (frequency compound) filter</b>	The frequency compounding filter allows to reduce speckle noise level of the obtained image. The detailed description of the filter could be found in subsection 4.6. There are three adjustable parameters: $fL$ , $fH$ – lower and upper frequencies of the frequency band which will be decomposed and $n$ – number of decomposition sub-bands (number of decomposition filters).
19	<b>B mode image display (II)</b>	<p>Active for the <b>Popup-menu</b> option (“<b>B mode and filters</b>”). Allows to display B mode sub-image formed without application of any digital filters and comparative image obtained applying filtering. There are two different filtering options: (i) band-pass filters and, (ii) FC (frequency compound) filter. The filters could be applied in a cascade (band-pass + FC filter).</p> <p><b>Note.</b> <u>The application of gain, TGC and band-pass filters resets the FC filter. The filtering should be re-applied (button “<b>Apply</b>”) if these controls will be adjusted.</u></p>
20	<b>B mode image display (III)</b>	Active for the <b>Popup-menu</b> option (“ <b>Scan conversion for sector probes</b> ”). The example demonstrates scan-converted B mode image and the image before scan conversion in rectangular coordinate system.
21	<b>Cine Loop controls</b>	<p>Active for the <b>Popup-menu</b> option (“<b>Cine Loop</b>”).</p> <p><b>Play</b> – starts playing sequence (B mode image in upper axes and RF signal of single selected line in the bottom axes),</p> <p><b>Stop</b> – stops playing recorded data,</p> <p><b>Export AVI</b> – allows to export B mode image sequence to AVI file (each 5<sup>th</sup> frame is recorded into AVI movie).</p>

## 4. RF data tool GUI functions and options

This section provides description of all the functions used in the RF data tools GUI. The functions allow to import and review beamformed RF data in MATLAB environment and demonstrate the conventional RF data processing stages which are used for B mode formation and imaging purposes. Figure below presents block diagram of the RF signal processing routines used in GUI for single RF scanline. There is option to apply digital frequency compounding filter<sup>b</sup> which could modify conventional processing chain stages<sup>a</sup>. In case of FC each decomposition sub-band is passed to envelope detector and logarithmic compression block separately.



Implemented RF data processing and B mode imaging engine contains following steps:

### 1. *Band-pass filter (optional).*

There are three filtering options: (i) IIR, (ii) FIR and (iii) None. The GUI allows to adjust lower (**fL**) and upper (**fH**) cut-off frequencies of the pass-band (in MHz). The boundary values for pass-band  $fL=0.5$  MHz,  $fH=19$  MHz. It is recommended to adjust the decomposition band [ $fL$ ,  $fH$ ] respective to the transducer transmission frequency spectrum. For the details read the subsection 4.3.

**Band-pass filters**

**Filter Type:**

☐ IIR ☒ **FIR** ☐ None

**fL:**  **MHz**

**fH:**  **MHz**

### 2. *Digital Gain.*

RF signal amplification consists of two components: depth dependent **TGC** curve and global component of the gain (**Gain**). Final amplification curve is defined as:

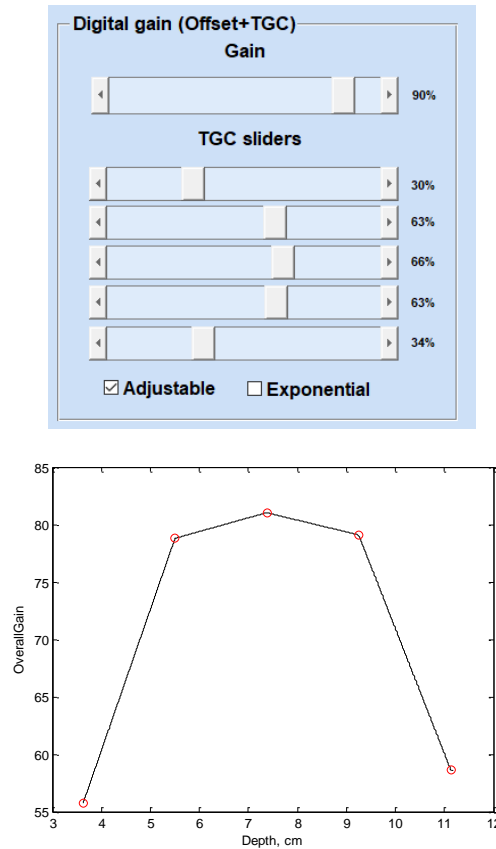
$$OverallGain = TGC \cdot Gain. \quad (1)$$

The TGC part of the amplification could be adjusted manually by five sliders which corresponds to equally spaced scanning depth intervals (option: **Adjustable**) or automatically (option: **Exponential**) by applying opposite amplification curve to the theoretical attenuation law:

$$OverallGain = [1 + (1 - \exp(-\alpha \cdot f \cdot z))] \cdot Gain, \quad (2)$$

where  $\alpha$  – attenuation coefficient (0.47 dB/[MHz\*cm]),  $f$  – ultrasound wave transmission frequency,  $z$  – penetration depth.

The examples of TGC sliders and corresponding TGC curve with 5 control points (red circles) are presented below.



### 3. Envelope detection.

This stage allows to detect envelope of the RF signal which represent magnitude of the reflections by taking the modulus of the analytical signal (for the details read subsection 4.4).

### 4. Logarithmic compression.

The compression reduces dynamic range in order to adapt the data for the imaging purposes, since the human ability to distinguish grayscale levels visually is limited. The actual dynamic range of the received signal depends on the RF data sample size, the TGC amplifier, and the depth of penetration. For the detailed description we refer to sub-section 4.5.

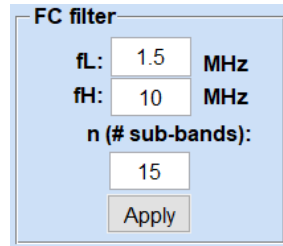
### 5. Scan-conversion.

The scan lines are aligned in space respective to geometry (rectangular or sector image) of the probe and position of RF window in an image frame. The scanning lines coordinates for sector image are obtained by using rotation matrix (see 4.7). The more explicit description of the main image and probe geometry defining parameters could be found in [1, 2]. Finally, the image data

are interpolated (applying piecewise bilinear interpolation method, MATLAB: `shading interp`) and displayed on screen.

### Frequency compounding

There is an option to try out frequency compounding (FC) filter for the speckle pattern reduction. The GUI allows to adjust lower (**fL**) and upper (**fH**) cut-off frequencies of the decomposition band and to choose the number of the decomposition filters (**n**).



FC filtering it's a trade-off between the spatial resolution and noise level. The number of decomposition sub-bands (band-pass filters) controls the balance. Resolution degrades by increasing **n**, meanwhile smoothing effect rises. It is recommended to adjust the decomposition band [fL, fH] respective to the transducer transmission frequency spectrum.

#### 4.1. GUI main function (`RF_data_tool_1_0_1.m`)

The main GUI function contains 9 external functions and defines controls described in the 3.1 subsection. The functions allow performing basic B mode imaging related signal processing and data visualization tasks and could be used in the development of new projects. The list of the functions is provided below and the functions (inputs and outputs) are described explicitly in the following subsections:

No.	Function	Description
1	<code>import_RFdata2MATLAB.m</code>	Function allows to import acquired RF data and main acquisition parameters needed for imaging into MATLAB.
2	<code>band_pass_filter.m</code>	The function could be used for zero-order digital filtering of received RF signals before envelope detection and scan conversion.
3	<code>envelope_detection.m</code>	The function allows to detect envelope of the RF signals applying Hilbert transform.
4	<code>envelope_2_image.m</code>	Function allows to adjust dynamic range of displayed image through log-compression of detected envelope of RF signal.
5	<code>FC_filter.m</code>	The function allows to apply digital frequency compounding for speckle pattern reduction.
6	<code>rotation_matrix.m</code>	Function rotates scan line coordinates vector around origin of coordinate system (0,0) in counter-clockwise direction by a predefined angle – $\theta$ .
7	<code>TGC_curve.m</code>	Function returns interpolated TGC scanning depth-dependent amplification curve.
8	<code>Display_B_mode.m</code>	Function converts received RF data of selected single frame to N Bit B mode image.
9	<code>show_plot_of_RF_line.m</code>	Function plots single selected RF scanning line (by slider in GUI or by passing the line number into the function) and detected envelope (optional) of the RF signal in the same figure. Function return x-axis values in selected time, depth or samples dimension.



## 4.2. Import RF data to MATLAB (`import_RFdata2MATLAB.m`)

Function allows to import acquired RF data and main acquisition parameters needed for imaging into MATLAB.

### Inputs of the function:

*DIR* – directory of the file,  
*filename* – name of the file with RF data, \*.bin binary file recorded using ArtUS device and Artus RF Data Control sample.

### Outputs of the function:

*RF\_DATA* – RF data in cell format:  $1 \times K$  – number of RF frames, where cells contain  $N$  (number of RF samples)  $\times M$  (number of scanning lines).

*RF\_DATA\_Q* – RF data Q component obtained after Hilbert transform in cell format:  $1 \times K$  – number of RF frames, where cells contain  $N$  (number of RF samples)  $\times M$  (number of scanning lines). Actual for Hilbert transform output.

*HEADER* – RF data acquisition parameters:

*HEADER{1,K}.number\_of\_frames* – number of RF frames in a file,  
*HEADER{1,K}.header\_size* – header size in bytes,  
*HEADER{1,K}.frame\_size* – RF frame size in bytes,  
*HEADER{1,K}.source\_ID* – RF data source ID,  
*HEADER{1,K}.tx\_frequency* – ultrasonic wave (transmission) frequency,  
*HEADER{1,K}.Length\_of\_RF\_row* – number of samples in each row of RF window,  
*HEADER{1,K}.Number\_of\_RF\_rows* – number of RF scanning lines in a window,  
*HEADER{1,K}.Sampling\_period\_ns* – sampling period in ns,  
*HEADER{1,K}.sample\_size* – sample size of RF data in bits,  
*HEADER{1,K}.beam\_x* – start point coordinates of each ultrasound beam in cm (sector width direction),  
*HEADER{1,K}.beam\_y* – start point coordinates of each ultrasound beam in cm (scanning depth direction),  
*HEADER{1,K}.angle* – angle in radians (the angle is given relative to the perpendicular to the center of the probe's surface).  
*HEADER{1,1}.time\_stamps* – time stamps for each ultrasound scanning line

*transducer\_code* – type (L – linear, C – convex, P – phased array probe), bandwidth limits (HF...LF), width of probe in mm, code of manufacturer,  
*flag* – returns 1 if file was successfully imported (otherwise – 0, i.e. empty file).

## 4.3. Band-pass filters (`band_pass_filter.m`)

The function could be used for zero-order digital filtering (forward and reverse directions) of received RF signals before envelope detection and scan conversion. The cut-off frequencies (upper fH and lower fL frequency of pass-band) are user predefined. There are 3 filtering options: (a) using infinite impulse response Butterworth type filter, (b) finite impulse response filter designed using window method, and 3<sup>rd</sup> (c) "None" turns off the filter. By default, taps of the filter ( $n$ ) are set to a)  $n=9$ , b)  $n=200$  (reduced to 100 if number of samples is lower than  $3n$ ).

### Inputs of the function:

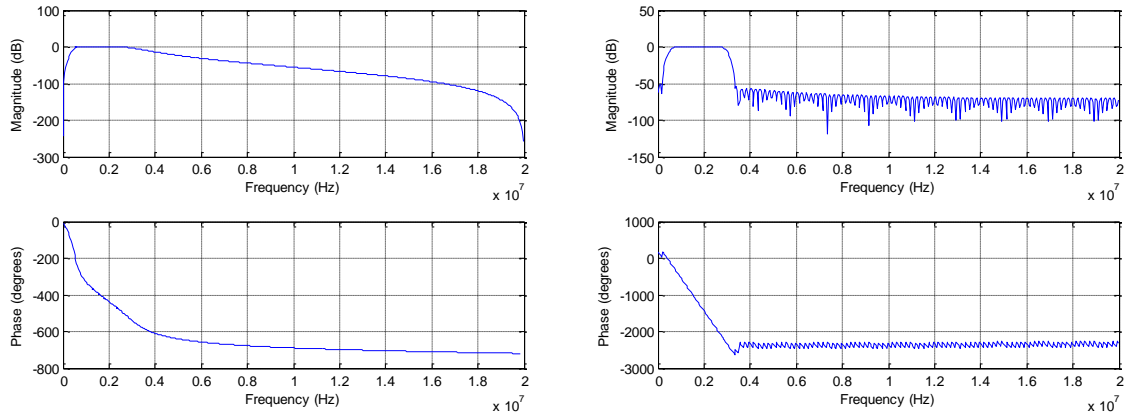
*in* – received single RF frame ( $N \times M$ ), where  $N$  – number of samples,  $M$  – number of scanning lines (rows),  
*low\_freq\_cutoff* – lower cut-off frequency of the pass-band,  
*up\_freq\_cutoff* – upper cut-off frequency of the pass-band,  
*Sampling\_frequency* – sampling frequency for TELEMED systems = 40 MHz,

*flag* – sets the filtering method 0 for infinite impulse response (Butterworth type), 1 - for finite impulse response (FIR filter designed using the window method), 2 - turns of the filters.

#### **Output of the function:**

*out* – filtered signals of single RF frame.

Figure below shows the examples of frequency responses of IIR and FIR filters with  $f_L=0.5$  MHz and  $f_H=3$  MHz.



**Fig.** Frequency responses of the infinite impulse response filter (left) and finite impulse response filter (right). Cut-off frequencies for both: lower cut-off frequency  $f_L = 0.5$  MHz, upper cut-off frequency  $f_H=3$  MHz.

#### **4.4. Envelope detection ([envelope\\_detection.m](#))**

The function allows to detect envelope of the RF signals applying Hilbert transform. Envelope of the signal could be found as follows:

$$env(t) = \sqrt{I^2 + Q^2}, \quad (3)$$

where  $I$  and  $Q$  are in-phase and quadrature components of input signal.

#### **Input of the function:**

*RF\_in* – RF signal (single scanning line).

#### **Outputs of the function:**

*envelope* – detected RF signal envelope.

*Q\_comp* – quadrature component of the RF signal (phase shifted by  $-\pi/2$ ).

#### **4.5. Logarithmic compression ([envelope\\_2\\_image.m](#))**

Function allows to adjust dynamic range of displayed image through log-compression of detected envelope of RF signal. The displayed image could be expressed as follows:

$$I = e^{\alpha \cdot \ln(env(t))} / \beta, \quad (4)$$

where  $\alpha$  – coefficient of non-linearity (set to  $\alpha=0.47$ ),  $env$  – detected envelope of signal,  $\beta = \alpha * \ln(2^{BIT} - 1) / k$ ,  $k$  – number of gray levels of output image,  $\ln$  – natural logarithm.

#### **Input of the function:**

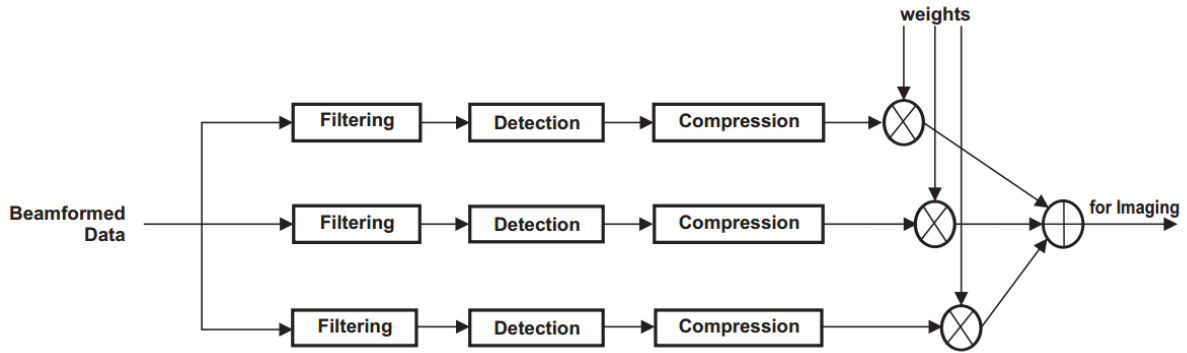
*alpha* – coefficient of non-linearity,  
*num\_gray\_levels* – number of gray levels of output image (i.e. 256 for 8-bits),  
*BIT* – sample size of RF data in bits (16 for TELEMED systems),  
*envelope* – detected envelope of RF signal.

#### **Output of the function:**

*image\_8\_BIT* – logarithmically compressed image.

#### **4.6. Frequency compounding (FC\_filter.m)**

The function allows to apply digital frequency compounding for speckle pattern reduction. The received beamformed RF signals are divided into adjustable frequency sub-bands by using bank of decomposition filters. The output of each decomposition filter is then passed to envelope detector and consequently to logarithmic compression block [3]. Each sub-band is weighted by a relative mean power of itself in order to preserve dynamic range before the summation. Figure below presents the frequency compound principle.

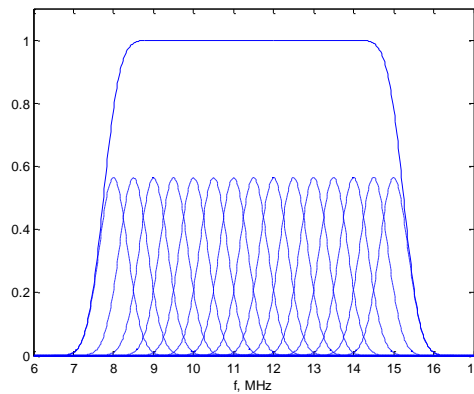


**Fig. Frequency compounding scheme [3]**

Used Gaussian decomposition filters are designed so that the combined frequency response is close to 1 for the pass-band frequencies. Decomposition filter for  $i$ -th pass-band is defined [4]:

$$B_i(f) = \frac{1}{\sqrt{\pi}} \cdot e^{-\left(\frac{f - f_L - (i-1) \cdot B}{B}\right)^2}, \quad (5)$$

where  $i = 1, 2, \dots, n$ ,  $n$  – number of sub-bands and bandwidth of each filter –  $B = (fH - fL)/(n - 1)$ .  $fL$  – lower frequency of the decomposition band,  $fH$  – upper frequency of the decomposition band,  $f$  – vector of frequencies. Fig. shows an example of decomposition filters and combined frequency response:



**Fig. Frequency responses of Gaussian decomposition filters and combined (summed):**  
 $fL=8$  MHz,  $fH=15$  MHz,  $n=15$ .

#### **Inputs of the function:**

*RF\_frame* – received single RF frame (N × M), where N – number of samples, M – number of scanning lines (rows),  
*fL* – lower frequency of the decomposition band (in MHz),  
*fH* – upper frequency of the decomposition band (in MHz),  
*n* – number of decomposition filters,  
*Nyquist\_freq* – Nyquist frequency limit (for TELEMED systems 20 MHz).

#### **Output of the function:**

*image\_FC* – frequency compounded 8-bit image.

### **4.7. Rotation matrix (*rotation\_matrix.m*)**

Function rotates scan line coordinates vector around origin of coordinate system (0,0) in counter-clockwise direction by a predefined angle –  $\theta$ . Rotation matrix is defined:

$$R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}, \quad (6)$$

where  $\theta$  – rotation angle.

#### **Inputs of the function:**

*vector\_in* – input vector (x, y) coordinates,  
*theta* – rotation angle.

#### **Outputs of the function:**

*out* – rotated vector (x, y) coordinates.

### **4.8. Interpolated Time gain compensation (TGC) curve (*TGC\_curve.m*)**

Function returns interpolated TGC scanning depth-dependent amplification curve. Five base points of the curve could be controlled by 5 GUI TGC sliders or passed into the function by a 1 × 5 vector. Function calculates the intermediate TGC curve values between the base points applying linear interpolation.

#### **Inputs of the function:**

*Length\_of\_RF\_row* – number of samples in each row of RF window,  
*amplification\_fract\_values* – base points (5) of TGC curve, i.e. 1 × 5 vector could be passed into the function.

#### **Output of the function:**

*interpolated\_ampl\_curve* – returns interpolated TGC curve. Number of amplification constants of the curve are equal to number of RF scanning line samples.

### **4.9. Convert RF frame to B mode image (*build\_b\_mode.m*)**

Function converts received RF data of selected single frame to N Bit B mode image ready for imaging.

#### **Inputs of the function:**

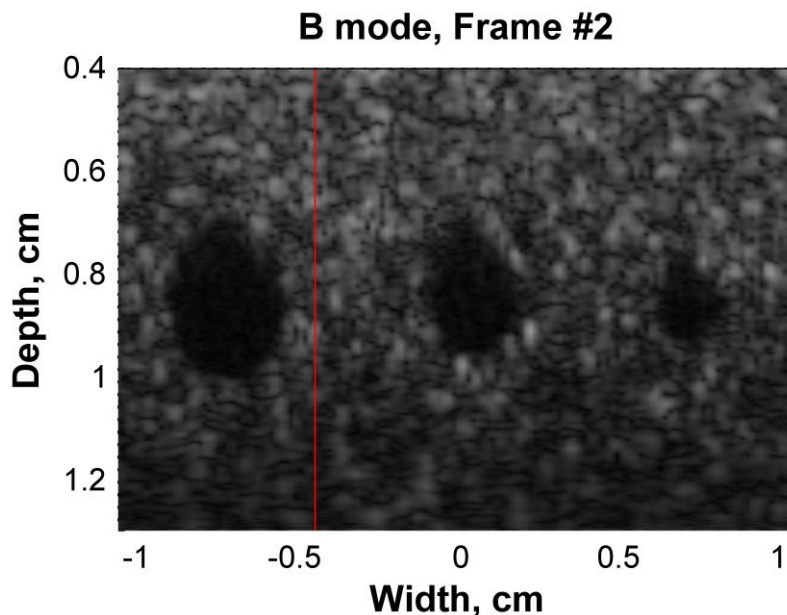
*RF\_frame* – RF data of selected frame ( $N$  (number of RF samples)  $\times$   $M$  (number of scanning lines)),  
*HEADER* - RF data acquisition parameters (see description in 2.5),  
*Number\_of\_frame2show* – number of selected frame in a sequence,  
*image\_bits* – number of B mode image bits (i.e. 8),  
*interpolated\_ampl\_curve* – depth-dependent TGC amplification curve,  
*flag* – option for RF signal band-pass filtering (see description 2.1),  
*low\_freq\_cutoff* – lower cut-off frequency of the pass-band,  
*up\_freq\_cutoff* – upper cut-off frequency of the pass-band.

#### **Outputs of the function:**

*RF\_frame* – returns RF data (set of signals) of single frame after application of TGC and band-pass filtering,  
*x\_axis* – spatial sector width coordinates (in cm) for B mode imaging (size:  $M(\text{rows}) \times 1$  for linear probe and  $M(\text{rows}) \times N$  (samples) for convex),  
*y\_axis* – spatial depth coordinates (in cm) for B mode imaging (size:  $1 \times N$  (samples) for linear probe and  $M(\text{rows}) \times N$  (samples) for convex),  
*image\_N\_BIT* – B mode image formed applying TGC, band-pass filter, envelope detector and logarithmic compression.

#### **4.10. Display B mode (*Display\_B\_mode.m*)**

Function plots the formed B mode (for the details see block diagram in the beginning of the 4<sup>th</sup> section) grayscale image in Cartesian coordinate system. Figure below depicts example of formed B mode image (2<sup>nd</sup> frame in acquired sequence) and marked position of the scanning line which will be plotted separately.



**Fig.** B mode image together with marked scanning line which will be displayed in separate plot (red line)

#### **Inputs of the function:**

*x\_axis* – spatial sector width coordinates (in cm) for B mode imaging (size:  $M$  (rows)  $\times$  1 for linear probe and  $M$  (rows)  $\times$   $N$  (samples) for convex),  
*y\_axis* – spatial depth coordinates (in cm) for B mode imaging (size:  $1 \times N$  (samples) for linear probe and  $M$  (rows)  $\times$   $N$  (samples) for convex),  
*image\_N\_BIT* – B mode image formed applying TGC, band-pass filter, envelope detector and logarithmic compression,  
*image\_bits* – number of B mode image bits (i.e. 8),

*Line\_to\_show* – determines position of single RF scanning line (indicated by red line) which will be displayed in the other plot (see 4.11),

*Frame\_to\_show* – number of RF frame in a received sequence which is displayed (used in the title of the figure),

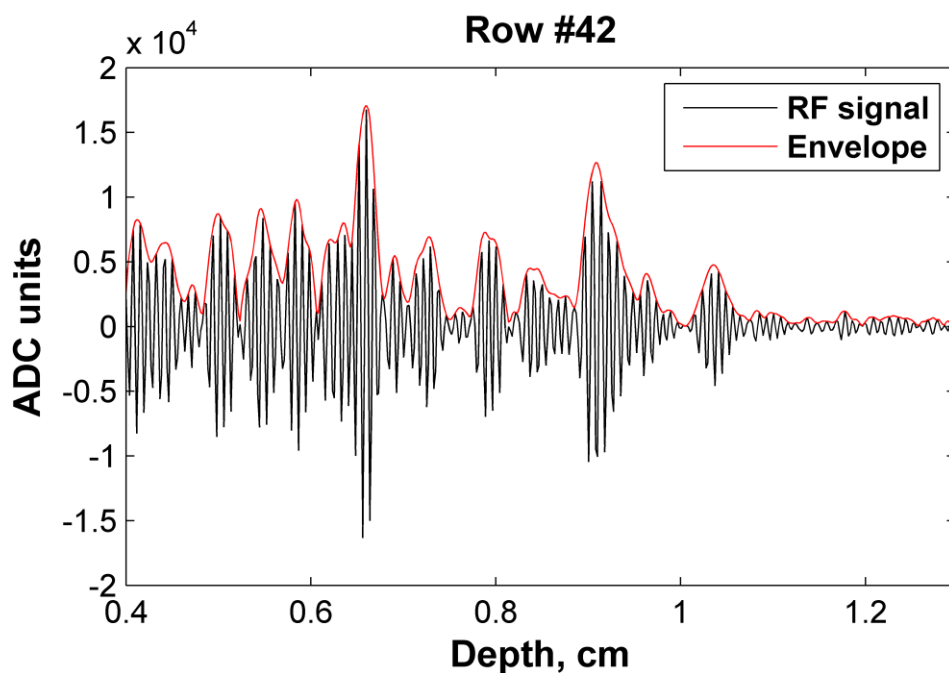
*Flag* – option for image type: 0 – for rectangular array (linear probe), 1 – for sector array (convex or phased array probes).

**Outputs of the function:**

*Shows B mode image in pcolor (pseudocolor) plot.*

**4.11. Display single RF line (`show_plot_of_RF_line.m`)**

Function plots single selected RF scanning line (by slider/left mouse button click in GUI or by passing the line number into the function) and detected envelope of the RF signal in the same figure. Figure shows an example of single RF scanning line (black color) of RF window and detected envelope of the signal (red color):



**Fig.** Single RF scanning line (black color) and detected envelope of the signal (red color)

**Inputs of the function:**

*y\_axis* – scanning depth coordinates (in cm),

*Line\_to\_show* – number of selected RF scanning line in a frame which will be plotted,

*RF\_frame* – selected single (raw) RF frame,

*RF\_frame\_Q* – Q component of selected RF frame (actual for Hilbert's transform output),

*envelope\_on\_of* – flag for turning display of envelope on/off,

*HEADER* – RF data header,

*scale\_in\_us* – flag for optional x axes coordinates (0 – cm, 1 –  $\mu$ s, 2 – samples)

**Outputs of the function:**

*y\_axis* – scanning depth coordinates (in optional units: 1)  $\mu$ s, 2) cm or 3) samples),

*Y\_lims* – display range of y axis [*y\_min* *y\_max*],

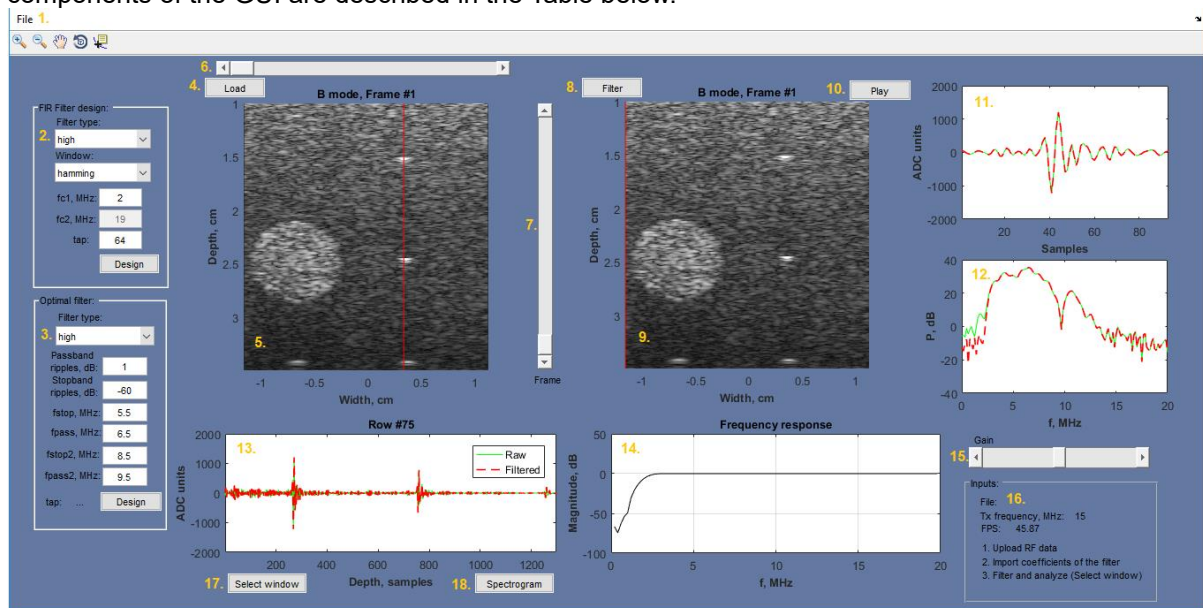
*Shows RF signal and its detected envelope in the single plot.*

## 5. GUI for filters

**GUI for filters** (`GUI_for_filters_v1_1.m`, `GUI_for_filters_v1_1.exe`) RF data tool allows to filter acquired RF signals and to observe the results and filtering influence to final ultrasonic B mode image. Various filters could be designed using built-in MATLAB filter design and analysis tool. Interface allows to upload RF data acquired by using ArtUS scanner. The GUI contains 6 axes to display: images before and after filtering, frequency response of a filter, raw and filtered RF signal representation in time and frequency domains.

### 5.1. Main window and controls

Figure below presents the front panel of the GUI together with numbered main components. The components of the GUI are described in the Table below.



Num	Component	Description
1	File selection menu and Interactive display tools	<div> <div>File</div> <div> Load RF data  Import Filter coefficients  Export filtered frame  Export result image as ...  Export initial image as ...  Export filter coefficients </div> </div>



There are 6 options for File menu:

- Load RF data – imports selected RF data record into MATLAB workspace,
- Import Filter coefficients – imports  $b$  coefficients of a FIR filter from \*.mat file. File should contain a vector of  $b$  coefficients of the filter (entitled "b"),
- Export filtered frame – exports RF data matrix corresponding to single filtered RF frame to \*.mat file. Exported file contains RF data matrix, header and transducer code,
- Export result image as ... – exports filtered B mode image to graphics file (options: \*.jpg, \*.bmp, \*.tiff, \*.png),



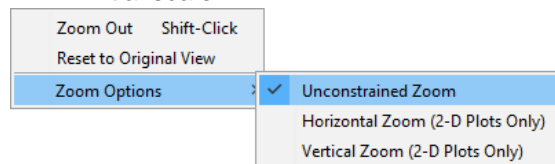
- Export initial image as ... – exports unfiltered initial B mode image to graphics file (options: \*.jpg, \*.bmp, \*.tiff, \*.png),
- Export filter coefficients – exports designed FIR filter coefficients to file (\*.mat).




The controls which allow to interactively control the plotted data in figure axes:

- Zoom in 
- Zoom out 

There are few Zoom Options:

- Unconstrained Zoom – default zoom,
- Horizontal Zoom (2-D Plots Only) – zoom changes only in horizontal direction,
- Vertical Zoom (2-D Plots Only) – zoom changes only in vertical direction,
- Reset to Original View – changes magnification to initial scale.



- Pan  – turns on mouse-based panning for axes in the current figure,
- Rotate 3D  – allows to rotate axes in space,
- Data Cursor  – enable you to read data directly from a graph by displaying the values of points you select on plotted lines.

2	<b>FIR filter design</b>	FIR filter designed by setting selected parameters in GUI. User can specify type of the filter (high-pass, low-pass or band-pass), window type, cut-off frequencies and tap.
3	<b>Optimal filter design</b>	Optimal filter could be designed by setting selected parameters in GUI. Filter design is based on Parks-McClellan method. User can specify filter type (high-pass, low-pass or band-pass), level of pass band ( <i>Passband ripples</i> ) and stop band ( <i>Stopband ripples</i> ) ripples (in dB), cut-off frequencies ( <i>fstop</i> , <i>fpass</i> and <i>fstop2</i> , <i>fpass2</i> for band-pass filter).
4	<b>Load button</b>	Loads RF data from file, updates B mode imaging window and shows the B mode image obtained on the basis of RF data.
5	<b>B mode imaging window (initial image)</b>	Draws a pseudocolor plot of gray scale B mode image part captured in an RF window build from collected RF signals of the selected scanning sub-frame. Title of the figure indicates the number of the acquired frame. Displayed image is obtained without any filtering in data processing chain.
6	<b>RF scanning line selection</b>	Slider allows to select RF line, which will be displayed in separate axes (13 GUI Component). Title of the figure indicates the number of scanline.
7	<b>Recorded frame selection</b>	Slider allows to select desirable frame for imaging and filtering.
8	<b>Filter button</b>	Performs filtering of RF data and displays filtered B mode image on the screen (GUI component 9).
9	<b>B mode imaging window (filtered image)</b>	Draws a pseudocolor plot of gray scale B mode image part captured in an RF window build from collected RF signals of the selected scanning sub-frame. Displayed image obtained after application of



		the designed filter.
10	Play button	Shows the sequence of filtered images in the axes which displays filtered B mode image. The displayed images are decimated and the quality is lower in comparison to original B scans.
11	Plot selected segment of RF line	Figure displays a segment of RF signal manually selected by marking two points (beginning and end) using graphical input command on the axes (GUI component 13). A comparison of selected signal segment before and after FIR filtering is presented.
12	Plot spectra	Figure displays a comparison of frequency spectra (in dB) obtained by taking FFT of selected signal segments (before and after filtering).
13	Plot RF line	Figure displays the beamformed RF signal of the selected scan line (could be selected by slider 6 or left mouse button click) before applying filtering (green solid line) and its filtered version (red dashed line). Title of the figure indicates the number of scanline in a RF window.
14	Plot frequency response of a filter	Figure displays frequency response of the designed filter.
15	Digital gain control	Slider adjusts the level of digital amplification of RF signals before envelope detection and logarithmic compression.
16	Data acquisition parameters	Shows few data acquisition parameters and suggestions how to use the GUI. Provided parameters and information are: transmission frequency, frame rate and filename of the loaded filter coefficients file (filename codes filter window type, cut-off frequency and tap of a filter, i.e. hamming_6_MHz_128 means Hamming window-based FIR filter with cut-off frequency = 6 MHz and tap = 128).
17	Select analysis window	Button activates the option to select subwindow in axes for the spectral analysis. The segment could be selected by left mouse button clicks at the beginning and end of the desired segment of RF line.
18	Spectrogram	Draws a spectrogram of selected filtered RF line. Observation of the spectrogram allows to evaluate how the filter performs.

## 5.2. Recommended sequence of actions

The procedure how to use interface could be divided into following steps:

- **Load RF data** (File=>Load RF data and press Load button). At first RF data record should be selected and loaded into workspace for further processing. There are two options: 1) load \*.bin file recorded by using ArtUS scanner and relevant software, or to load 2) \*.mat file which contains RF data of single frame.
- **Filter design stage.** There are three options: 1) to load filter coefficients from a file (the file could be generated by using MATLAB built-in Filter Design and Analysis Tool *fdatool*) or 2) FIR filter designed by setting selected parameters in GUI, 3) Optimal filter designed by setting selected parameters in GUI. For the 2) option there is possibility to design window-based FIR filter by using a) Hamming, b) Nuttall, c) rectangular, d) Blackman, e) Blackman-Harris, f) Gaussian, g) Hann, h) Parzen, i) Taylor and j) triangular window. Filter could be designed of one of these types: high-pass (*high*), low-pass (*low*) or band-pass (*bandpass*). User can specify desired cut-off frequencies (*fc1* and *fc2* for band-pass filter) and tap (*tap*) of a filter.



Option 3) is dedicated for optimal filter design, which is based on Parks-McClellan method. Filter could be designed of one of these types (*Filter type*): high-pass (*high*), low-pass (*low*) or band-pass (*bandpass*). User can specify level of pass band (*Passband ripples*) and stop band (*Stopband ripples*) ripples (in dB), cut-off frequencies (*fstop*, *fpass* and *fstop2*, *fpass2* for band-pass filter). Panel of controls used during optimal filter design is presented below. If the “Design” button is pressed GUI displays tap (*tap*) of the designed optimal filter.

Optimal filter:

Filter type: high

Passband ripples, dB: 1

Stopband ripples, dB: -60

fstop, MHz: 5.5

fpass, MHz: 6.5

fstop2, MHz: 8.5

fpass2, MHz: 9.5

tap: ... Design

- When RF data and filter coefficients are ready – **filtering** could be performed by applying “Filter” button. User can compare the filtered image (displayed on the right) to initial one (left side, 5 GUI component).
- For the **more detailed analysis** RF signals could be visually evaluated in the user predefined window (press button “*Select window*”). Button click activates graphical input function and user has to choose two points: beginning of the analysis window and the end point. Selected filtered RF signal segment is displayed (GUI right upper corner) together with RF signal segment before filtering (*raw*). Figure below shows frequency domain representations (spectra) of these RF signal segments.  
 “Spectrogram” button allows to calculate and to display time-frequency representation of RF signal (single scanning line) obtained using short-time Fourier transform.

## 6. RF data tool for dynamic range adjustment

The graphical user interface (`dynamic_range_v_1_1.m`, `dynamic_range_v_1_1.exe`) allows to adjust dynamic range curve and to observe how its shape affects final B mode image. The used “mixed” curve is composed from three parts: 1) reject part, or part of zeros, which filters small values most likely created by noise, 2) logarithmic part – nonlinear suppression of echoes to reduce dynamic range, and 3) linear part. Figure below presents the sketch of the mixed curve. The proportion of these parts can be adjusted by the setting the parameters in the GUI. It will be possible to compare B mode images obtained applying classical purely logarithmic compression curve and the mixed curve by using the GUI.

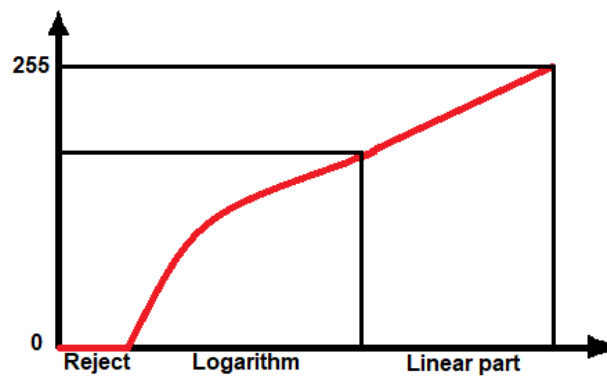
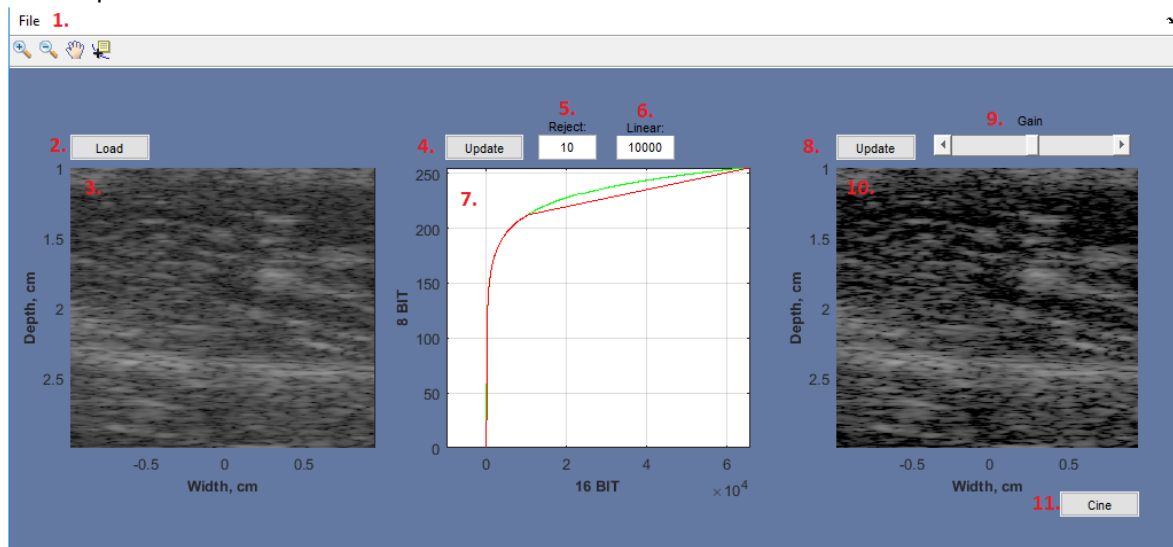


Fig. The example of implemented mixed dynamic range curve

### 6.1. Main window and controls

Figure below presents the front panel of the GUI together with numbered main components. The components of the GUI are described in the Table below.





Num	Component	Description
1	File selection menu and Interactive display tools	<div> <div>File</div> <div> Load RF data  Export log compressed image  Export result image as jpg  Export initial image as jpg </div> </div>

There are 4 options for File menu:

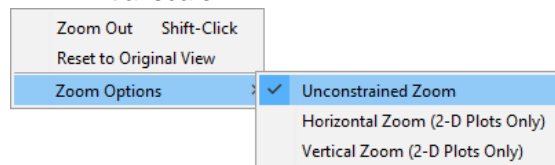
- Load RF data – imports selected RF data record into MATLAB workspace,
- Export log compressed image – exports 8 BIT image obtained applying dynamic range compression to \*.mat file. Exported file contains RF data matrix, header, transducer code, and 8 BIT image data,
- Export result image as ... – exports B mode image, obtained applying mixed compression curve, to graphics file (options: \*.jpg, \*.bmp, \*.tiff, \*.png),
- Export initial image as ... – exports B mode image, obtained applying purely logarithmic compression curve, to graphics file (options: \*.jpg, \*.bmp, \*.tiff, \*.png),



The controls which allow to interactively control the plotted data in figure axes:

- Zoom in 
- Zoom out 

There are few Zoom Options:

- Unconstrained Zoom – default zoom,
- Horizontal Zoom (2-D Plots Only) – zoom changes only in horizontal direction,
- Vertical Zoom (2-D Plots Only) – zoom changes only in vertical direction,
- Reset to Original View – changes magnification to initial scale.



- Pan  – turns on mouse-based panning for axes in the current figure,
- Data Cursor  – enable you to read data directly from a graph by displaying the values of points you select on plotted lines.

2	<b>Load button</b>	Loads RF data from file, updates B mode imaging window and shows the B mode image obtained on the basis of RF data.
3	<b>B mode imaging window</b>	Draws a pseudocolor plot of gray scale B mode image part captured in an RF window build from collected RF signals of the selected scanning sub-frame. Displayed image is obtained applying classical logarithmic compression curve.
4	<b>Update button</b>	Confirms selected parameters for mixed dynamic range reduction curve and updates the displayed curves in axes.
5	<b>Reject part</b>	Adjust the first part of the mixed curve. <i>Reject</i> parameter corresponds number of values to be assigned as zero.
6	<b>Linear part</b>	Adjust the proportion between second and third parts of the mixed curve. <i>Linear</i> parameter corresponds the start value of linear part of the curve.
7	<b>Plot dynamic range reduction curves</b>	Displays curves obtained calculating classical logarithm (green) and mixing 3 parts (red).
8	<b>Update button</b>	Updates the image displayed in axes below (GUI component 10).
9	<b>Digital gain control</b>	Slider adjusts the level of digital amplification of RF signals before envelope detection and dynamic range compression.
10	<b>B mode imaging</b>	Draws a pseudocolor plot of gray scale B mode image part captured

	<b>window (result)</b>	in an RF window build from collected RF signals of the selected scanning sub-frame. Displayed image is obtained applying mixed compression curve, which consists of three parts.
<b>11</b>	<b>Cine button</b>	Shows and exports as *.avi the sequence of B mode images obtained using mixed dynamic range reduction curve.

## 6.2. Recommended sequence of actions

The procedure how to use interface could be divided into following steps:

- **Load RF data** (File=>Load RF data and press Load button). At first RF data record should be selected and loaded into workspace for further processing. There are two options: 1) load \*.bin file recorded by using ArtUS scanner and relevant software, or to load 2) \*.mat file which contains RF data of single frame.
- **Adjust** the parameters (*Reject* and *Linear*) of mixed dynamic range compression curve and press "Update" button (4 GUI component).
- **Display** B mode image obtained using adjusted dynamic range curve by pressing "Update" button (8 GUI component).

## 7. RF data tool for post processing

GUI **post\_processing** (`post_processing.m`, `post_processing.exe`) allows to filter scan converted ultrasound image with aim to reduce speckle noise presence. GUI contains two filters (anisotropic diffusion and Wiener) which remove speckle noise. Both these filters smooth the image, but skip the edges. Anisotropic diffusion filter could be expressed by the following equation:

$$I_{i,j}^{t+1} = I_{i,j}^t + \Delta t [c_N \cdot \nabla_N I + c_S \cdot \nabla_S I + c_E \cdot \nabla_E I + c_W \cdot \nabla_W I + c_{NE} \cdot \nabla_{NE} I + c_{SE} \cdot \nabla_{SE} I + c_{NW} \cdot \nabla_{NW} I + c_{SW} \cdot \nabla_{SW} I]_{i,j}^t,$$

where  $0 \leq \Delta t \leq \frac{1}{4}$  constant for numerical scheme to be stable,  $\nabla I$  – nearest neighbour difference in the predefined direction,  $N, S, E, W$  – north, south, east and west directions,  $t$  – iteration number,  $c$  – the conduction coefficient. In general  $c$  could be expressed as follows:

$$c(\nabla I) = \frac{1}{1 + \left(\frac{\|\nabla I\|}{\kappa}\right)^2},$$

where  $\kappa$  – constant which controls the sensitivity to edges and is usually chosen experimentally.

Wiener filter has a general form:

$$f_{i,j} = \bar{g} + k_{i,j}(g_{i,j} - \bar{g}),$$

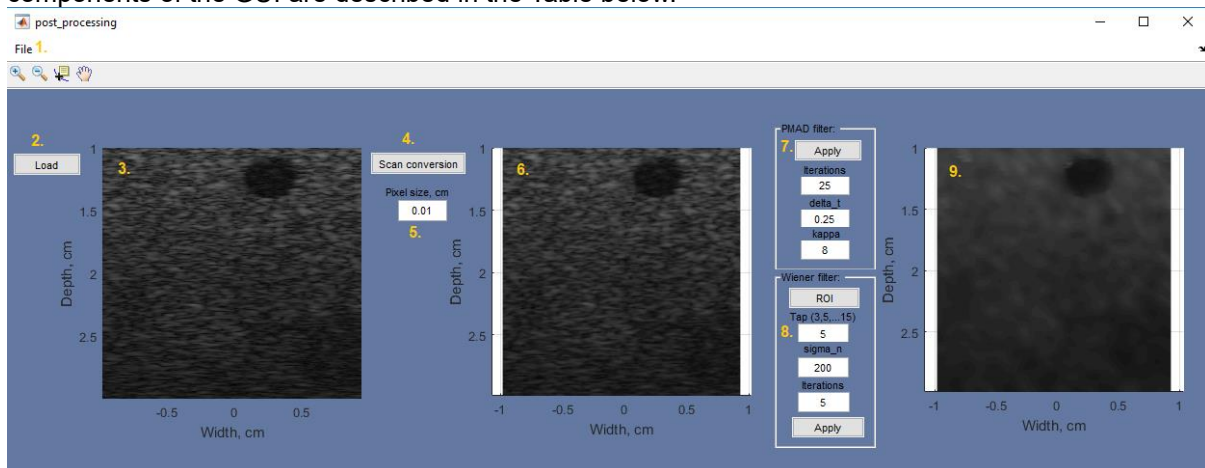
where  $f_{i,j}$  – noise-free pixel,  $g_{i,j}$  – noisy pixel value in the moving window,  $\bar{g}$  – local mean value in a moving window (size  $N \times N$ ),  $k_{i,j}$  – is a weighting coefficient  $k \in [0, 1]$ . The coefficient is a function of the local statistics in a moving window and is defined as:

$$k_{i,j} = \frac{\sigma^2}{\sigma^2 + \sigma_n^2},$$

where  $\sigma^2$  – variance in a moving window (size  $N \times N$ ) and  $\sigma_n^2$  – reference noise variance (could be estimated taking the variance of region in a noisy background of the image).

### 7.1 Main window and controls

Figure below presents the front panel of the GUI together with numbered main components. The components of the GUI are described in the Table below.





Num	Component	Description
1	File selection menu and Interactive display tools	<div>File</div> <div>Load RF data</div> <div>Export result image as...</div>

There are 2 options for File menu:

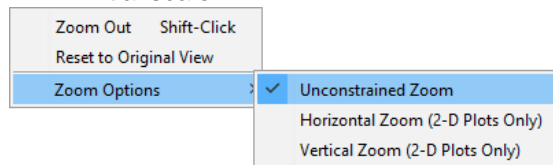
- Load RF data – imports selected RF data record into MATLAB workspace,
- Export result image as ... – exports B mode image, obtained applying speckle reduction filtering, to graphics file (options: \*.jpg, \*.bmp, \*.tiff, \*.png),



The controls which allow to interactively control the plotted data in figure axes:

- Zoom in 
- Zoom out 

There are few Zoom Options:

- Unconstrained Zoom – default zoom,
- Horizontal Zoom (2-D Plots Only) – zoom changes only in horizontal direction,
- Vertical Zoom (2-D Plots Only) – zoom changes only in vertical direction,
- Reset to Original View – changes magnification to initial scale.



- Pan  – turns on mouse-based panning for axes in the current figure,
- Data Cursor  – enable you to read data directly from a graph by displaying the values of points you select on plotted lines.

2	<b>Load button</b>	Loads RF data from file, updates B mode imaging window and shows the B mode image obtained on the basis of RF data.
3	<b>B mode imaging window</b>	Draws a pseudocolor plot of gray scale B mode image part captured in an RF window build from collected RF signals of the selected scanning sub-frame.
4	<b>Scan conversion button</b>	Performs scan conversion of obtained image data. Converts data to pixel-space. The conversion is performed applying bilinear interpolation.
5	<b>Pixel size</b>	Assigns pixel size for scan conversion.
6	<b>B mode imaging window (scan converted)</b>	Draws a pseudocolor plot of gray scale B mode image after scan conversion.
7	<b>PMAD filter</b>	Anisotropic diffusion filter (based on Perona and Malik paper) and its corresponding parameters: Iterations – number of filtering iterations, delta_t – constant in the range $0 \leq \Delta t \leq \frac{1}{4}$ , kappa – constant which controls the sensitivity to edges.
8	<b>Wiener filter</b>	Wiener filter based on local statistics of the image. Parameters of the filter: tap – size of filtering window (recommended in the 3 – 15 range), sigma_n – reference noise variance, Iterations – number of filtering iterations. Reference noise variance could be determined in two ways: 1) setting the parameter value in edit window, and 2) pressing <b>ROI button</b> and outlining the reference region in image

		background (the image for the selection is displayed in second axes).
<b>9</b>	<b>B mode imaging window (filtered)</b>	Draws a pseudocolor plot of gray scale B mode image after speckle filtering by using one of the proposed filters (anisotropic diffusion or Wiener).

## 7.2 Recommended sequence of actions

The procedure how to use interface could be divided into following steps:

- **Load RF data** (File=>Load RF data and press **Load** button). At first RF data record should be selected and loaded into workspace for further processing.
- Obtain scan converted image by setting pixel size and pressing “**Scan conversion**” button. The image is mapped to pixel space by applying bilinear interpolation.
- **Filter** the image by using one of the filters (Anisotropic diffusion or Wiener). **Adjust** the parameters of a filter and press “Apply” button. Filtered image will be displayed in the axes (9 GUI component).



## 8. References

- [1] Echo Blaster 64, Echo Blaster 128, LS64, LS128, ClarUs, SmartUs, MicrUs and ArtUs Series Ultrasound Systems Ultrasonography for Windows II Software Development Kit (Usgfw2 SDK) Programmer's Guide, (main sub-section – 4.9).
- [2] USG For Windows, Reference Manual, Revision 1.2. Sub-section 5.5. Getting ultrasonic transducer surface radius.
- [3] M. Ali, D. Magee, U. Dasgupta. Signal Processing Overview of Ultrasound Systems for Medical Imaging. Texas instruments, White Paper. P. 12, 2008.
- [4] Ping He. Simulation of Ultrasound Pulse Propagation in Lossy Media Obeying a Frequency Power Law. IEEE Transactions on ultrasonics ferroelectrics, and frequency control, Vol. 45, P. 114 – 125, NO. 1, JANUARY 1998.