Instruction manual for:

PhaseWare™:

Phase map retrieval for fringe projection profilometry and off-axis digital holographic interferometry

APPLICATION DEVELOPED IN MATLAB APPDESIGNER

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OVERVIEW

PhaseWare retrieves phase maps for off-axis digital holographic interferometry (off-axis DHI) and fringe projection profilometry (FPP) systems. This graphical application is designed to operate in both static and dynamic imaging modes. In static mode, a phase map is retrieved from a single captured frame providing topographical information of the surface of the object. In dynamic mode, a stream of frames is used to extract phase map information across time to track dynamic surface changes

PhaseWare utilizes a graphical user interface consisting of six tabs, each designed for a specific function:

1- *Import Data*,
2- *Pre-Processing*,
3- *Phase Extraction*,
4- *Post-Processing*,
5- *Display & Save*, and
6- *Report*.

This instruction manual walks the user through installing and using these functions.

STEP-BY-STEP INSTRUCTIONS

RUNNING THE SOFTWARE

PREREQUISITES

MATLAB 2019a or newer

This software is written in MATLAB 2019a. Application functions may perform incorrectly if used with earlier versions of MATLAB.

For full functionality, the MATLAB Image Processing, Wavelet, Optimization, and Deep Learning Toolboxes are required.

INSTALLATION

There are two ways to run the software:

Option 1:

1. Double click on *PhaseWare.mlappinstall* to install it,
2. Find the app in your installed apps (MATLAB, APPS tab) and run it.

⚠ After installation, the app will remain in "MATLAB apps" unless uninstalled (right click -> Uninstall).

Option 2:

1. Open the *AppDesigner* by typing *appdesigner* in MATLAB workspace,
2. Open the app *PhaseWare.mlapp* in the Designer tab.

⚠ This method permits modifications to the source code.

IMPORT DATA TOOLBOX

The ***Import Data*** toolbox has tools for importing two different types of data: ***Main Data*** (Figure 2) and ***Reference Data***.

MAIN DATA TOOL

- Required input
- Accepts raw data captured from a target object with the imaging system
- The input can be a single image (.tif, .png, .bmp), or a video (.avi)
- When loading a video, a dialog box will appear to let the user select specific frames (Figure 1).

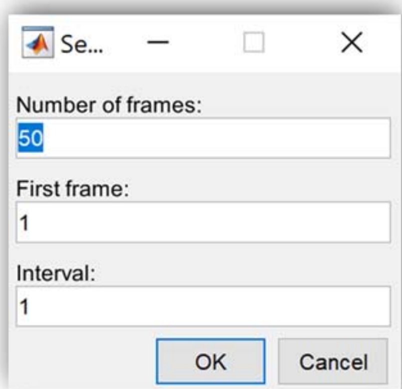


Figure 1. Dialog box to allow user selection of specific frames in a video

- This dialog box asks for three user inputs matching a *for* loop:

```
for i = firstFrame: interval: lastFrame
    statements
end
```

Number of frames:	• `totalFrames`, • The default number is the number of frames for the loaded video.
First frame:	• `firstFrame`, • The default is frame number *1*.
Interval:	• `interval`, • The default is *1*.

Internally, the software will calculate `lastFrame = firstFrame + interval * (totalFrames - 1)`

REFERENCE DATA TOOL

- Optional input
- Takes the raw data from the imaging system captured without a target object
- Takes a single image as input (.tif, .png, .bmp)

⚠ Note that to use ***Reference Data*** for processing, you should turn on the ***Use Reference in the Reconstruction*** switch in the corresponding tab.

⚠ Note that ***Reference Data*** should be acquired with the exact same system, using a flat plate as the object.

The ***Import Data*** toolbox offers several tools for fast overview of the loaded data such as:

- frame by frame display of the data,
- histogram of the selected frame,
- vertical line profile (controlled by x slider),
- horizontal line profile (controlled by y slider),
- and for multi-frame data, it is possible to display a combination of two of the frames with adjustable gains and arithmetic operations (Figure 3).

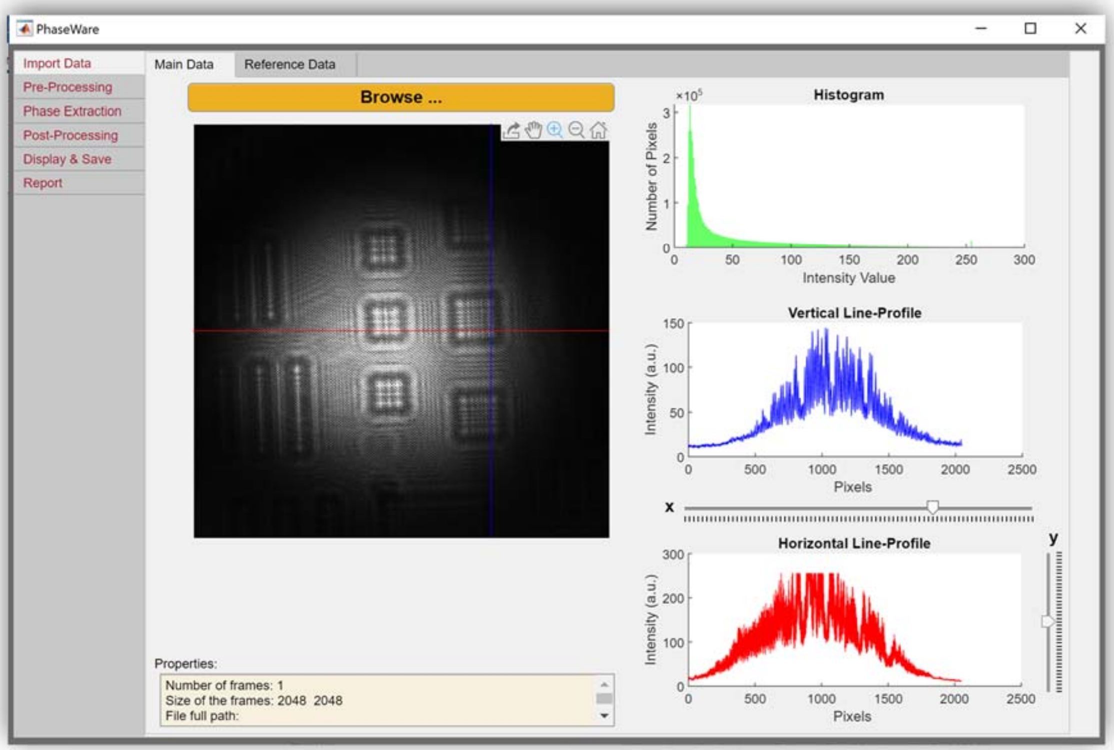


Figure 2. Main Data tool from Import Data toolbox

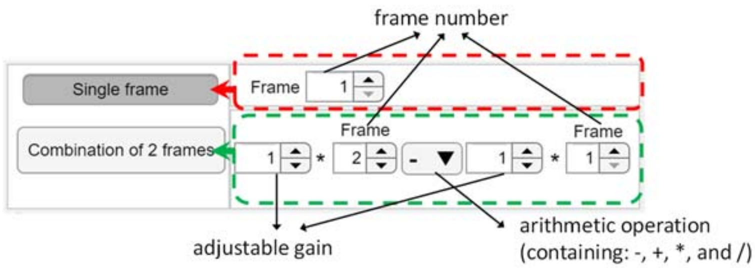


Figure 3. Display options for Main Data, present only when multiple frames are loaded to show a combination of two of the frames with adjustable gains and arithmetic operations

PRE-PROCESSING TOOLBOX

The pre-processing toolbox (Figure 5) provides access to modules for cropping, DC offset removal, and filtering the input data.

CROPPING TOOL

This tool is for cropping a region of interest (RoI).

It presents different options such as:

- ***no crop,***
- ***manual square,***
- ***square, and***
- ***circle.***

For multi-frame data, it is possible to select a subset of the loaded frames formatted as an iterative loop in MATLAB (e.g. `firstFrame: interval: lastFrame`).

⚠ The cropped image size must be equal or smaller than the input frame size.

DC OFFSET REMOVAL TOOL

For most phase retrieval algorithms, removal of the DC component leads to better results. The DC Offset Removal Tool compiles multiple methods of DC removal. The user can also load a custom function.

When the ***Remove DC*** button is pressed, a MATLAB figure (Figure 4) will appear showing the result. This figure includes the special and Fourier domains of both the input and output.

✓ If the function is successful, the DC component of the Fourier domain, located at the center, will be removed.

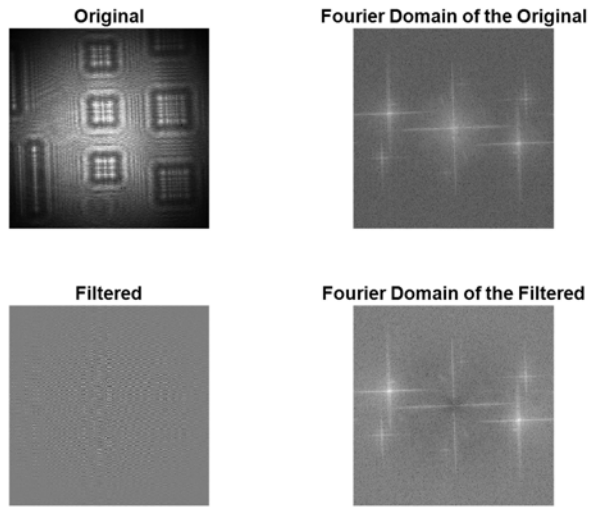


Figure 4. Example MATLAB figure with spatial and fourier domains presented after DC offset removal

DATA FILTERING TOOL

This optional tool performs noise reduction image enhancement with the following methods:

- ***averaging filter*** (`filter2(fspecial('average',[filterSizeY,filterSizeX]),I)`),
- ***median filter*** (`medfilt2(I, [filterSizeY, filterSizeX])`),
- ***adaptive low-pass Wiener filter*** (`wiener2(I,[filterSizeY, filterSizeX])`),
- ***deep neural network filter*** (`net=denoisingNetwork('DnCNN');denoiseImage(I,net)`), **and**
- ***user-provided MATLAB function.***

⚠ The deep neural network filter requires MATLAB's Deep Learning Toolbox.

Another feature of this module is a ***Window Normalization*** method to enhance contrast. This can be done by defining the fringe pattern as:

$$f_{enhanced}(x,y) = \frac{1}{2} + \frac{f(x,y) - \langle f(x,y) \rangle}{f_M(x,y) - f_m(x,y)}$$

where $\langle f(x,y) \rangle$, $f_M(x,y)$, and $f_m(x,y)$ are the local average, maximum, and minimum of the fringe pattern over a selected window. The window is centred at (x,y) and its size is defined by ***window size [m n]***.

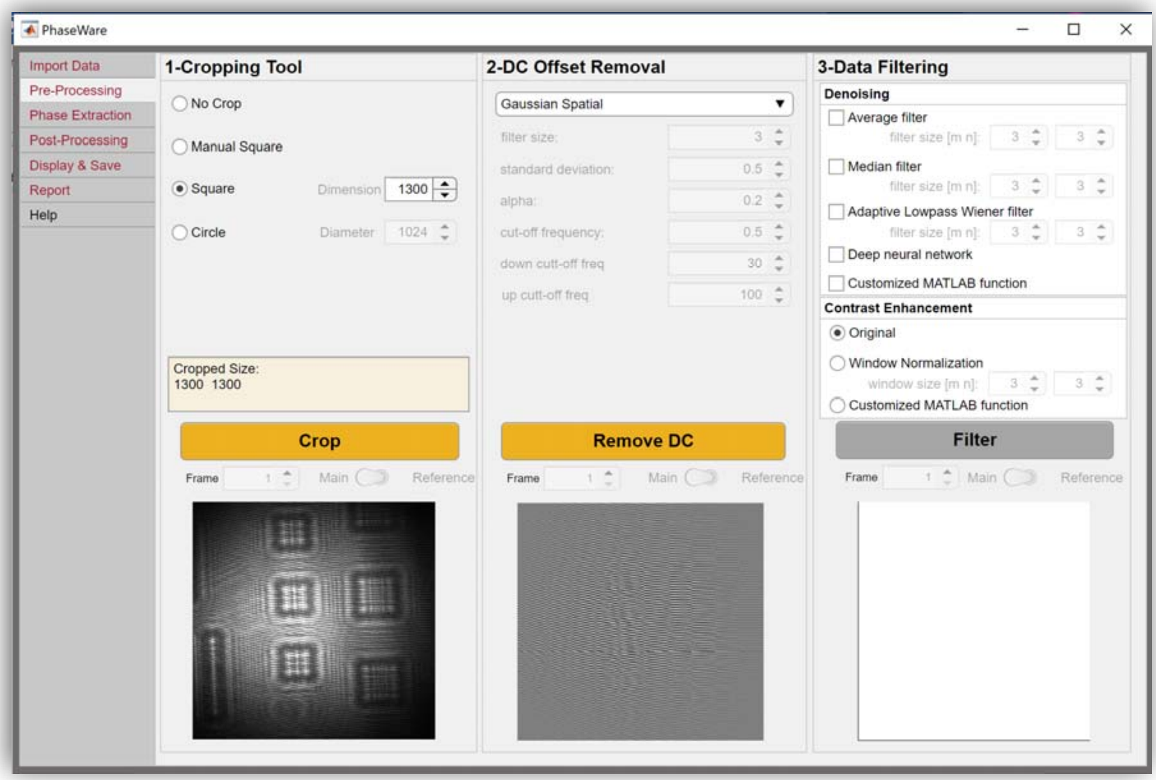


Figure 5. Pre-processing toolbox interface

PHASE EXTRACTION TOOLBOX

After choosing the appropriate sub-tab (off-axis DHI vs FPP, Figure 7), the following methods and algorithms are available as shown in Figure 6:

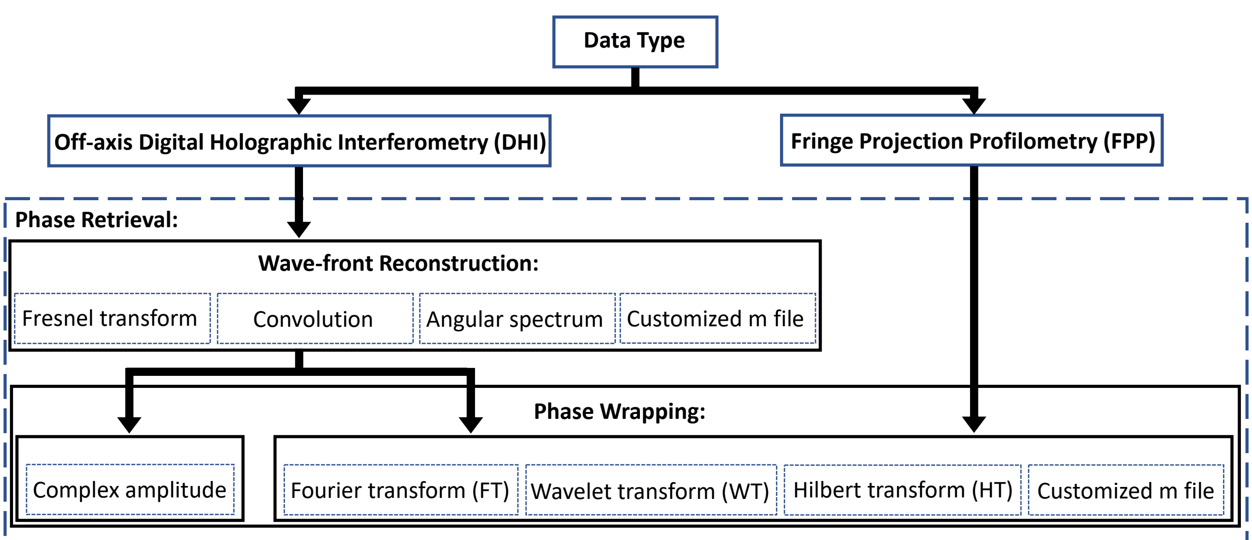


Figure 6. Algorithms listed in the Phase Extraction Toolbox

- For FPP inputs, there are four transform-based phase wrapping algorithms.
- For off-axis DHI, there are three wave-front reconstruction algorithms alongside five phase wrapping algorithms. Four of the phase wrapping algorithms are shared with FPP.
- User-provided algorithms can be used for both wave-front reconstruction and phase wrapping.
- As a general guideline, the Fourier transform (FT) method is preferable in cases of low signal-to-noise ratio (SNR) where the fringe periods are contained within the image. If non-stationary signals are present and/or fringe periods are not contained, then the wavelet transform (WT) method should be used instead. If the data has good SNR and meets the requirements for FT, then the Hilbert transform could be considered as an alternative.

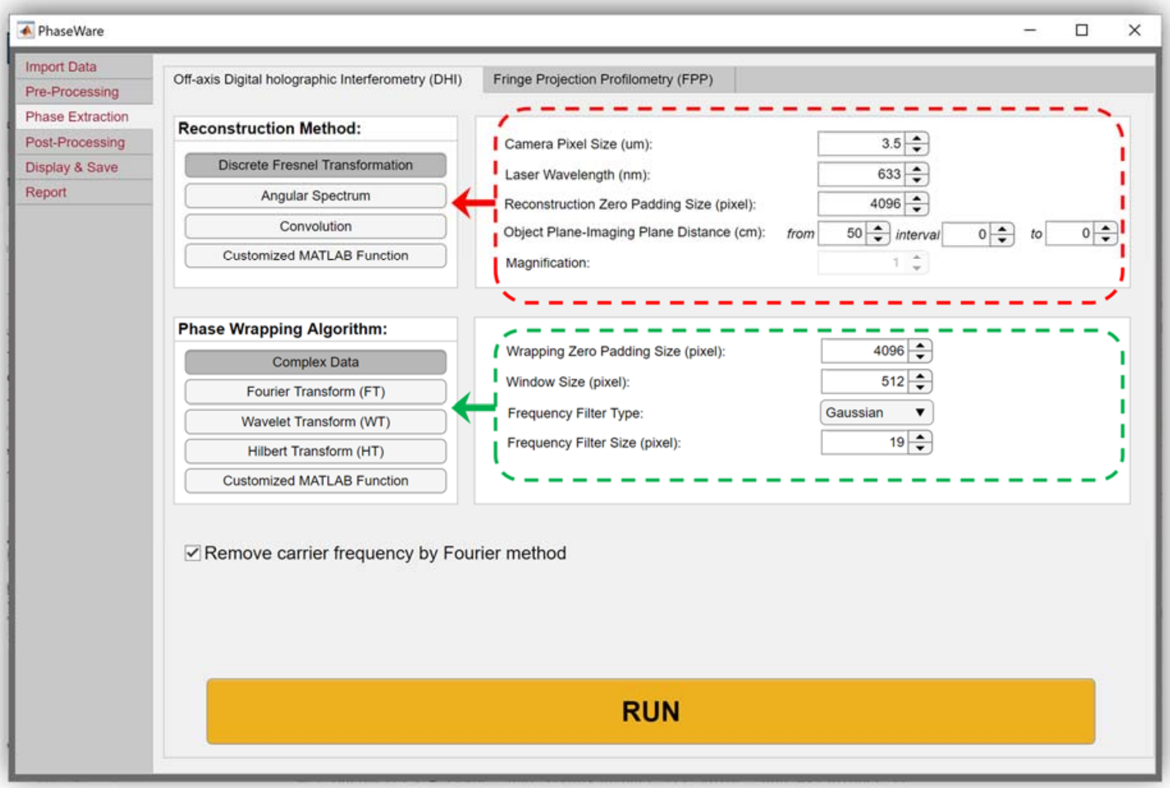


Figure 7. Phase Extraction toolbox interface

For off-axis DHI, the right panel provides fields to enter several input parameters required by the reconstruction and phase wrapping algorithms. The parameters are explained briefly below:

OFF-AXIS DHI

- ***Camera Pixel Size (µm):*** the pixel size of the recording camera.
- ***Laser Wavelength (nm):*** the wavelength of the laser.
- ***Reconstruction Zero Padding Size (pixel):*** the final image size after zero padding.
- ***Object Plane-Imaging Plane Distance (cm):*** the distance between the object plane (reconstruction plane) and the imaging plane (camera).
    - If the focal distance for the reconstruction is unknown, multiple reconstructions can be performed starting at the ***from*** value until the ***to*** value in intervals ***interval****.*
    - The ***interval*** value must be a non-zero positive value. Otherwise, a single focal distance will be reconstructed at a distance defined by the ***from*** input parameter.

⚠ Choosing ***Convolution*** as the reconstruction method will enable one more parameter(s) named ***Magnification***, which represents the magnification in the reconstruction plane.

- ***Wrapping Zero Padding Size (pixel):*** the final image size after zero padding.
- ***Window Size (pixel):*** the size of the radius of a circular filter window used for selecting the fundamental frequency component in the Fourier domain of the input phase.
- ***Frequency Filter Type:*** this dropdown provides three types of filters for the window used in the Fourier domain (***Gaussian***, ***Butterworth***, or ***Ideal***).

✔ Butterworth and Gaussian filters are recommended because they provide fewer artifacts and unwanted rings after inverse Fourier transform.

- ***Frequency Filter Size (pixel):*** the size of the filter that was defined in ***Frequency Filter Type.***
- ***Remove carrier frequency by Fourier method***: this check box allows the option to remove the carrier frequency by the Fourier method.

⚠ Note that the wrapping process is defined by the selected Phase Wrapping Algorithm and this check box is only used for the Fourier method with parameters previously defined.

When the ***Run*** button is pressed, the selected algorithm is used to generate the wrapped phase. If ***Remove carrier frequency by Fourier method*** is enabled, the RUN button generates the carrier removed wrapped phase as well. A MATLAB figure will appear showing the absolute values of the reconstructed complex amplitudes of the data.

- This figure contains three separate parts: real image, virtual image, and DC offset.
- The user must then select the in-focus image by dragging the cursor over the chosen image, then double-clicking on the highlighted area. The size of the window can also be adjusted manually in this step.
- Applying an appropriate DC removal function during pre-processing ensures the elimination of the DC component in reconstruction as in Figure 8.

When the ***Run*** button is pressed, the selected algorithm is used to generate the wrapped phase both with and without the carrier frequency. A MATLAB figure will appear showing the absolute values of the reconstructed complex amplitudes of the data. The figure contains three separate parts: real image, virtual image, and DC offset. The user must then select the in-focus image by dragging the cursor over the chosen image, then double-click the highlighted area. The size of the window can also be adjusted manually during this step. Applying an appropriate DC removal function during pre-processing ensures the elimination of the DC component in reconstruction as shown in Figure 8.

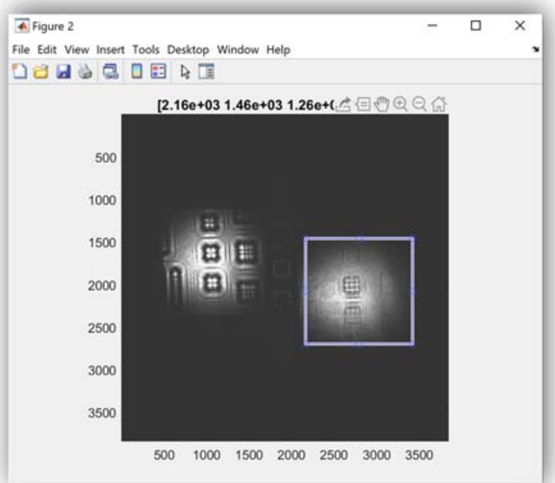


Figure 8. Example MATLAB figure showing the absolute values of the reconstructed complex amplitudes of the data

After cropping, if ***Fourier Transform (FT)*** has been selected as the wrapping algorithm and/or ***Remove carrier frequency by Fourier method*** is enabled, another MATLAB figure (Figure 9) will appear displaying the absolute value of the Fourier domain of the phase component.

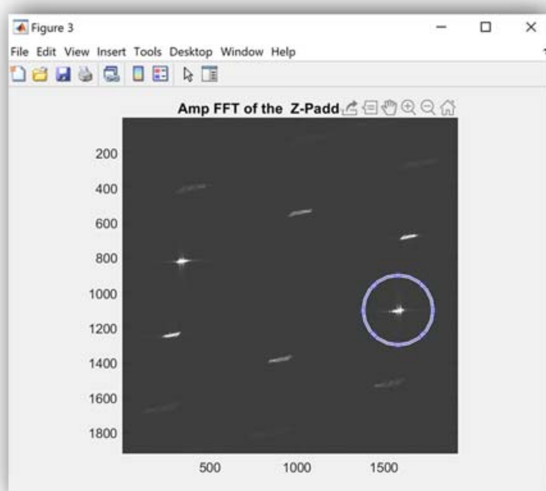


Figure 9. Example MATLAB figure showing the absolute value of the Fourier domain of the phase component. This is only available when a Fourier transform method has been chosen

- The Fourier transform may show multiple frequency components. Based on the directionality of the carrier fringes, the proper component should be selected using a circular window.
- The size of the window is adjustable using the ***window size (pixel)*** parameter.
- The location of the maximum intensity value within the selected window will be transferred to the center of the Fourier domain.

⚠ Ensure that the window includes only one of the main frequency components.

⚠ When ***Fourier Transform (FT)*** is selected as the wrapping method, if the user enables ***Remove carrier frequency by Fourier method,*** only one MATLAB figure will appear to select the main component in Fourier domain to be used for both wrapping and carrier removal (Figure 10).

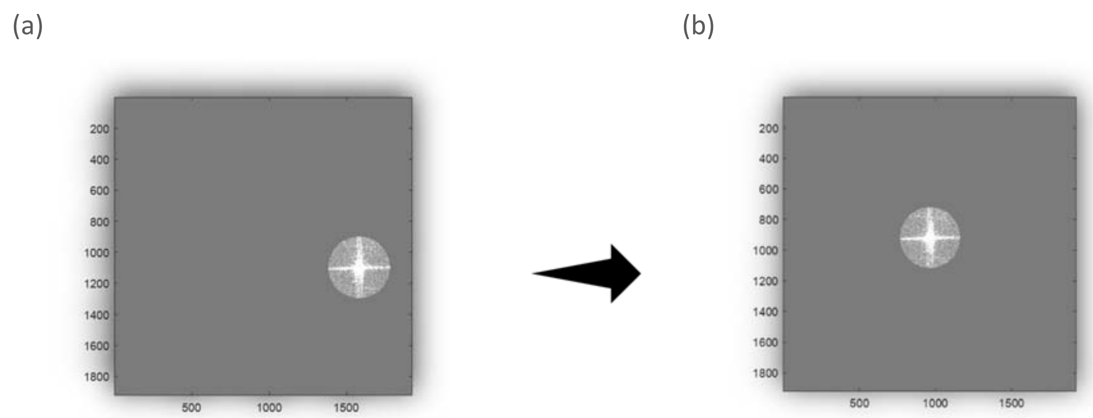


Figure 10. Carrier removal process with the Fourier method. a) Selecting the proper component by using a circular window, b) transferring the location of the maximum intensity value within the selected window to the center of the Fourier domain

FRINGE PROJECTION PROFILOMETRY

- ***Wrapping zero padding size (pixel):*** the total image size after zero padding.
- ***Window size (pixel):*** the size of the radius of a circular window filter used for selecting the fundamental frequency in the Fourier domain of the input phase. The filter is circular, and this value indicates the radius of the circle used.
- ***Frequency filter type:*** this dropdown provides three types of filter for the window used in the Fourier domain (***Gaussian***, ***Butterworth***, or ***Ideal***).

✓ Butterworth and Gaussian filters are recommended because they provide fewer artifacts and unwanted rings post inverse Fourier transform.

- ***Frequency filter size (pixel):*** the size of the filter that was defined in ***frequency filter type.***

POST-PROCESSING TOOLBOX

The phase map information to be entered into the Post-Processing toolbox (Figure 11) as either a ***wrapped phase*** or a ***carrier- removed wrapped phase***. There is a dropdown at the top of the panel to select between these two options.

⚠ This dropdown is active only if the ***Remove carrier frequency by Fourier method*** was previously selected; otherwise, the only input for this panel is ***wrapped phase***.

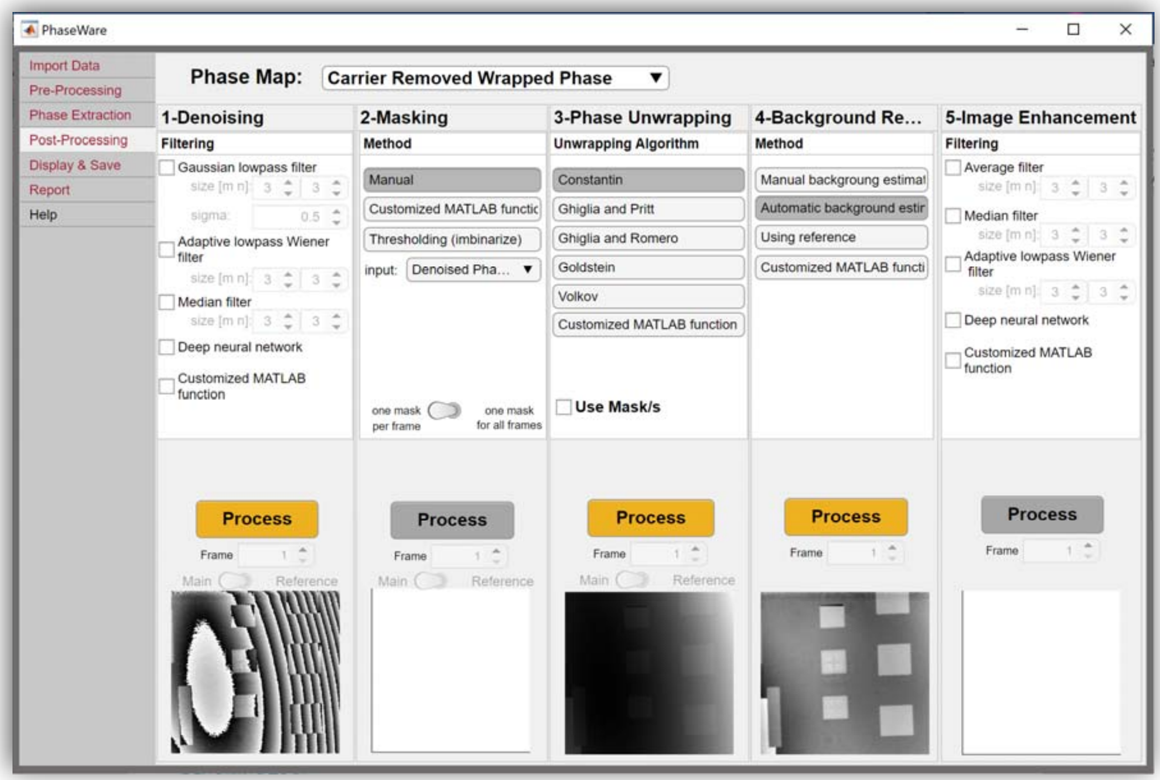


Figure 11. Post Processing toolbox interface

DENOISING TOOL

Apply pre-defined filters such as:

- ***Gaussian lowpass filter,***
- ***Adaptive lowpass filter,***
- ***Median filter,***
- ***Deep neural network, and***
- ***Customized MATLAB function.***

MASKING TOOL

There are three options to generate a region of interest (RoI):

1. The ***Manual*** method uses the CROIEditor (author: Jonas Reber, Figure 12) to manually define a binary mask.

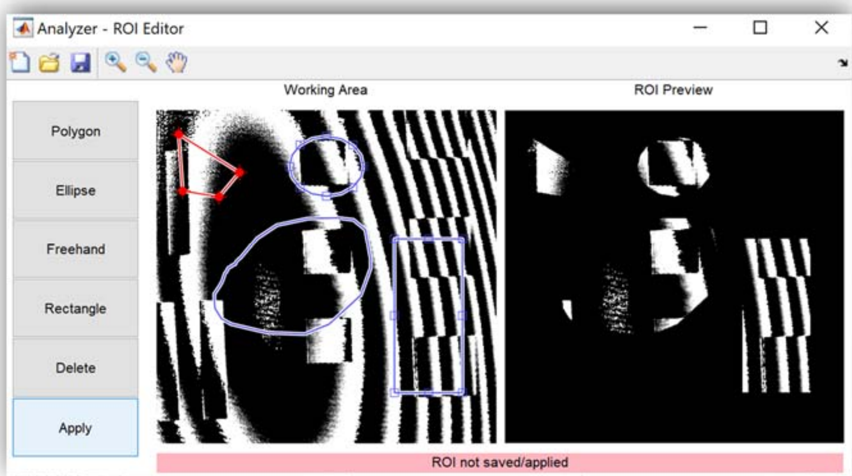


Figure 12. CROIEditor Masking Tool

⚠ Don't forget to press the ***Apply*** button after drawing the desired RoI.

2. ***Customized MATLAB Function*** allows the use of a user-provided method.
3. ***Thresholding (imbinarize)*** generates a binary mask by thresholding the image(s), locally or globally. PhaseWare uses a MATLAB internal function named `imbinarize` to perform this task. This function allows for two options for thresholding: global or adaptive. The global option is based on Otsu's method and takes one input specifying the thresholding value (Figure 13a). The adaptive option accepts up to two arguments to adjust local thresholding. Sensitivity is specified as a number in the range [0, 1] and ForegroundPolarity is defined as either 'bright' or 'dark' (Figure 13b). Further information on this method can be found in MATLAB documentation.

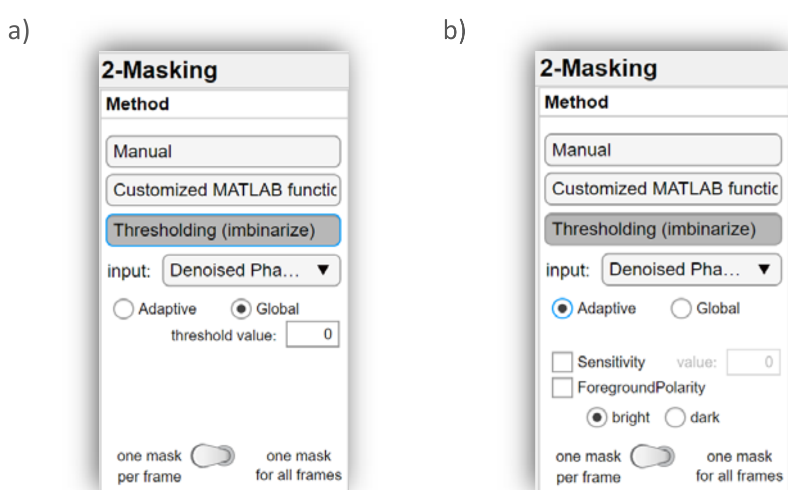


Figure 13. Thresholding (imbinarize) Masking Tool

- The dropdown ***input*** allows for choosing the input data to be used to generate the mask.
- The tool provides a switch to set one mask common to all frames (***one mask for all frames***) or a unique mask for each frame (***one mask per frame***).

PHASE UNWRAPPING TOOL

Phase unwrapping processes a wrapped phase ($-\pi\ to + \pi$) into an absolute phase (unlimited values).

The following algorithms have been included:

- ***Constantin,***
- ***Ghiglia and Pritt*** (warning: time-consuming!)***,***
- ***Ghiglia and Romero,***
- ***Goldstein,***
- ***Volkov,*** **and**
- ***Customized MATLAB function.***

BACKGROUND REMOVAL TOOL

This tool removes a non-uniform background in the absolute phase data. Background variation can occur due to poor illumination, variations in the camera sensor, and tilted object surfaces.

⚠ Ideally, the non-uniform background should be accounted for using ***Reference data***; however, an alternative is to use image post-processing to achieve a similar effect.

Three different methods are provided:

1. ***Manual Background Selection:*** multiple user-selected points in the background area are manually assigned a 2D polynomial factor, and then used to estimate the background.

✔ The use of more points leads to better background estimation.

2. ***Automatic Background Estimation***: the same as the first method but with automatic polynomial estimation.
3. ***Using Reference***: uses the absolute phase map extracted from the loaded ***Reference Data*** as the background.

IMAGE ENHANCEMENT TOOL

This is another optional function to enhance the result by applying 2D filtering to the unwrapped phase data using the following methods:

- ***averaging filter*** (`filter2(fspecial('average',[filterSizeY,filterSizeX]),I)`)**,**
- ***median filter*** (`medfilt2(I, [filterSizeY, filterSizeX])`)**,**
- ***adaptive lowpass Wiener filter*** (`wiener2(I,[filterSizeY, filterSizeX])`)**,**
- ***deep neural network filter*** (`net=denoisingNetwork('DnCNN');denoiseImage(I,net)`)**, and**
- ***user-provided MATLAB function.***

DISPLAY & SAVE TOOLBOX

This toolbox is for viewing and saving computational results.

DISPLAY

- User defines what to view in the ***Output*** dropdown.
    - A 2D view, vertical and horizontal intensity line profiles, and a histogram are then shown.

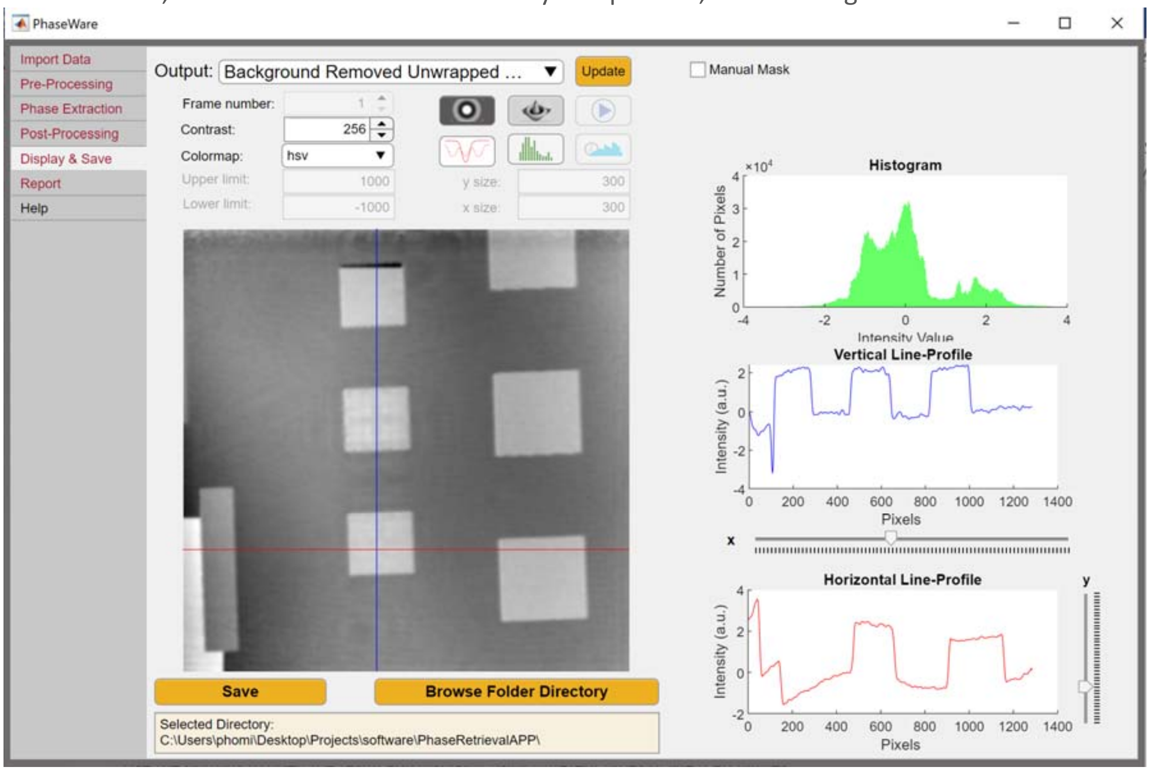


Figure 14. Display & Save Toolbox

The checkbox option ***Manual Mask*** allows users to apply a mask to the selected **Output** data. The selected mask can either be used to select for the data to be kept (***Keep selection***), or to select for the data to be removed (***Remove selection***), in which case the remaining areas of the image are retained. (Fig. 15).

⚠ After checking the box, you should either change the **Output** dropdown or press the **Update** button.

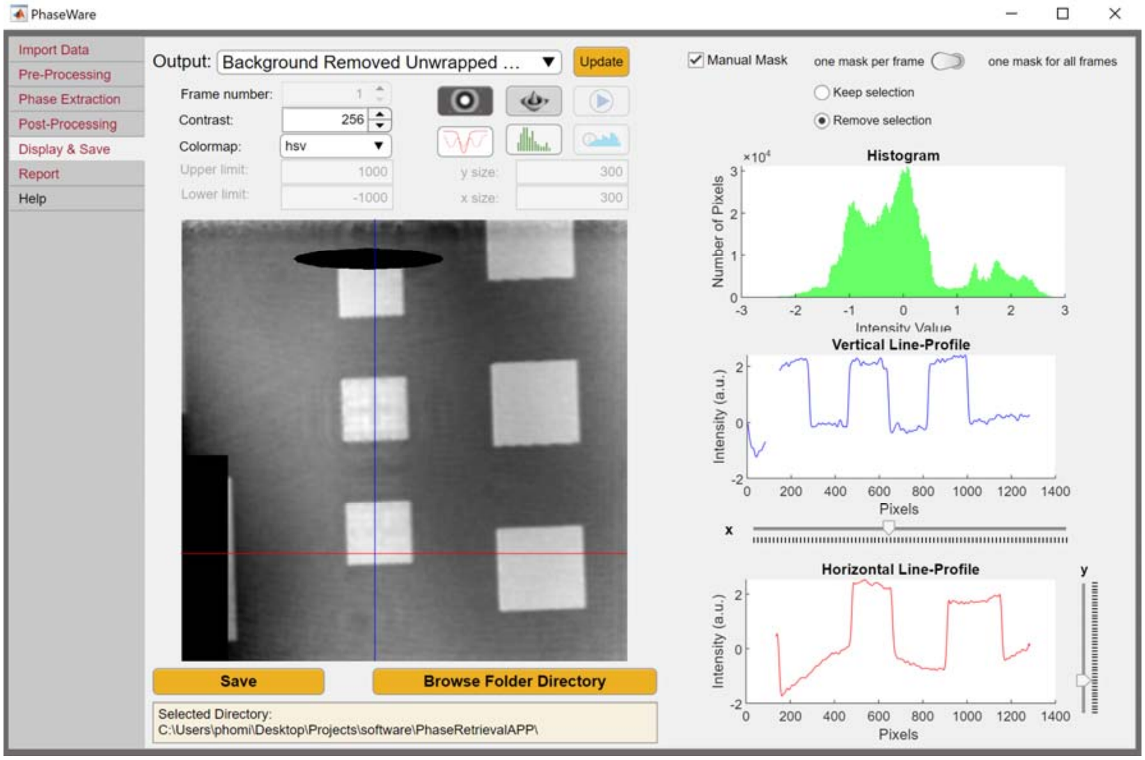
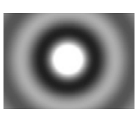


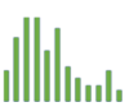
Figure 15. Display & Save Toolbox with Manual Mask Selection

Use the buttons to open the result and display it using different types of MATLAB figures.



Display a 2D image for the selected ***Frame Number.*** Controlled by ***Contrast*** and ***Colormap.***

Display vertical and horizontal intensity line profiles for the selected ***Frame Number.***
The user should select a point in the figure to have vertical and horizontal line profiles passing through that point.



Display histogram for the selected ***Frame Number.***

Display a surface image (Figure 16) for the selected ***Frame Number.*** Controlled by ***Contrast*** and ***Colormap.***

Play a video of the surface display. Controlled by ***upper limit*** and ***lower limit*** for the upper and lower limits for the z-axis in the plot and ***Colormap*** for the color map.

Only works if multiple frames were provided as ***Main Input*** (inactive for single frame input).
Time plot of the average intensity over a selected area. The size of the area is controlled by ***y-size*** and ***x-size*** in the y and x directions, respectively. Only works if multiple frames were provided as ***Main Input*** (inactive for single frame input).

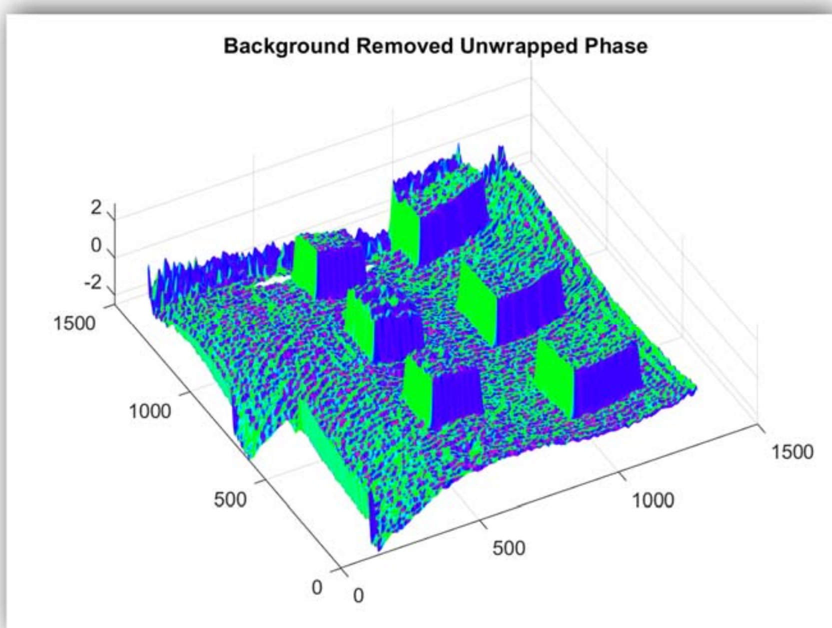


Figure 16. Example MATLAB figure for the "3D surface display" selection

SAVE

In order to save a MATLAB (.mat) file of the results, select the data to save in the ***Image*** dropdown. Next, select a target directory through ***Browse Folder Directory***. Finally, press the ***Save*** button.

⚠ The default directory is the folder that the user loaded the main data from.

⚠ To save the results as an image (.png, .tif, .pdf, .jpg, .bmp, .fig, etc.), use the MATLAB figure pop-up in the Display section.

⚠ To save a video for surface plotting, a dialog box will appear after pressing the icon and request permission to save. Therefore, there is no need to separately save it with the ***Save*** button.

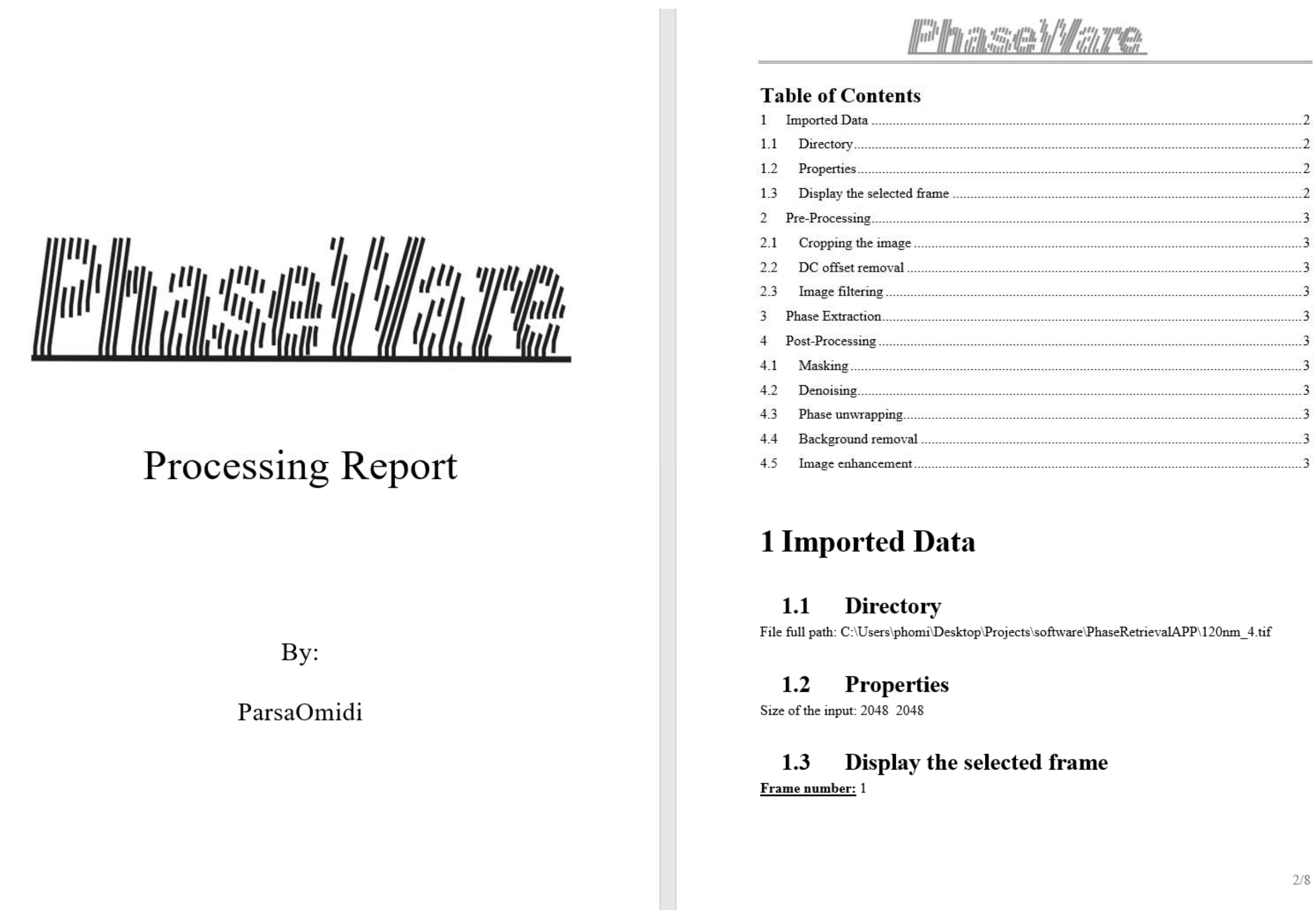
REPORT

To generate a summary of the workflow containing all parameters and images that the user used.

- Allows swift comparison to previous results.
- The name of the report will show the date and the time of report generation (e.g., ***Report_March,26,2020- 2.09.30 PM***).

⚠ If any user-provided functions are used, it is recommended to add the function directory to the MATLAB current directory.

SAMPLE REPORT (FOR THE EXAMPLE ILLUSTRATED THROUGHOUT THE INSTRUCTION MANUAL)



Processing Report

By:

ParsaOmidi

Table of Contents

1 Imported Data

1.1 Directory

File full path: C:\Users\phomi\Desktop\Projects\software\PhaseRetrievalAPP\120nm_4.tif

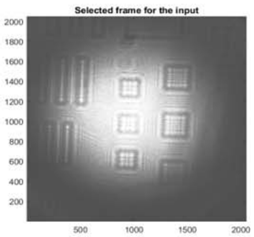
1.2 Properties

Size of the input: 2048 2048

1.3 Display the selected frame

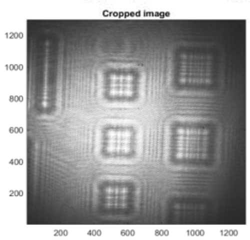
Frame number: 1

2/8



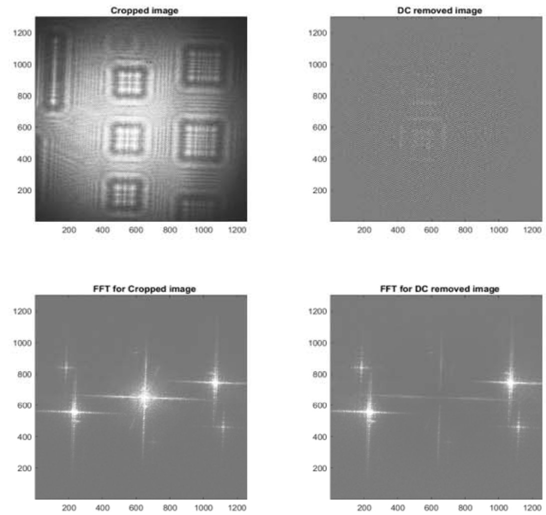
2 Pre-Processing

2.1 Cropping the image



2.2 DC offset removal

Method: Gaussian Spatial



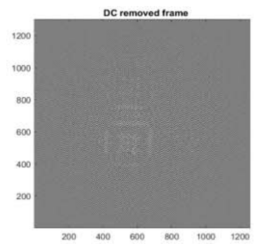
2.3 Image filtering

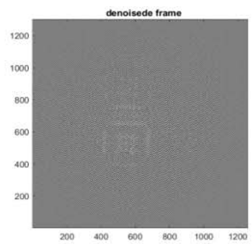
Denoising:

No denoising filter is applied

Contrast Enhancement Method:

Original

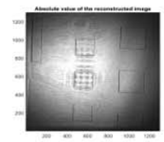


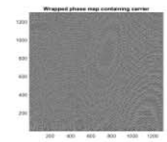


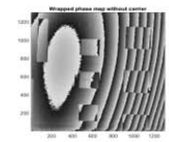
3 Phase Extraction

System:	Off-axis Interferometry
Algorithm:	Discrete Fresnel Transformation
Algorithm Parameters:	
Camera pixel size (um) =	3.5
Laser wavelength (nm) =	633
Reconstruction Zero Padding Size (pixel) =	4096
Filter radious (pixel) =	1024
Object Plane-Imaging Plane Distance (cm) =	from 50 , interval 0 ,to0
Wrapping Zero Padding Size (pixel) =	4096
Window Size (Radius) =	1024
Frequency Filter Type =	Gaussian

Frequency Filter Size = 400





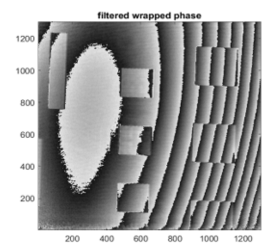


4 Post-Processing

Selected Phase Map = Carrier Removed Wrapped Phase

4.1 Denoising

No denoising filter is applied



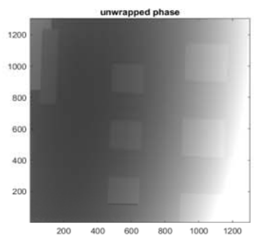
4.2 Masking

No Mask has been picked

4.3 Phase unwrapping

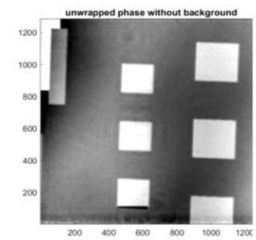
Unwrapping Algorithm = Constantin

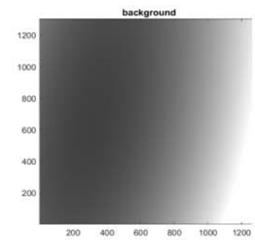
Using Mask = No



4.4 Background removal

Automatic background estimation





4.5 Image enhancement

No denoising filter is applied