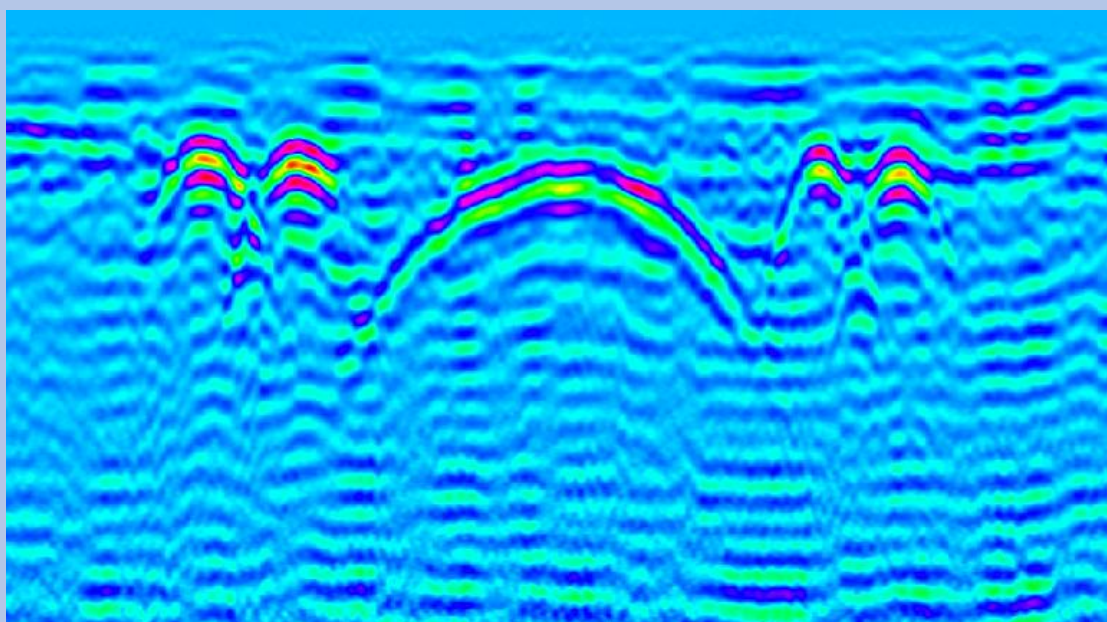


GPRLab: Ground Penetrating Radar Data Processing and Analysis Software User Manual



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1 Introduction

The software is an open-source and free software for Ground Penetrating Radar (GPR) data analysis and research. The software was developed using the MATLAB programming language and compiled with MATLAB R2020b. The software is named GPRlab because it is designed for GPR technology research, and it provides researchers with a laboratory to process, distribute, and visualize GPR data freely.

The software can read commercial software formats, such as dzt, rd3, DT1, and matrix arrangement GPR data. It can save processing workflows and processed data and transfer data to MATLAB's workspace. The software can display radar and waveform graphs, and it has complete data processing functions, such as DC removal, background removal, signal gain, mathematical operations, 1D filtering, 2D filtering, waveform analysis, and other algorithms. The software's image functions include saving images, zooming in and out of images, deleting data points, observing data points, and saving data points.

The software is free and cannot be used for commercial purposes. We also hope that you will not use it for research on offensive weapons. If you use the software in your research, please acknowledge that you used GPRlab to facilitate software sharing and dissemination. The ownership of GPRlab is the responsibility of Hongqiang Xiong, and if you encounter any difficulties in using the software, please contact the software author via email at 1014007697@qq.com.

2 Software Installation

We recommend installing this software as an APP in MATLAB, although GPRlab can also be installed as a standalone desktop software.

2.1 Installing GPRlab in MATLAB

(1) First, make sure that your computer has MATLAB R2020b or later versions installed.

(2) As shown in Figure 2.1, open MATLAB, enter the APP module, click Install App, and select the GPRlab.mlappinstall we provide.

(3) After installation, GPRlab will appear as an app in your MATLAB (as shown in Figure 2.2), click to use it.

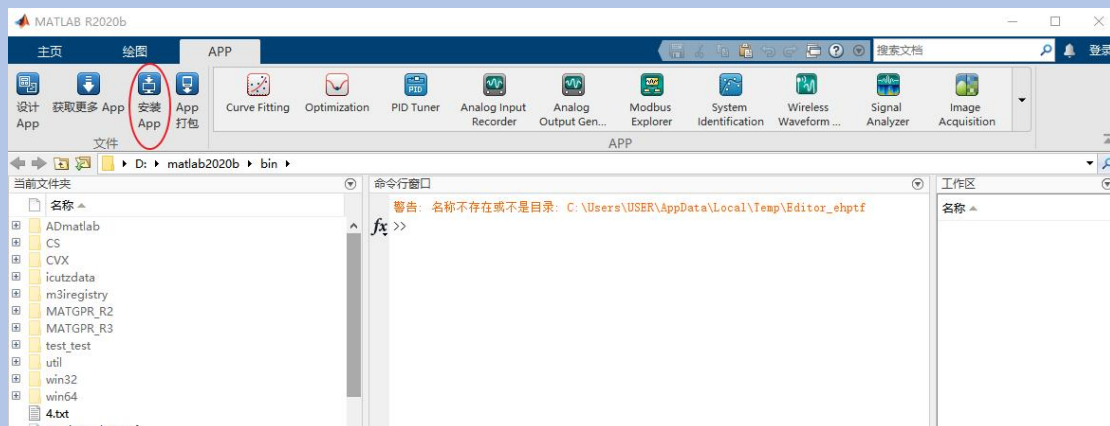


Figure 2.1 Installing GPRlab in MATLAB

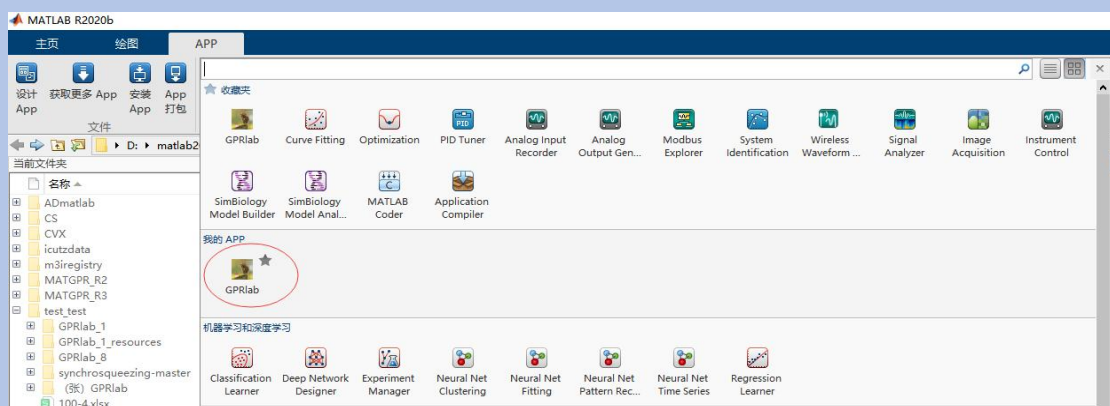


Figure 2.2 GPRlab installed in MATLAB

2.2 Standalone desktop software"

if you already have MATLAB R2020b or later version installed on your computer, you can directly open the **exe/for_redistribution_files_only** and click on **GPRLab.exe** to run GPRLab or create a shortcut of GPRLab.exe on your desktop.

If you do not have MATLAB R2020b or later version installed on your computer, you can install GPRLab using the installation program **MyAppInstaller_mcr.exe** located in the **exe/for_redistribution**.

Note: We recommend that you use the installation method provided in section 2.1. The standalone desktop software is not a recommended option as it may encounter some unknown issues.

2.3 Uninstall GPRLab

If GPRLab is installed as an APP in MATLAB, you can right-click on it in the MATLAB APP module and select "Uninstall". If GPRLab is installed as a standalone desktop software, the uninstallation method is the same as any other desktop software.

3 software interface

The software interface is shown in Figure 3.1. The top of the software is the menu bar, which contains all the algorithms provided by GPRlab. Below the menu bar are three module windows provided by this software:

- (1) The Data module, which is used for GPR data reading and parameter settings.
- (2) The Image Processing module, which is used for GPR data processing.
- (3) The Wave module, which is used for GPR waveform analysis, which can be used to analyze the spectrum of a single signal.

(4) Time-frequency analysis module, which is used for analyzing the time-frequency spectrum and synchronous compression spectrum of a A-Scan.

After reading the data and setting the parameters in the Data module, you can switch to the Image Processing and Wave modules to process and analyze the data.

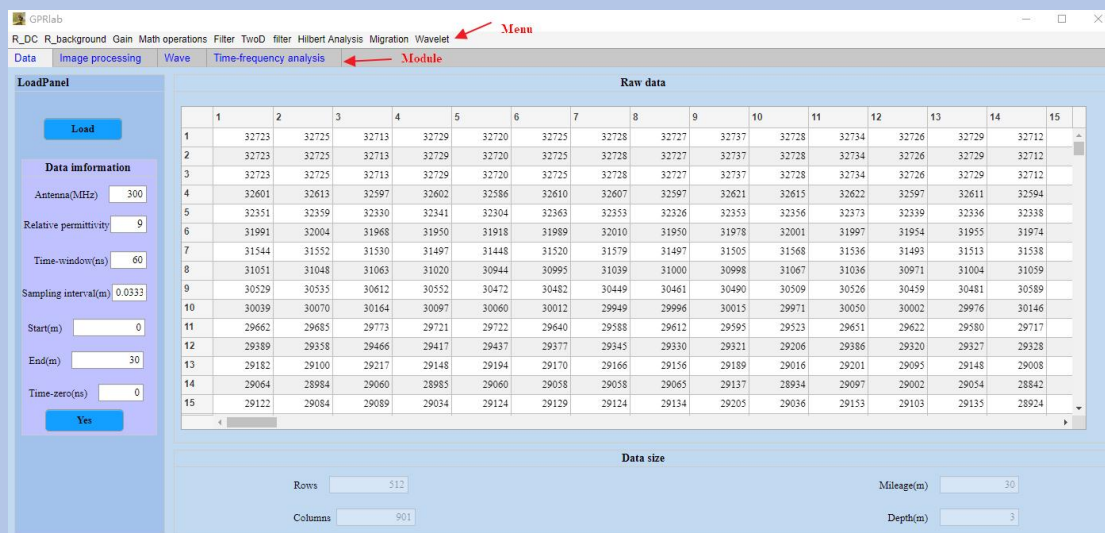


Figure 3.1 GPRlab interface

4 Data module

The Data module is used to load data and set parameters.

4.1 Reading in data

When GPRlab reads in single-channel DZT or dzt files (GSSI devices), the time window in the file header will be loaded.

When GPRlab reads in single-channel rd3 files (MALA devices), the header file rd needs to be placed in the same directory as the data, and the time window in the header file will be loaded.

When GPRlab reads in single-channel DT1 files (EKKO devices), the header file HD needs to be placed in the same directory as the data, and the time window in the header file will be loaded.

For matrix-arranged data (such as a 512x1600 B-Scan shown in Figure 4.1), it can be directly read in. Supported formats include: txt, dat or csv (for text files with delimiters); xls, xlsb, xlsx, xltm, xlsx or ods (for spreadsheet files). The speed of reading data matrices in different formats varies, with txt, dat, and csv being the fastest, and electronic spreadsheet formats being generally slower. It is recommended to use csv files because they can be opened with Excel and the data can be directly viewed.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	30945	30982	30934	30960	30989	30975	30955	30957	30970	30973	30932	30951	30906	30944
2	29813	29865	29873	29838	29828	29834	29846	29805	29865	29845	29875	29788	29833	29847
3	27531	27435	27506	27441	27466	27444	27446	27513	27524	27480	27544	27558	27497	27464
4	24479	24533	24488	24528	24531	24537	24480	24550	24533	24514	24538	24510	24486	24516
5	22974	22954	22960	22947	22956	22937	22898	22955	22942	22973	22977	22936	22939	22935
6	24740	24626	24642	24721	24650	24660	24695	24668	24569	24639	24499	24645	24743	24649
7	29515	29211	29402	29393	29392	29353	29365	29350	29344	29403	29297	29437	29368	29307
8	35023	34869	34928	35044	34917	35025	35049	35028	35014	34976	35026	34957	35038	34954
9	39634	39519	39574	39644	39605	39563	39627	39554	39533	39574	39568	39501	39568	39615
10	43000	42987	43049	42998	43026	43063	43000	42944	42952	42996	42975	42942	42936	42980
11	46055	46013	46097	46048	46067	46078	46032	46046	46003	46026	46037	46014	45957	45999
12	48962	48977	48992	48927	48988	48899	48920	48875	48910	48912	48915	48907	48798	48895
13	51021	51013	51031	51018	51016	50994	50978	51002	50982	51028	51003	51016	51011	50954
14	51026	51017	51038	51024	51030	51040	50971	51003	51045	51040	51060	51002	51019	51035
15	49077	48991	48922	48968	48977	48907	48992	49004	48944	48986	48943	48949	48948	49095
16	44895	44968	44799	44860	44994	44759	44863	44899	44936	45081	44804	44999	44919	44955
17	39470	39536	39527	39498	39465	39479	39438	39649	39509	39525	39495	39483	39418	39559
18	33751	33804	33900	33753	33824	33762	33821	33833	33813	33915	33716	33756	33749	33892
19	28512	28558	28698	28611	28536	28594	28628	28445	28628	28637	28525	28621	28491	28649
20	24285	24391	24379	24401	24365	24471	24403	24307	24433	24365	24414	24352	24314	24392

Figure 4.1 Matrix arranged data

When loading data, click the "Load" button. Loading large amounts of data may take some time. Once the "success!" dialog box pops up, the data loading is complete. After successful data loading, the values of the data can be viewed in the Raw Data panel on the right-hand side. As shown in Figure 4.2, we have loaded a file named "test.dzt".

Figure 4.2 Read in data

4.2 Data parameter setting

Setting parameters for GPR data is important because subsequent data processing algorithms may use the parameters set. After reading in the data, GPRlab must set the parameters in the Data information panel. The Data information panel includes the

following parameters:

Antenna frequency (required);

Relative permittivity (required);

Time window (required);

Sampling interval (if the data is evenly spaced, fill in the spacing; otherwise, set it to 0);

Start point (default is 0);

End point (default is 0).

If it is free acquisition (or time acquisition mode), please fill in the **Start** and **End** point positions, and set the spacing to 0. The software will automatically calculate the spacing after confirmation. If it is evenly spaced acquisition (or distance acquisition mode), set **End** to 0, and the software will automatically calculate the position of the end point.

Time zero position (the position of the zero point on the time window, default is 0).

If the data is in commercial software format, the software will automatically import the time window, and the user needs to set the other parameters. After filling in the parameters, click the "Yes" button to confirm. As shown in Figure 4.3, we have filled in the parameters for "test.dzt" (which was acquired in free acquisition mode).

a) LoadPanel

Load

Data information

Antenna(MHz) 300

Relative permittivity 9

Time-window(ns) 60

Sampling interval(m) 0

Start(m) 0

End(m) 30

Time-zero(ns) 0

Yes

b) LoadPanel

Load

Data information

Antenna(MHz) 300

Relative permittivity 9

Time-window(ns) 60

Sampling interval(m) 0.0053

Start(m) 0

End(m) 30

Time-zero(ns) 0

Yes

Figure 4.3 Parameter settings. a) after filling in the parameters and b) after confirming the parameters

When the parameter data is successfully set, a "Succeed!" dialog box will pop up, and the software's table below will display the size information of the loaded data, including: Rows, Columns, Mileage, and Depth. Figure 4.4 shows the results of setting the data loading and parameters for "test.DZT" in the Data module.

R_DC R_background Gain Math operations Filter TwoD filter Hilbert Analysis Migration Wavelet

Data Image processing Wave

LoadPanel

Load

Data information

Antenna(MHz) 300

Relative permittivity 9

Time-window(ns) 60

Sampling interval(m) 0.0053

Start(m) 0

End(m) 30

Time-zero(ns) 0

Yes

Raw data

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	32748	32734	32739	32739	32735	32731	32730	32732	32734	32735	32726	32721	32726	32722	
2	32748	32734	32739	32739	32735	32731	32730	32732	32734	32735	32726	32721	32726	32722	
3	32748	32734	32739	32739	32735	32731	32730	32732	32734	32735	32726	32721	32726	32722	
4	32641	32622	32626	32627	32620	32621	32624	32612	32623	32627	32617	32609	32611	32603	
5	32408	32381	32389	32389	32379	32383	32390	32368	32385	32399	32375	32375	32359	32360	
6	32035	32011	32021	32024	32025	32019	32030	32016	32014	32031	31996	32016	31981	32004	
7	31567	31568	31585	31576	31598	31583	31600	31568	31524	31561	31548	31558	31520	31557	
8	31036	31056	31057	31052	31104	31080	31078	31046	30990	31045	31063	31062	31032	31063	
9	30510	30521	30476	30481	30547	30537	30535	30521	30487	30540	30568	30576	30564	30558	
10	30003	30028	29961	29959	30020	30004	29999	30017	30038	30080	30092	30098	30083	30036	
11	29604	29653	29593	29562	29576	29530	29509	29557	29628	29669	29663	29667	29636	29585	
12	29370	29374	29348	29286	29279	29149	29153	29235	29325	29372	29341	29346	29278	29256	
13	29207	29151	29149	29089	29091	28920	28973	29064	29143	29161	29081	29069	28991	28992	
14	29108	29018	29028	28974	28984	28834	28915	28968	29052	29035	28946	28895	28839	28862	
15	29143	29057	29075	29032	29041	28949	29026	29030	29108	29065	29003	28934	28908	28949	

Data size

Rows 512

Columns 5607

Mileage(m) 30

Depth(m) 3

Figure 4.4 Data module is set successfully

5 Image processing module—GPR data processing

The Image processing module (as shown in Figure 5.1) is used to process GPR data. After reading the data and corresponding parameters in the Data module, the right-hand side of the Image processing module will display an image of the original data, with Time and Depth on the left and right y-axes, and Mileage on the x-axis, showing the entire profile. The lower part of the image area displays the display settings and data saving options. On the left side of the image are the data processing flowchart and data processing adjustment buttons.

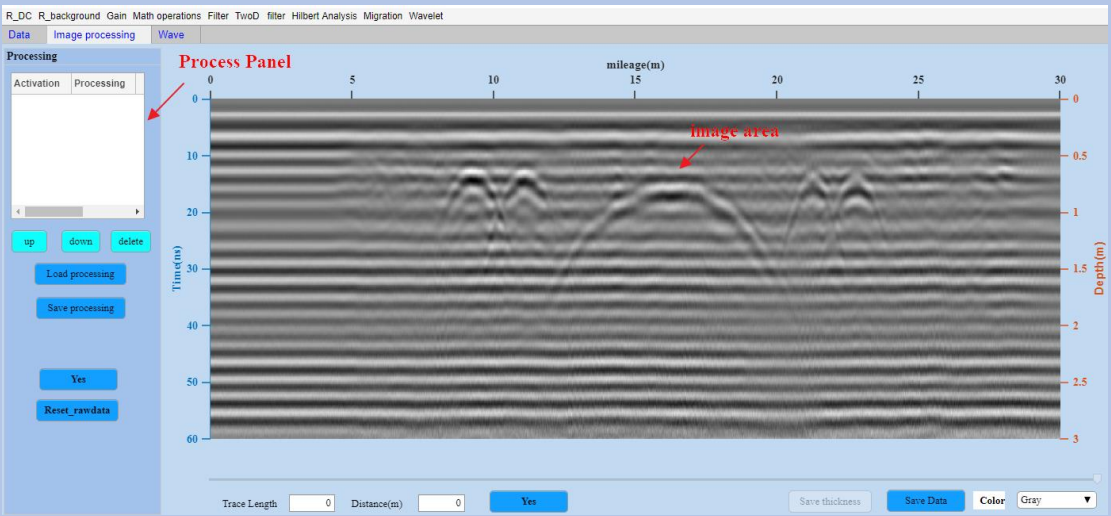


Figure 5.1 Image processing module

5.1 Data flow table

The data processing flowchart in the Image processing module saves the processing steps and corresponding parameters. Each processing flow will occupy one row in the chart. The flowchart will display the algorithms added by the user.

The first column of each row in the flowchart is "Activation," which will be

assigned a value of 1 when a processing flow is added, indicating that the flow is activated. The second column of each row is "Processing" (the processing algorithm), and the subsequent columns are the parameters corresponding to the processing algorithm. Users can select a certain algorithm and use the "up," "down," and "delete" buttons to change the order of the processing algorithm in the flowchart. After setting up the flowchart, click the "Yes" button, and the data will be processed. After waiting for a period of time, the processed data will be displayed in the image area on the right-hand side. As shown in Figure 5.2, we have simply added three processing flows to process "test.DZT".

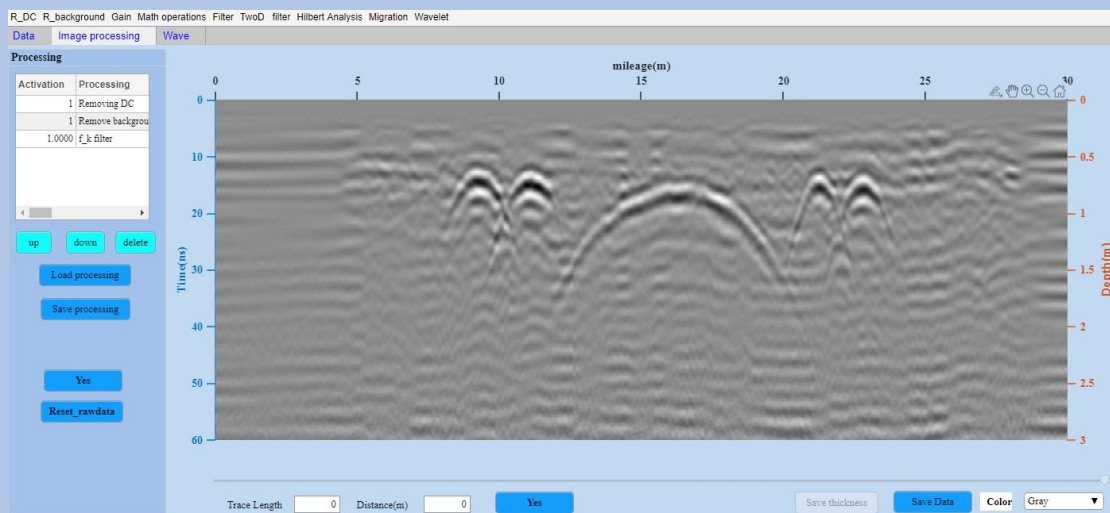


Figure 5.2 Processing test.DZT

5.2 Process flow operations

The operation of the processing flow mainly includes moving the position of the processing flow, and saving and loading the processing flow. After selecting a certain flow, the algorithm execution steps can be adjusted by moving the flow up or down.

The "up" button moves the selected flow up;

The "down" button moves the selected flow down;

The "delete" button deletes the selected flow;

"Save processing" saves the processing flow in the current processing chart, with

formats such as txt, csv, xlsx, xls, and dat. We recommend saving it in csv format for easy opening with office software. An example of a saved flow is shown in Figure 5.3.

"Load processing" loads an existing processing flow.

The "Reset_rowdata" button resets the processed data to the original data. After clicking this button, the data in the image area will be reset to the entire profile of the original data. This button makes it very convenient for using GPRLab.

The "Yes" button applies the algorithms in the processing flowchart to process the original data.

	A	B	C	D	E	F	G	H	I	J	K
1		1 Removing DC	0	0	0	0	0	0	0	0	0
2		1 Remove background	1	200	0	0	0	0	0	0	0
3		1 f_k filter	10	0.2	0	0	0	0	0	0	0
4											
5											

Figure 5.3 Saved process

Note: If the user installs the app in Matlab, the processed data and original data will be directly transferred to the Matlab workspace and named Processing_data and Raw_data.

5.3 Image Setting and Data Saving

The image defaults to a grayscale image displaying the entire profile. The buttons in the lower part of the image area can be used to set the color and profile length of the image display, where:

"Trace Length" determines how many traces are displayed in one image and is associated with "Distance."

"Distance (m)" determines the length of the profile displayed in one image and is associated with "Trace Length."

"Yes" confirms the size of the displayed image.

"Contrast" adjusts image contrast.

"Color" sets the color mode. GPRlab provides five color modes: Gray, Parula, Turbo, Jet, and HSV.

"Save Data" saves the processed data in txt, csv, xlsx, or dat format.

After clicking the "Yes" button, the slider below the image will be activated. In addition, clicking the image area once allows you to use the left and right arrow keys on the keyboard to scroll the image, with one click scrolling one image distance. Figure 5.4 shows processed data using the HSV color mode, and Figure 5.5 shows an image with 1000 traces displayed.

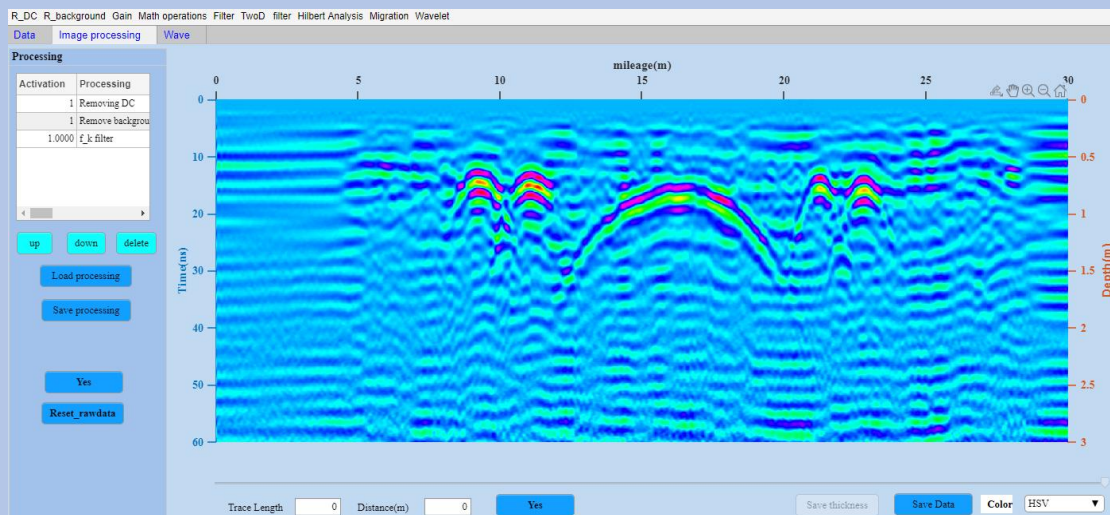


Figure 5.4 HSV display data

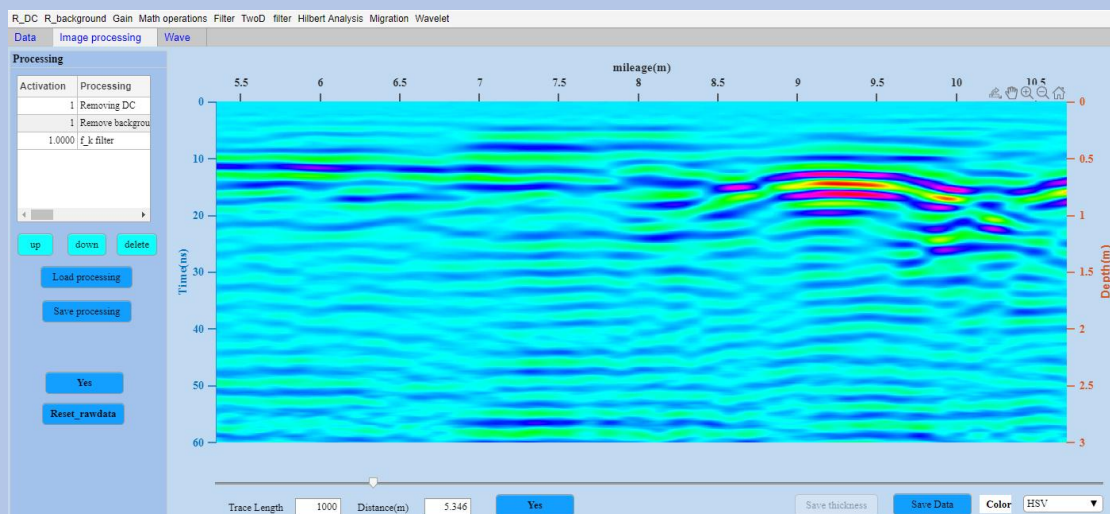


Figure 5.5 1000 channels show the results in each picture

Note: You can use the "Reset_rowdata" button to reset the image display to show the entire profile.

6 Processing algorithm in menu—Function

6.1 R_DC

In general, the amplitude of the GPR echoes should be symmetrically distributed about the mean value. However, due to the instability of the receiver circuit, some DC offsets may be displayed. The DC offset is a physical phenomenon related to the structure and composition of the sampling gate. DC removal means removing the DC component of the signal. When the waveform is shifted from the zero baseline, it is adjusted to the zero baseline, as shown in Figure 6.1. The algorithm formula for DC removal is:

$$u_{x,t}^* = u_{x,t} - \frac{1}{N} \sum_{i=0}^{N-1} u_{x,t+i} \quad (0-1)$$

In the formula, $u_{x,t}^*$ represents the signal after DC removal, and $u_{x,t}$ represents the signal before DC removal.

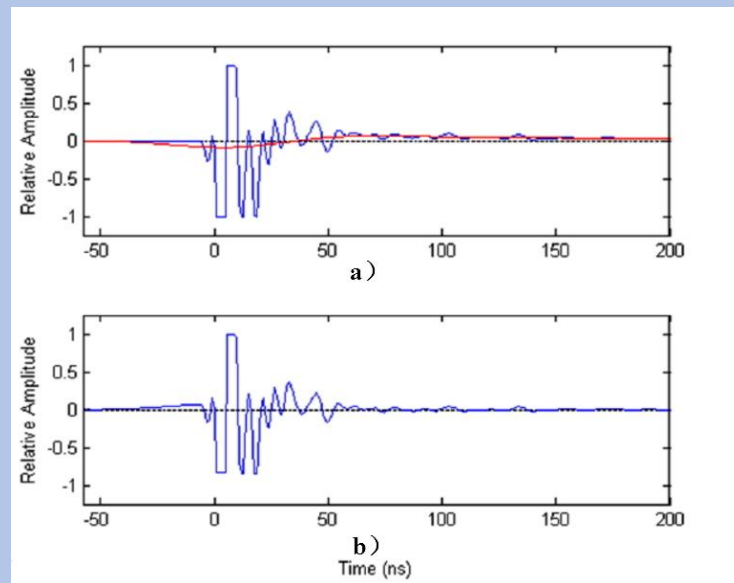


Figure 6.1 a) before removing DC and b) after removing DC

6.2 R_background

As shown in Figure 6.2, GPRlab provides four ways to remove the background: Remove background, SVD, Dynamic window background, and Remove file.

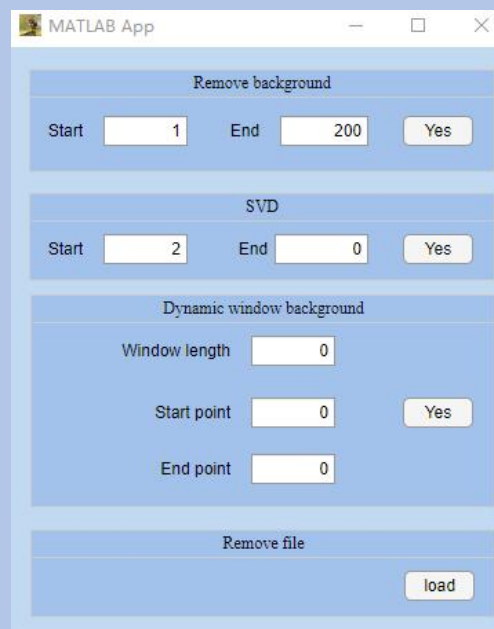


Figure 6.2 R_background

6.2.1 Remove background

The "Remove background" method selects the average of a portion of the profile as the background value for each trace. Set the starting and ending traces for the background. This is the most commonly used method. If the average of the entire profile is used as the background, set Start = 1 and End to the total number of traces in the entire profile. Note: End must be greater than Start.

6.2.2 SVD

The SVD method uses singular value decomposition to remove the background. This is a background removal method that uses principal component analysis (PCA). SVD decomposes GPR data into N (sample number, for example 512 or 1024) components, with the first few components being the main information, decreasing in magnitude. The components before Start are discarded, and the components after End are discarded. Generally, Start should be greater than or equal to 2 but not exceed 5. End is recommended to be set to 0 by default.

In simple terms, the main component is the strong background component. Therefore, discarding the components is equivalent to removing the background of the data. The specific mathematical process can be found by the user, and is not detailed in this manual.

6.2.3 Dynamic window background

The Dynamic window background method removes the background by selecting the average value of the surrounding traces as the background for each trace. This is equivalent to using a sliding window to remove the background of the data. This method is mainly used for high-frequency antennas or when there are many horizontal target anomalies and other background removal methods are not suitable. For example,

when detecting steel bars, this method can be used. Note that this method will also eliminate stratigraphic information.

Window length: The size of the sliding window.

Start point: The starting sample point to be processed. If this method is applied to the entire trace, Start point = 1.

End point: The ending sample point to be processed. If this method is applied to the entire trace, End point = N (number of sample points).

6.2.4 Remove file

The Remove file method removes the background by loading a background data file. The background can be read in the same format as the data, and is a single trace data. This processing method is suitable for special cases such as antenna testing, numerical simulation, and air-coupled antennas.

Note that when using this method, an external file is required. Therefore, if the saved processing flow contains this method, the saved processing flow will be invalid.

6.3 Gain

Gain is the process of amplifying data using a gain function curve. As shown in Figure 6.3, GPRlab provides five gain methods.

The figure shows a software interface for selecting a gain processing algorithm. It consists of five vertically stacked panels, each with a title bar and a 'Yes' button.

- Exponent gain:** Contains input fields for 'scale' (value: 1), 'start(times)' (value: 1), 'exponent' (value: 2), and 'end(times)' (value: 1000).
- Liner automatic gain:** Contains input fields for 'length' (value: 70) and 'Average value' (value: 3000).
- RMS automatic gain:** Contains an input field for 'length' (value: 40).
- GRMS automatic gain:** Contains an input field for 'length' (value: 40).
- Manual gain:** Contains input fields for 'points' (value: 1,512) and 'value(times)' (value: 1,100).

Figure 6.3 Gain

6.3.1 Exponent gain

Exponent gain is the process of multiplying the original signal by the corresponding exponential gain function. Therefore, the parameters are set to specify this gain function: $y = scale * x.^{exponent}$

scale: The multiplier before the exponential gain, cannot be 0.

exponent: The exponent, cannot be 0.

start: The multiplier for the starting sample point gain, cannot be 0.

end: The multiplier for the ending sample point gain, cannot be 0.

Note: The algorithm uses start and end to obtain the value of x.

6.3.2 Automatic gain

1) Liner Automatic gain

The Linear Automatic Gain method first calculates the average of the absolute amplitude value within a certain window range, and then calculates the gain value within the window based on the set "Average value", so that the average absolute amplitude value within the window reaches the set value. The size of the window is the parameter "length", and the smaller the window is selected, the smoother the gain curve will be. The selected window overlaps with the adjacent window as each trace data slides from the beginning to the end, and the overlap rate is 50%. The value of "length" is determined according to the number of sample points, and in general, it can be set to 1/7 of the total number of sample points.

2) RMS Automatic gain

The Root Mean Square Automatic Gain method calculates the root mean square value based on the current sample point and the gain window (with the current sample point as the center), and then divides the amplitude value of the current sample point by this root mean square value. The size of the window is the parameter "length", and the smaller the window, the stronger the constraint on high amplitude values, while the larger the window, the stronger the constraint on low amplitude values. "Length" is the number of sample points included in the window.

3) GRMS Automatic gain

The Gaussian-Root Mean Square Automatic Gain method calculates the square of the amplitude value based on the current sample point and the gain window (with the current sample point as the center), and then uses a Gaussian window for weighting to calculate the mean square value. Finally, the amplitude value of the current sample point is divided by this mean square value. The size of the window is

the parameter "length", and the smaller the window, the stronger the gain, while the larger the window, the weaker the gain. "Length" is the number of sample points included in the window.

6.3.3 Manual gain

The gain function of the Manual Gain method is a piecewise linear function. The breakpoint positions "points" and the corresponding gain multipliers "value" can be freely set by the user. The setting method is to use commas or spaces to separate them.

Note that the first and last sample points must be set in the array.

6.4 Math operations

As shown in Figure 6.4, the Math Operations function provides basic mathematical operations for each trace data, including addition, multiplication, absolute value, gradient, and square root.

The screenshot displays the 'Math Operations' menu with the following settings:

- Plus:** value Yes
- Multiplication:** times Yes
- Absolute:** times Yes
- Square:** times Yes
- Gradient:**
 - ☒ down ☐ up
 - scale points Yes

Figure 6.4 Math operations

6.4.1 Plus

The Plus function adds a specified value "value" to each sample data. This method can be used to adjust the size and contrast of the data.

6.4.2 Multiplication

The Multiplication function multiplies each sample data by a specified value "times" (which cannot be set as 0). This algorithm belongs to a type of gain method and adds a constant gain to the original data. This method can be used in conjunction with other mathematical operations.

6.4.3 Absolute

The Absolute function calculates the absolute value of each sample data and then multiplies it by "times" (which cannot be set as 0).

6.4.4 Gradient

In a trace data, the Subtract function subtracts the sample data at a certain distance ("points") from each sample data and then multiplies it by a coefficient "scale". The distance and coefficient can be freely set by the user and are denoted as r and a , respectively. The operation can be expressed as:

$$F(x) = scale(f(x) - f(x - points))$$

GPRLab provides gradient operations that can be performed in the upward or downward direction.

6.4.5 Square

The Square function calculates the square root of each sample data, and then multiplies it by a "times" parameter (which cannot be set as 0). This operation can weaken strong reflections and to some extent enhance weak reflections. After the operation, the amplitude differences of various reflection waves in the data are reduced, which can achieve the purpose of data balance.

6.5 Filter

As shown in Figure 6.5, GPRLab provides one-dimensional filtering, including vertical filtering, horizontal filtering, and deconvolution. The filtering methods mainly used are frequency domain filtering, FIR wavelet filtering, and IIR Chebyshev Type II filtering. The deconvolution method uses the predicted error deconvolution algorithm.

The figure shows a software interface for configuring filters. It is divided into three main sections:

- Vertical filtering:**
 - Radio buttons: ☒ Frequency domain filtering, ☐ FIR, ☐ IIR.
 - stop1(MHz): 150
 - pass1(MHz): 300
 - pass2(MHz): 600
 - stop2(MHz): 850
 - A "Yes" button is located to the right of the pass2 field.
- Horizontal filtering:**
 - Radio buttons: ☒ FIR, ☐ IIR.
 - stop1(1): 3
 - pass1(1): 5
 - pass2(1): 10
 - stop2(1): 15
 - A "Yes" button is located to the right of the pass2 field.
- Predictive deconvolution:**
 - Length(ns): 40
 - Lag(ns): 35
 - A "Yes" button is located to the right of the Lag field.

Figure 6.5 Filter

6.5.1 Vertical filtering

Vertical filtering refers to filtering the data in the time domain, which is a necessary step in GPR data processing. Filtering is the process of changing the relative sizes of various frequency components of a signal or completely eliminating certain frequency components. Commonly used filters are designed to pass certain frequencies without distortion, while significantly attenuating or eliminating other frequencies. The frequency range that passes without distortion is called the passband, and the frequency range that needs to be attenuated or eliminated is called the stopband. The lowest frequency in the passband is the low-pass frequency, and the highest frequency in the passband is the high-pass frequency.

In actual field measurements, in order to preserve as much information as possible, a full-band recording method is often used, so that the effective and interfering waves are recorded simultaneously. In order to remove interference signals from the data, filtering methods need to be used to eliminate interference waves based on the different frequency ranges of effective signals and interference signals in the data. If there is a clear boundary between the frequency spectra of the effective signal and the interference signal, the passband of the filter can be designed as the main frequency spectrum of the effective signal, and the interference noise band outside the signal band can be filtered out to obtain the filtered result. In data acquisition, for each trace data, a Fourier transform is first performed on it, and the spectral range between the low-pass frequency and the high-pass frequency, that is, the passband spectrum, is selected for inverse Fourier transform to obtain the filtered data.

Frequency domain filtering, also known as ideal frequency domain filtering, transforms the data to the frequency domain by FFT, multiplies it by a rectangular window, and then IFFT is used to obtain the filtered data. However, it should be noted that the rectangular window corresponds to a sinc function in the time domain, which extends infinitely. After adding the window in the frequency domain, the IDFT actually only takes a part of the main value. Therefore, when filtering, oscillations (high-frequency signals cannot directly become 0) will be formed at the beginning and end of the signal, causing distortion at the beginning and end positions of the signal. This has little effect on the vertical direction, but for the horizontal direction in the wave number domain, it will cause discontinuity and abrupt changes between the front and back images.

FIR, also known as finite impulse response filtering, is a filter type with a ripple equal to a wavelet, with a stopband attenuation of 40dB, a passband gain of 0dB, and a passband ripple limit of 1dB.

IIR, also known as infinite impulse response filtering, is a filter type of Chebyshev Type II, with a stopband attenuation of 40dB, a passband gain of 0dB, and

a passband ripple limit of 1dB.

In FIR and IIR filters, the stopband low frequency (stop1), passband low frequency (pass1), passband high frequency (pass2), and stopband high frequency (stop2) need to be set, as shown in Figure 6.6.

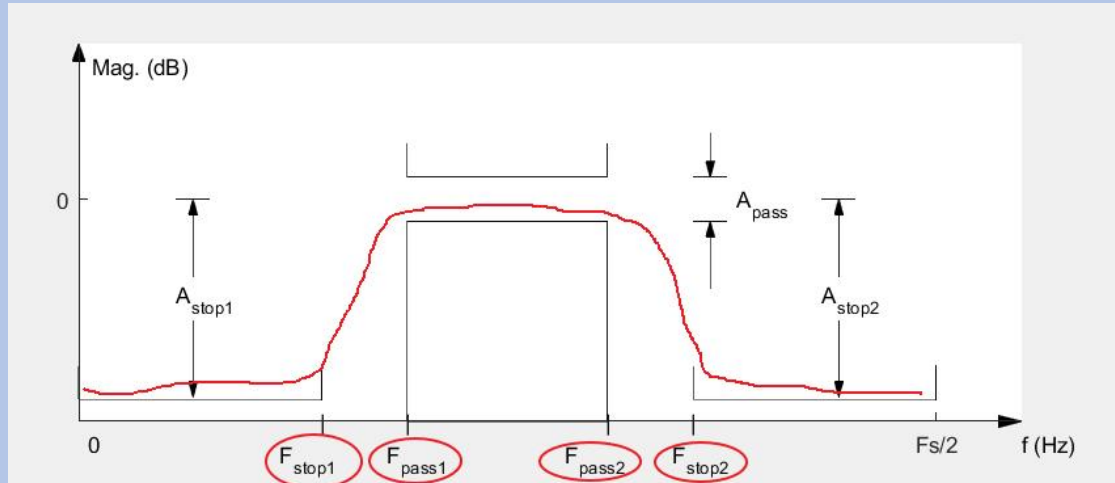


Figure 6.6 Schematic diagram of filtering parameters

6.5.2 Horizontal filtering

The filtering method is consistent with the previous section, with the direction being horizontal. The frequency in the wave number domain refers to the number of wavelengths per meter, with a maximum frequency value of 0.5/sampling interval. It should be noted that horizontal filtering often eliminates layer information and highlights horizontal changes. Users need to understand the meaning of the frequency in the horizontal direction in order to use this method proficiently.

6.5.3 Predictive deconvolution

The prediction error deconvolution is a vertical prediction filtering method provided by the Wiener filtering method. An operator length, Length, and a prediction step, Lag, need to be set. The operator length, Length, should be less than half of the

time window, and the Lag should be less than the operator length. When performing multiple wavelet filtering, Lag should be greater than the position of the first reflection in the time window. In general, Length can be set to three times the antenna's main frequency cycle. If there is strong horizontal interference in the data but some layer information needs to be preserved, this method can be used.

6.6 TwoD filter

Two-dimensional filtering is an operation performed on the entire two-dimensional data. GPRlab provides three filtering methods: mean filtering, median filtering, and f_k two-dimensional bandpass filtering, EMD and VMD filtering as shown in Figures 6.7.

The figure shows a MATLAB App window titled "MATLAB App" with a blue background. It contains four sections for different filtering methods:

- 2D filter:** Includes radio buttons for "median filter" (selected) and "mean filter". It has input fields for "rows" (5) and "columns" (5), and a "Yes" button.
- f_k filter:** Includes input fields for "Lg(m)" (40) and "Ls(m)" (0.2), and a "Yes" button.
- EMD:** Includes radio buttons for "Horizontal" (selected) and "vertical". It has input fields for "Start(imf)" (1) and "-End(imf)" (2), and a "Yes" button.
- VMD:** Includes radio buttons for "Horizontal" (selected) and "vertical". It has input fields for "Start(imf)" (1), "End(imf)" (4), and "Num(imf)" (5), and a "Yes" button.

Figure 6.7 TwoD filter median filter

This method views the GPR profile as a two-dimensional image and uses image processing ideas for filtering. In median filtering, the sampling value of each point is

sorted among all sampling points within a certain size neighborhood window, and the value in the middle is taken as the new sampling value for that point. Median filtering is a nonlinear signal processing technique based on sorted statistical theory, which is particularly effective for isolated noise points. The specific method is to use a "rows" x "columns" two-dimensional sliding template. For each data point, the center of the two-dimensional sliding template is placed on that point, and the sampling values within the template are sorted by size to generate a monotonically increasing (or decreasing) data sequence. The value at the middle position of the sequence is taken as the value for that point, and the final filtered data is obtained. This algorithm has a good effect on high-frequency random noise in the data, while preserving the details of the image to some extent.

6.6.1 mean filter

This method views the GPR profile as a two-dimensional image and uses image processing ideas for filtering. Mean filtering takes the average of all the sampling values within a certain size neighborhood window for each point's sampling value, and takes the average as the new sampling value for that point. The specific method is to use a "rows" x "columns" two-dimensional sliding template. For each data point, the center of the two-dimensional sliding template is placed on that point, and the sampling values within the template are averaged to obtain the average as the value for that point, and the final filtered data is obtained. This algorithm has a certain smoothing effect on the data, but it can also make the image blurry and lose details and contours. The larger the parameter setting, the better the smoothing effect, but the more blurred the image becomes.

6.6.2 F-k filter

F-k filtering is a typical two-dimensional filtering method that decomposes the image into the two-dimensional frequency domain through two-dimensional Fourier

transform and performs bandpass filtering in the two-dimensional frequency domain. Due to the characteristics of GPR echoes, clutter mainly manifests as changes in the horizontal direction. Therefore, bandpass filtering in the k -direction is generally used for filtering settings.

The filtering parameters are L_g (m) for the length of the low-frequency signal in the horizontal direction and L_s (m) for the maximum displacement of the system's micro-vibration. L_g represents the low-frequency part in the horizontal direction, which is generally selected near $1/2$ of the profile length. When L_s is unknown, a small value, such as 10 times the trace spacing, can be selected.

The F- k filtering method is similar to the horizontal filtering method and will suppress low-frequency information in the horizontal direction. This means that this algorithm will weaken multiple reflections and suppress low-frequency interference in the horizontal direction of the layer.

6.6.3 Empirical mode decomposition filter

EMD is a novel time-frequency analysis method that decomposes a signal into different hierarchical modal classifications called Intrinsic Mode Functions (IMFs). IMFs differ from the traditional trigonometric-based decomposition approach as they are not constructed using base functions. Instead, they represent the envelope components containing different time-scale features of the original signal. EMD first extracts IMF₁ and then decomposes it layer by layer until IMF _{n} , leaving a residual component. Therefore, shallow IMFs represent high-frequency variations, while deeper IMFs represent low-frequency variations. In the context of Ground Penetrating Radar (GPR), EMD can be applied in both horizontal and vertical directions for signal decomposition. In practical applications, we have observed that EMD performs better in horizontally filtering out multiple reflections compared to F- k filtering. This method requires the user to set three parameters:

Firstly, the user needs to choose either the horizontal (Horizontal) or the vertical

(Vertical) direction.

Start represents the starting IMF component to be retained. The value of Start cannot exceed 10.

-End represents the position of the ending IMF component to be retained, counting from the last IMF.

6.6.4 Variational modal decomposition Filter

VMD is an advanced method similar to EMD but with some notable differences. The IMFs obtained from VMD are signals with finite bandwidth, making the decomposition more well-defined compared to EMD, and it allows users to specify the number of IMFs. However, VMD's computational complexity is higher. When applying EMD and VMD methods, users need to understand the basic principles of both approaches. VMD requires the setting of four parameters:

Firstly, the user needs to choose either the horizontal (Horizontal) or the vertical (Vertical) direction.

Start represents the starting IMF component to be retained. The value of Start cannot exceed 10.

End represents the ending IMF component to be retained.

Num represents the number of IMFs to be obtained through VMD decomposition.

Note: VMD is typically more time-consuming, so it is recommended to first use EMD to test the signal processing performance and then replace it with the VMD method if necessary.

6.7 Hilbert Analysis

The A-scan of GPR is a real signal $x(t)$ that can be represented in polar coordinates:

$$x(t) = A(t) \cos \varphi(t) \quad (0-2)$$

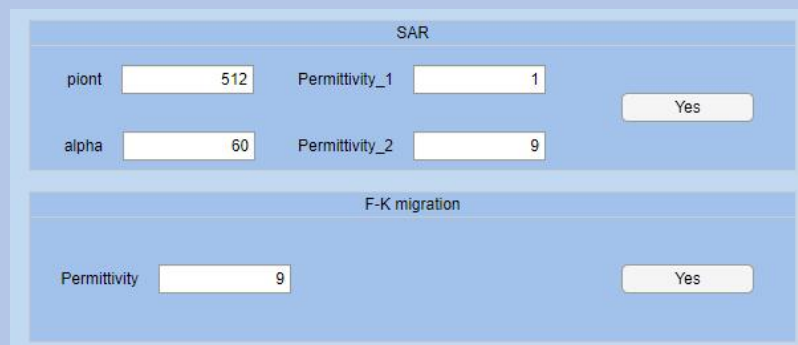
Where $A(t)$ represents the instantaneous change of the signal's envelope (instantaneous amplitude), $\varphi(t)$ represents the phase change of the signal (instantaneous phase), and $\varphi'(t)$ represents the frequency change of the signal (instantaneous frequency). The Hilbert Analysis is a method for obtaining these three instantaneous attributes. To obtain the instantaneous attributes, a Hilbert Analytic function needs to be constructed:

$$X(t) = x(t) + i\hat{x}(t) \quad (0-3)$$

Among them, $\hat{x}(t)$ represents the Hilbert transform of the signal. Based on the equation above, the instantaneous attributes can be calculated. GPRlab provides the calculation of Hilbert instantaneous amplitude, instantaneous phase, and instantaneous frequency without the need for input parameters.

6.8 Migration

As shown in Figure 6 8, Migration currently provides Synthetic Aperture Radar (SAR) and FK migration algorithms.



The screenshot shows a software interface for migration algorithms. It is divided into two main sections: 'SAR' and 'F-K migration'. The 'SAR' section contains four input fields: 'piont' with the value '512', 'Permittivity_1' with the value '1', 'alpha' with the value '60', and 'Permittivity_2' with the value '9'. A 'Yes' button is located to the right of these fields. The 'F-K migration' section contains one input field: 'Permittivity' with the value '9', and a 'Yes' button to its right.

Figure 6.1 Migration

6.8.1 SAR

GRPlab provides synthetic aperture focusing algorithm (SAR) for offset

processing, which can be used to collect data from both ground-coupled antennas and air-coupled antennas. This algorithm is similar to the time domain BP algorithm. In this method, the medium is divided into two layers for synthetic aperture focusing. The theoretical part of this method can be found in "Research on Synthetic Aperture Focusing Imaging of Vehicle-mounted GPR Data" by Hongqiang Xiong (2018). This method has good imaging effects and is not sensitive to parameters. This algorithm requires four input parameters.

Point: the number of sampling points at the layer interface. If you want to process ground-coupled antenna data with a homogeneous model, you can set it to the maximum sampling point number. For air-coupled antenna data, it should be set to the longitudinal sampling points corresponding to the target interface position. This parameter cannot be negative.

Alpha: antenna beam angle (in degrees). This value is the most important control parameter for the aperture length and should be set based on the antenna performance. With the performance requirements met, the smaller the value of this parameter, the smaller the edge effect. If the antenna beam angle is unknown, you can try different values to get the best image effect that can be used to infer the antenna beam angle. This parameter has a value range of (0, 360).

Permittivity_1: relative permittivity of the first layer medium. If it is air, it should be set to 1. This parameter has a value range of [1, 81].

Permittivity_2: relative permittivity of the second layer medium. If it is air, it should be set to 1. This parameter has a value range of [1, 81].

6.8.2 F-K migration

The algorithm allows for setting a uniform permittivity for the space. It can be used as a conventional method for offset processing.

6.9 Wavelet

According to Figure 6-9, this software includes 1D and 2D wavelet analysis tools, specifically including 1D discrete wavelet denoising, 2D discrete wavelet denoising, and 1D continuous wavelet filtering.

Figure 6.2 Wavelet OneD-dwt

The software uses the Sym4 wavelet for 1D discrete wavelet denoising.

6.9.1 TwoD-dwt

The software uses the Sym4 wavelet for 2D discrete wavelet denoising.

6.9.2 OneD-cwt

The software uses the Morse wavelet for 1D continuous wavelet (CWT) analysis and applies it to partial time windows and partial profiles within a given frequency range. This method is the opposite of bandpass filtering and removes signal components within the set frequency range, which is equivalent to removing in-band interference.

LF (MHz): the low-frequency cutoff of the frequency band to be removed;

HF (MHz): the high-frequency cutoff of the frequency band to be removed;

LT (ns): the start time;

HT (ns): the end time;

Start track: the trace position where the profile starts;

End track: the trace position where the profile ends.

7 Wave view—waveform analysis view

The Waveform Analysis view allows users to perform time-domain waveform analysis and spectrum analysis on the A-Scan of the ground-penetrating radar. This provides users with a more intuitive understanding of the changes in the raw data waveform and processed waveform. The waveform graph has functions such as direct zooming in and out, saving data, and displaying data point values.

7.1 waveform analysis

As shown in Figure 7-1, the Waveform Analysis view displays the time-domain signal waveform in the upper part and the half-spectrum (with a maximum frequency of $f_s/2$) in the lower part. The reason for displaying the half-spectrum is that the discrete Fourier transform (DFT) is symmetric. There are four types of waveform analysis supported:

Raw data: the original data, displayed as a green line;

Processed data: the processed data, displayed as a red line;

Background: the background data, which uses the mean background and is displayed as a black line;

Difference: the difference between the original data and the background data, displayed as a blue line.

Before displaying the waveform, the following parameters need to be set:

Track number: which track to observe specifically;

Background start: the start track of the background data;

Background end: the end track of the background data;

DC+YES: whether to keep the DC component in the spectrum graph;

DC+No: whether to remove the DC component in the spectrum graph.

Note: considering whether to keep the DC component is because the original data and background data may have a large relative DC value, which makes the other parts of the spectrum weak in comparison. Here, it is recommended to choose "No". GPRlab can not only analyze the waveform data but also save the waveform and spectrum data in the same format as other data

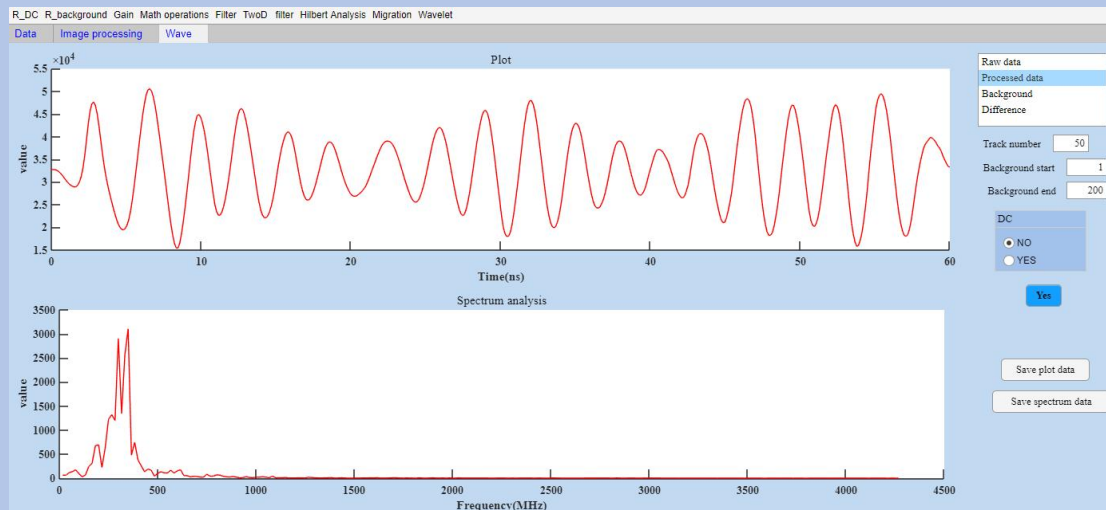


Figure 7.1 Wave module

7.2 Waveform operation

GPRlab provides various interactive operations for the waveform graph. When the mouse is placed on the corresponding waveform or spectrum graph, the operation options will appear in the upper right corner, which can be used to select saving, brightening, reducing, and zooming. Brightening means that a portion of the points on the image can be brightened, as shown in Figure 7-2:

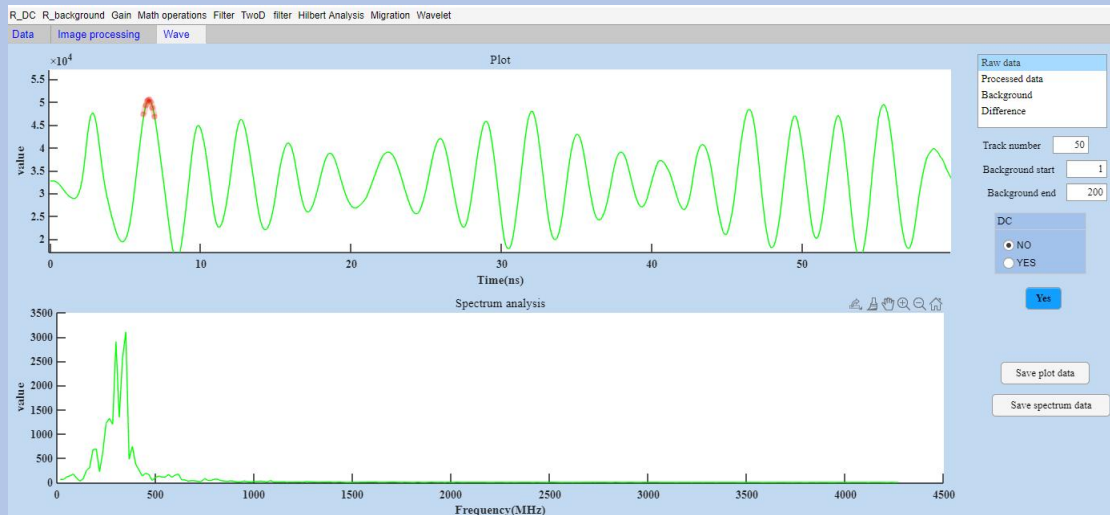


Figure 7.2 Brush data

After brightening the image, right-clicking on the image will bring up the Properties dialog box, and you can also perform operations such as copying, replacing, and deleting data. Clicking on a small gray dot directly on the waveform graph with the mouse will display the coordinates of that point in a small box, which can be moved up, down, left, and right with the mouse, as shown in Figure 7-3.

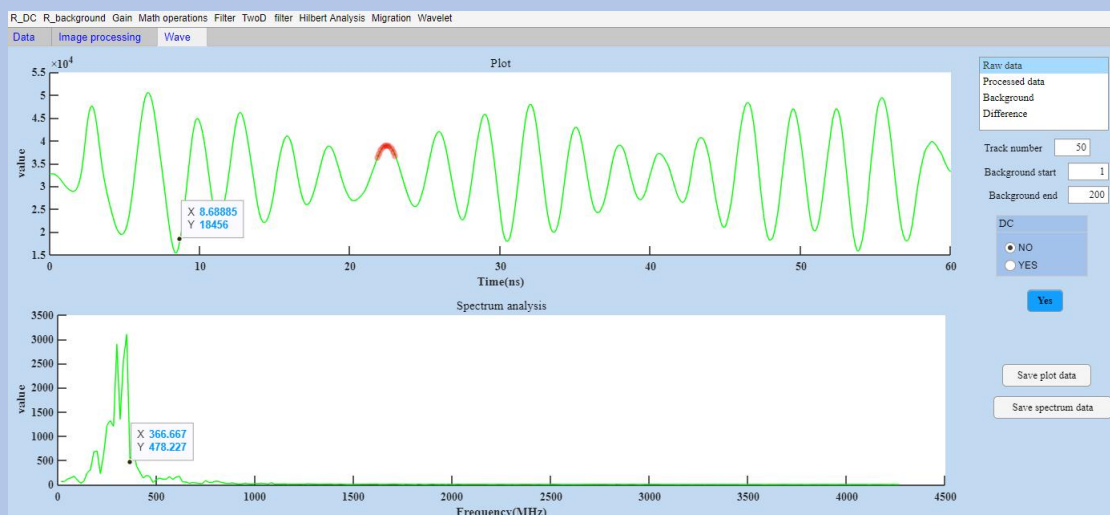


Figure 7.3 Display data

8 Time-frequency analysis view—time-frequency analysis

Time-frequency analysis view can be used for conducting time-frequency analysis on GPR A-Scan data. The basic settings for this view are consistent with the Wave view. In the view, we provide two methods for time-frequency analysis: Generalized Phase-shifting S-Transform (GPST) as the conventional approach and Synchrosqueezing Generalized Phase-shifting S-Transform (SSGPST) as its high-resolution counterpart in the synchronous compressed domain.

GPST and SSGPST are newly proposed time-frequency analysis methods that can be regarded as variations of ST (S Transform) and SSST (Synchrosqueezing S Transform), or CWT (Continuous Wavelet Transform) and SS-CWT (Synchrosqueezing Wavelet Transform), respectively. Users can make use of their experience with publicly available ST, SSST, CWT and SS-CWT to adjust the settings for the Time-frequency analysis view. The parameters that need to be set include:

Num_Fpoints: The number of frequency points to be retained ($< \text{sampling points}/2$).

General parameter: This parameter allows users to adjust the behavior of the time-frequency analysis method based on their specific requirements.

Figure 8.1 shows the Time–frequency analysis results of the 500th trace data.

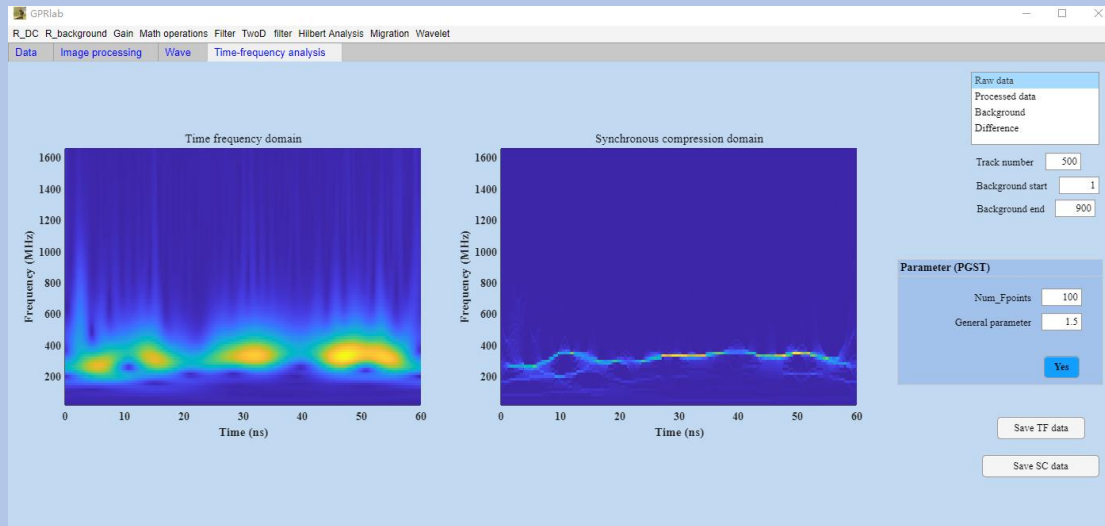


图 8.1 Time-frequency analysis

Figure 8.2 shows the time-frequency plot when the reserved frequency point is 200. The data is sampled 512 times.

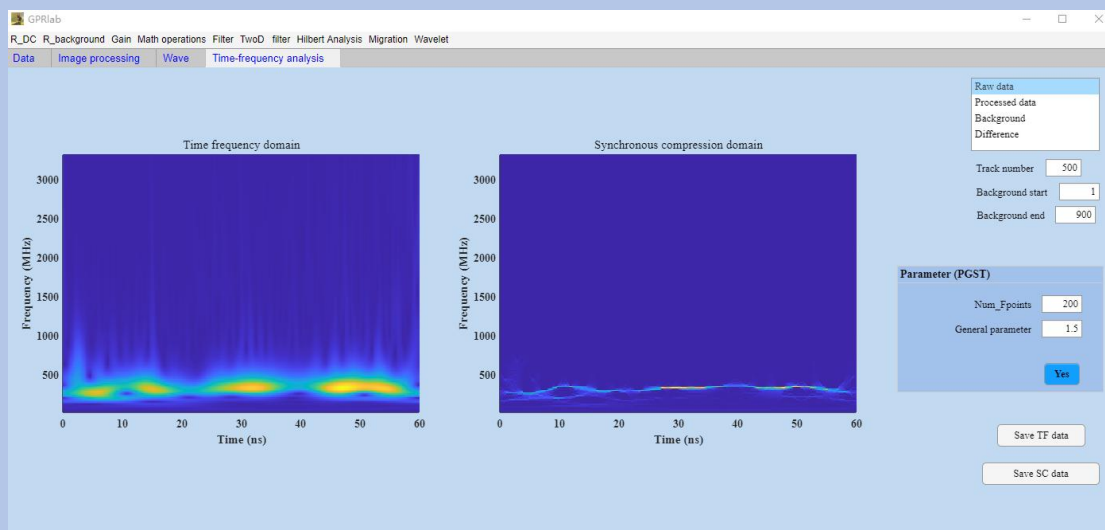


图 8.2 Num_Fpoints = 200

As shown in the time-frequency plot Figure 8.3 when General parameter=0.6. It can be observed that the temporal resolution increases while the frequency resolution decreases.

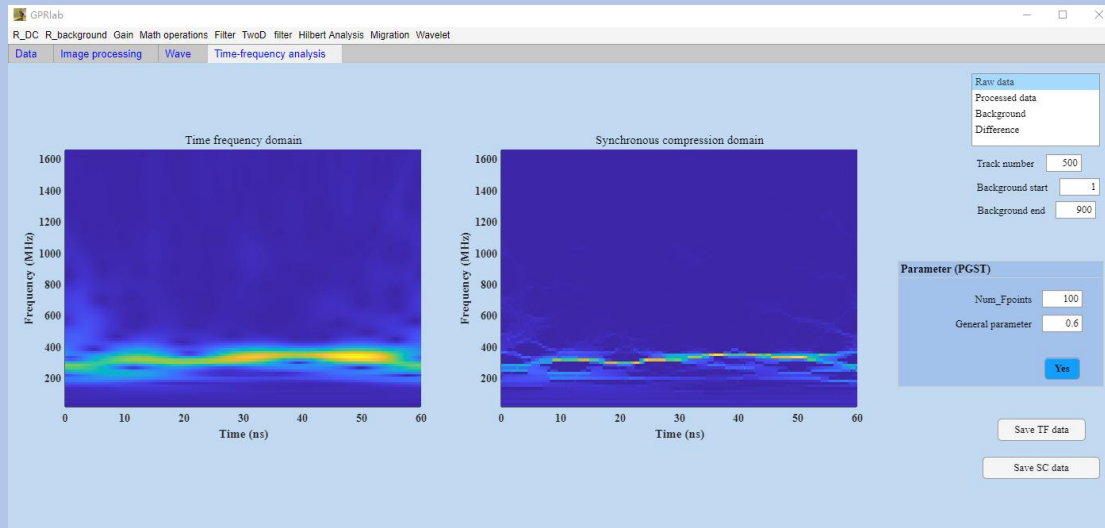


图 8.3 General parameter = 0.6

9 Examples

9.1 Case1

case 1 data comes from testing a 30m arch bridge with four arches using the free acquisition mode of a GSSI device.

(1) To read in the data, as shown in Figure 9-1, we can see that the data is sampled at 512 and has 5607 traces.

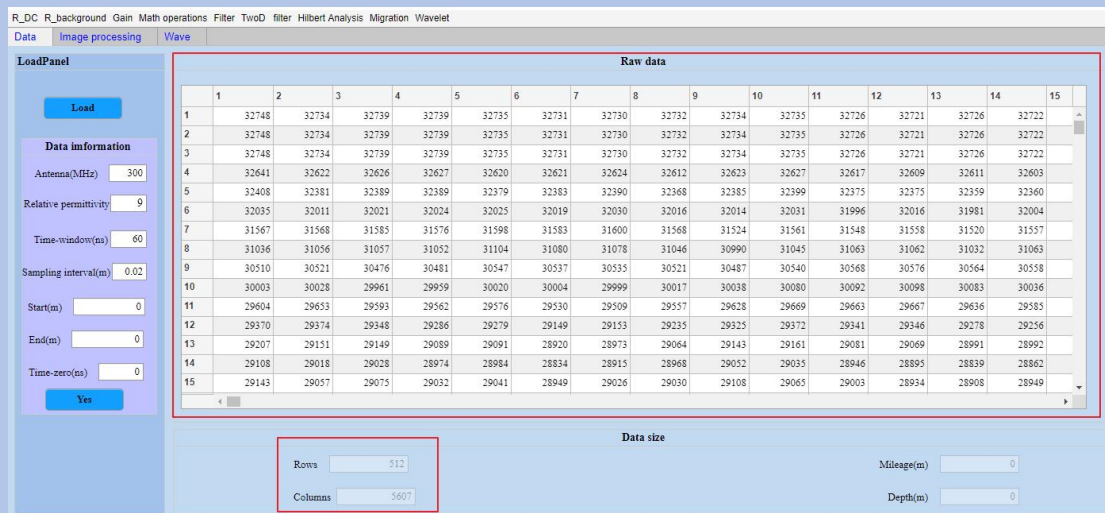


Figure 9.1 Case1 loading data

(2) Setting the parameters, as shown in Figure 9-2a, since free acquisition is used, the Sampling Interval is set to 0, and the End is set to 30. After clicking Yes, GPRlab automatically calculates the Sampling Interval value as 0.0053, as shown in Figure 9-2b. After that, as shown in Figure 9-3, we can see that the Mileage is set to 30m, and the Depth is calculated based on the dielectric constant as 3.182m.

a) Data information

Antenna(MHz)

Relative permittivity

Time-window(ns)

Sampling interval(m)

Start(m)

End(m)

Time-zero(ns)

b) Data information

Antenna(MHz)

Relative permittivity

Time-window(ns)

Sampling interval(m)

Start(m)

End(m)

Time-zero(ns)

Figure 9.2 Case1 setting parameters. a) After entering the parameters and b) after confirming the parameters

LoadPanel

Data information

Antenna(MHz)

Relative permittivity

Time-window(ns)

Sampling interval(m)

Start(m)

End(m)

Time-zero(ns)

Raw data

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	32748	32734	32739	32739	32735	32731	32730	32732	32734	32735	32726	32721	32726	32722	
2	32748	32734	32739	32739	32735	32731	32730	32732	32734	32735	32726	32721	32726	32722	
3	32748	32734	32739	32739	32735	32731	32730	32732	32734	32735	32726	32721	32726	32722	
4	32641	32622	32626	32627	32620	32621	32624	32612	32623	32627	32617	32609	32611	32603	
5	32408	32381	32389	32389	32379	32383	32390	32368	32385	32399	32375	32375	32359	32360	
6	32035	32011	32021	32024	32025	32019	32030	32016	32014	32031	31996	32016	31981	32004	
7	31567	31568	31585	31576	31598	31583	31600	31568	31524	31561	31548	31558	31520	31557	
8	31036	31056	31057	31052	31104	31080	31078	31046	30990	31045	31063	31062	31032	31063	
9	30510	30521	30476	30481	30547	30537	30535	30521	30487	30540	30568	30576	30564	30558	
10	30003	30028	29961	29959	30020	30004	29999	30017	30038	30080	30092	30098	30083	30036	
11	29604	29653	29593	29562	29576	29530	29509	29557	29628	29669	29663	29667	29636	29585	
12	29370	29374	29348	29286	29279	29149	29153	29235	29325	29372	29341	29346	29278	29256	
13	29207	29151	29149	29089	29091	28920	28973	29064	29143	29161	29081	29069	28991	28992	
14	29108	29018	29028	28974	28984	28834	28915	28968	29052	29035	28946	28895	28839	28862	
15	29143	29057	29075	29032	29041	28949	29026	29030	29108	29065	29003	28934	28908	28949	

Data size

Rows

Columns

Minage(m)

Depth(m)

Figure 9.3 Data module completes the setup

(3) Switching to the Image Processing module, we can observe the raw data as shown in Figure 9-4.

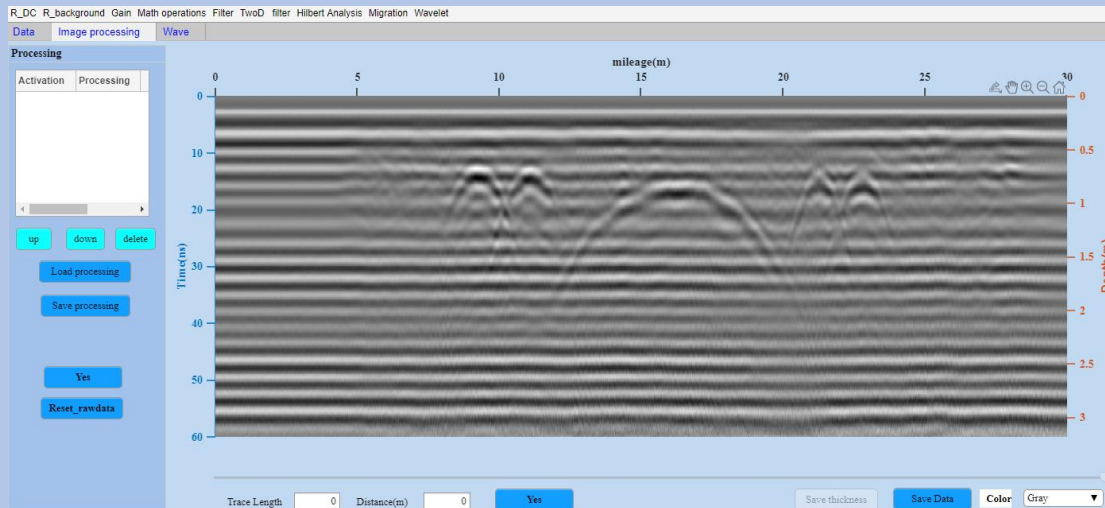


Figure 9.4 Raw data

(4) First, we applied the R_DC algorithm to prevent DC interference from the device. Then, we applied the "Remove background" algorithm in R_background to set the background data to 1-800 traces. This is because this data comes from the instrument in a stationary state at the bridge head. Finally, through our observation, we found that the strong multiple reflections between the air-coupled antenna and the ground had interfered with the entire profile. We selected the f_k filter method in TwoD filter to remove the multiple waves. Lg is set to 10 (1/3 of the profile), and Ls is kept at the default value. The processing flow is set as shown in Figure 9-5.

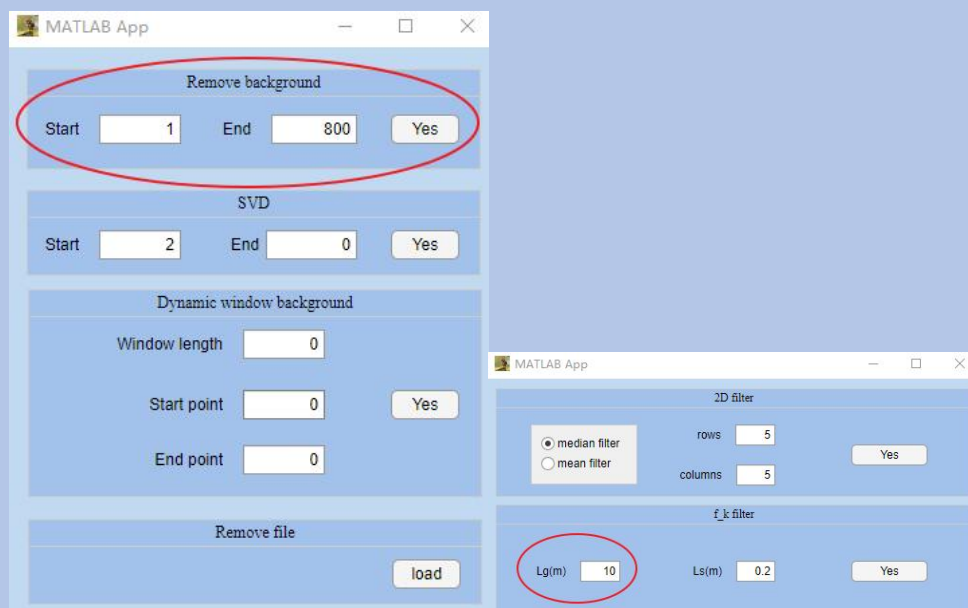


Figure 9.5 Case1 processing flow settings

(5) Click Yes to complete the data processing and adjust the color to obtain the processing result as shown in Figure 9-6.

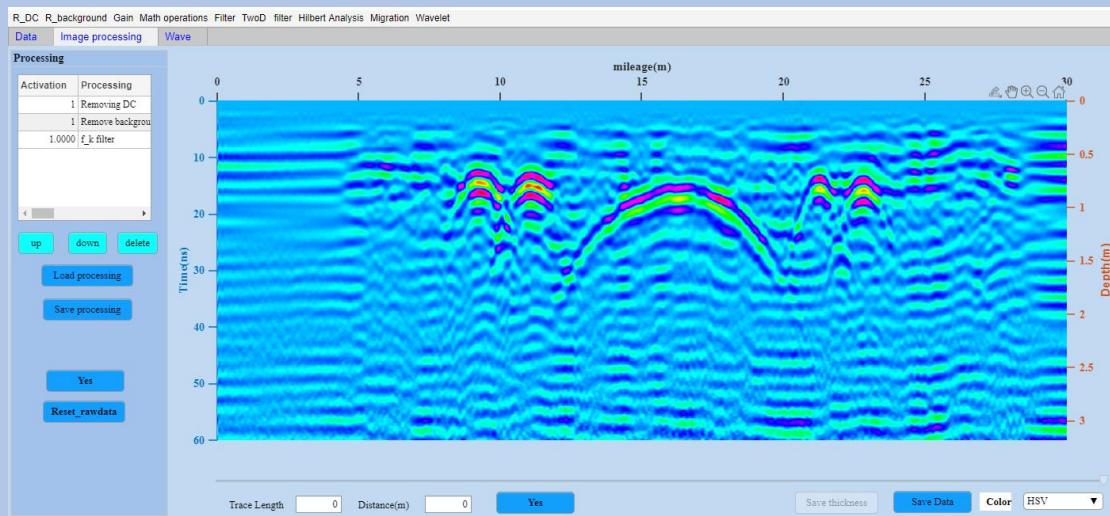


Figure 9.6 Processing results of Case1

The data and processing flow of this case are saved in examples/Case1. Users can also directly load or view the processing flow we provided.

9.2 Case2

Case 2 data comes from the 500MHz high-frequency channel GPR of Chang'e 4, which collected data in front of the Von Karman Crater on the moon during the first two lunar days. The data is about 105m, and the acquisition mode is unknown (here we assume it is free acquisition).

(1) To read in the data, as shown in Figure 9-7, we can see that the data is sampled at 2048 and has 9032 traces.

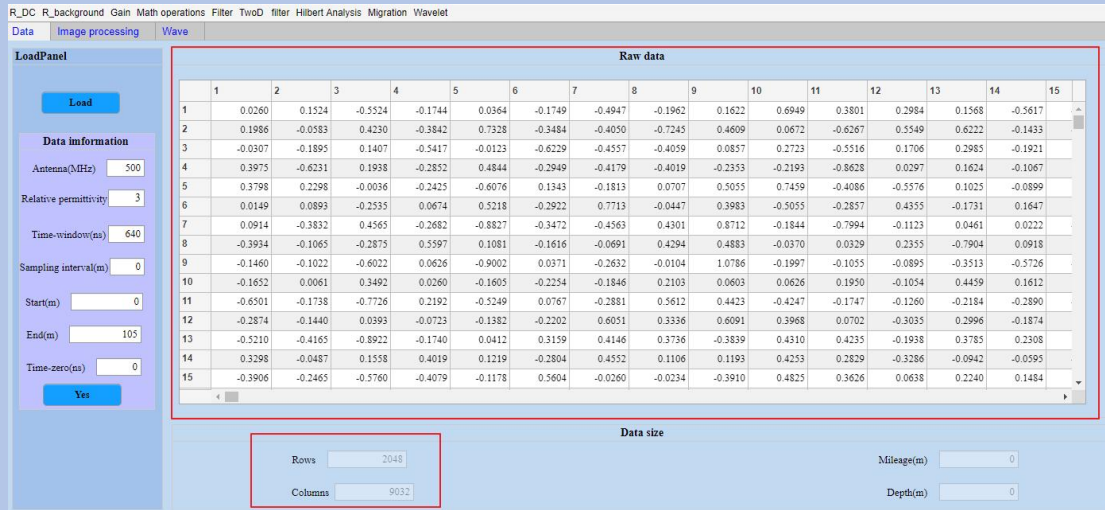


Figure9.7 Case2 loading data

(2) Setting the parameters, as shown in Figure 9-8a, since free acquisition is used, the Sampling Interval is set to 0, and the End is set to 105. After clicking Yes, GPRlab automatically calculates the Sampling Interval value as 0.0116, as shown in Figure 9-8b. After that, as shown in Figure 9-9, we can see that the Mileage is set to 105m, and the Depth is calculated based on the dielectric constant as 55.43m.

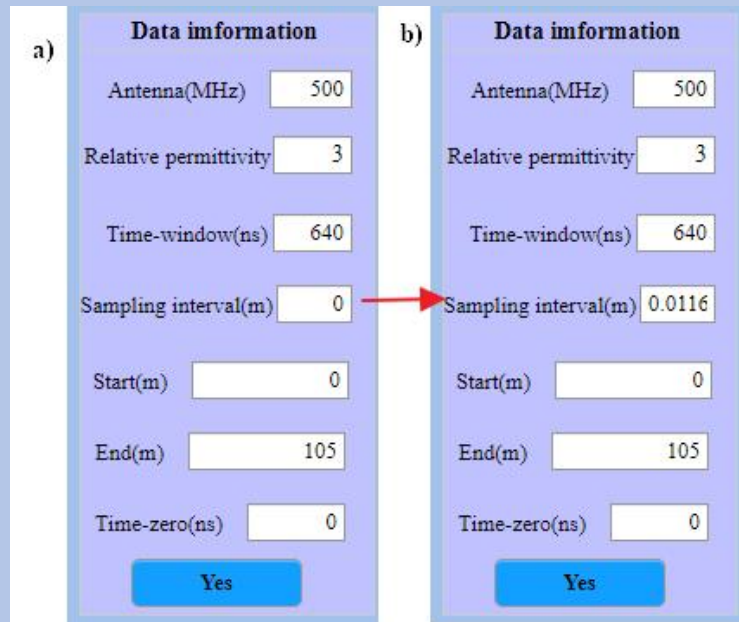


Figure 9.8 Case2 setting parameters. a) After entering the parameters and b) after confirming the parameters

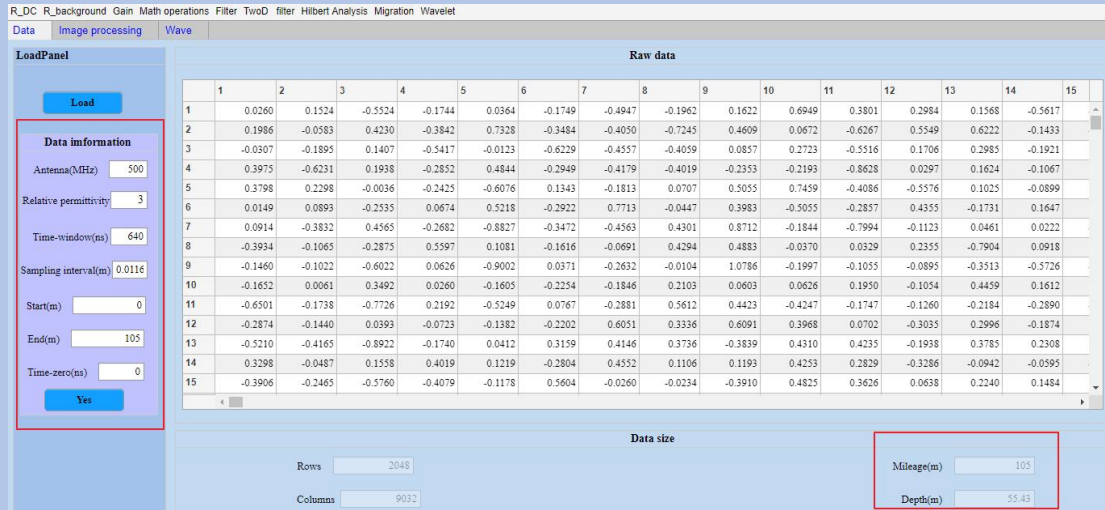


Figure 9.9 Data module completed setting

(3) Switching to the Image Processing module, we can observe the raw data as shown in Figure 9.10.

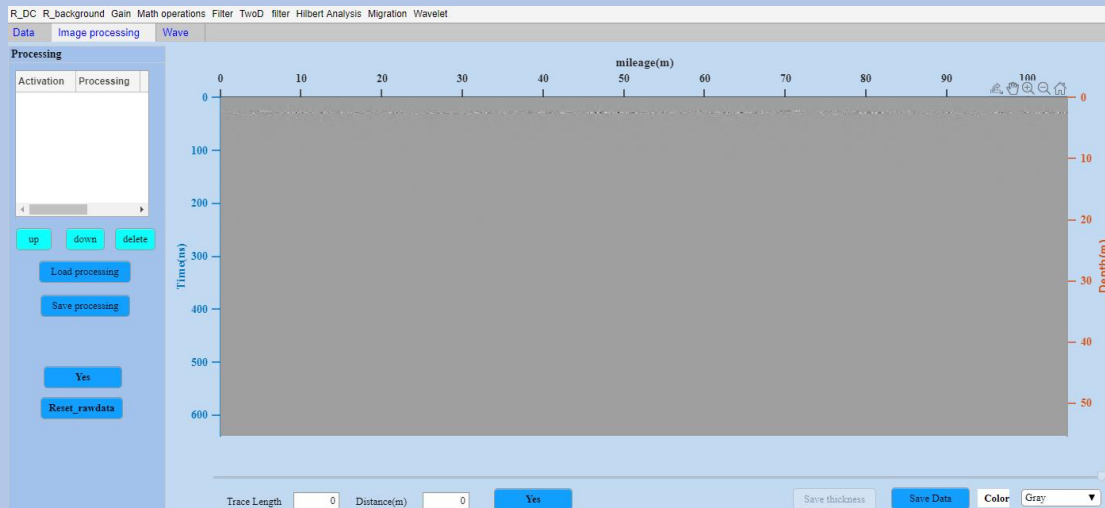


Figure 9.10 Case3 raw data

(4) Unlike Case 1, in Case 3, a provided processing flow (containing 7 algorithms) is loaded, and the parameters can be displayed in the Processing panel, as shown in Figure 9.10.

Processing										
Activation	Processing									
1	Removing DC	0	0	0	0	0	0	0	0	
1	SVD	2	0	0	0	0	0	0	0	
1	Vertical filtering	FIR	50	260	500	700	0	0	0	
1	Linear automatic gain	300	3000	0	0	0	0	0	0	
1	Absolute	0.2	0	0	0	0	0	0	0	
1	Square	1	0	0	0	0	0	0	0	
1	2D filter	mea	15	15	0	0	0	0	0	

Figure9.10 Case2 loading processing flow

(5) Click Yes to complete the data processing, and then set the Color to Jet to obtain the processing result as shown in Figure 9-11.

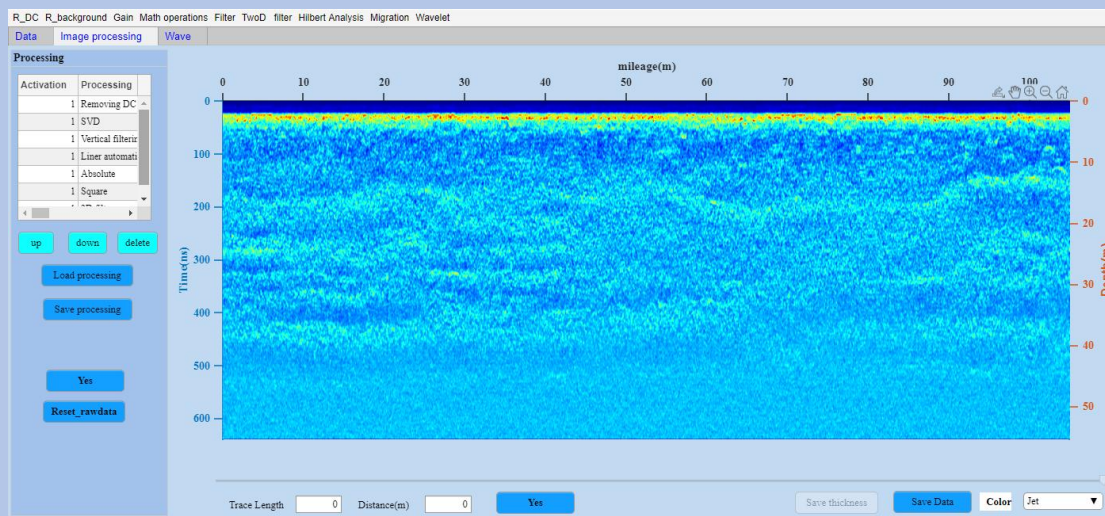


Figure 9.11 Case2 processing results

10 Version update instructions

Version 11.0 updates:

1. Fixed some issues with 32-bit saved formats in DZT format.

This update enhances the interactivity of the software, providing further improvements.