

User Guide for Virtual Coherence Scanning Interferometer (VCSI)

Manufacturing Metrology Team
Faculty of Engineering
University of Nottingham

Author: Rong Su

Reviewer: Richard Leach

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Tel +44 0115 74 86230
Email: Richard.Leach@nottingham.ac.uk
Rong.Su@nottingham.ac.uk

Address:
Faculty of Engineering,
University of Nottingham
Advanced Manufacturing Building
Jubilee Campus
Nottingham, NG8 1BB

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Introduction

Uncertainty evaluation for optical measurement of surfaces with complex topography (such as freeform and biomimetic artificial surfaces) is an open issue in industrial metrology capability. A promising approach to uncertainty evaluation is to use a “virtual instrument” – the digital twin of a specific real instrument. This approach has been successfully used to provide uncertainty evaluation in the contact coordinate metrology world, but the virtual instrument is not yet available in the context of optical surface metrology. This software is the first virtual coherence scanning interferometer (VCSI) for surface measurement. The VCSI is fully powered by physical models derived from first principles and provides deterministic measurement result for surfaces with complex topography as is obtained using a real instrument.

The primary function of the virtual instrument is task-specific uncertainty evaluation; it can also be used to predict the instrument response and measurement result, in order to assess the feasibility of an instrument for a specific surface, find optimal instrument settings, improve the understanding of the measurement process and test new instrument configurations. For more technical details of the VCSI technique, please consult *R. Su and R. K. Leach (2021) Physics-based virtual coherence scanning interferometer for surface measurement. Light: Advanced Manufacturing, in press.* (<https://doi.org/10.37188/lam.2021.009>)

This software was developed by Dr Rong Su at the University of Nottingham (email: rongs@me.com). The development was supported by the Engineering and Physical Sciences Research Council [grant numbers EP/M008983/1; EP/R028826/1]. The software can be used without limitations in any not-for-profit scientific research. The only request is that in any publication where the software is used the source of the software be acknowledged and proper references be made. Some colour maps are extracted from <https://peterkovesi.com/projects/colourmaps>.

This software was developed for research purposes. We are open for any form of collaborations to develop the virtual instrument technique further. Any feedback is very welcome.

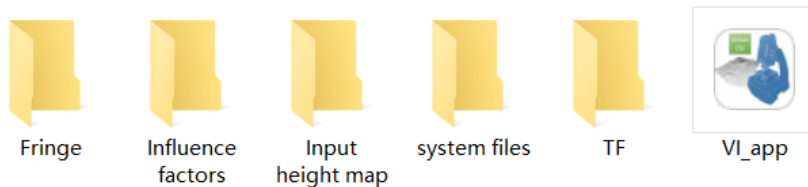
Acknowledgement Special thanks go to Matthew Thomas, Carlos Gomez and Joe Eastwood at the University of Nottingham for testing the software and providing feedback, Prof. Peter de Groot at Zygo Corporation and Prof. Jeremy Coupland at Loughborough University for fruitful technical discussions on optical modelling.

1. Getting started

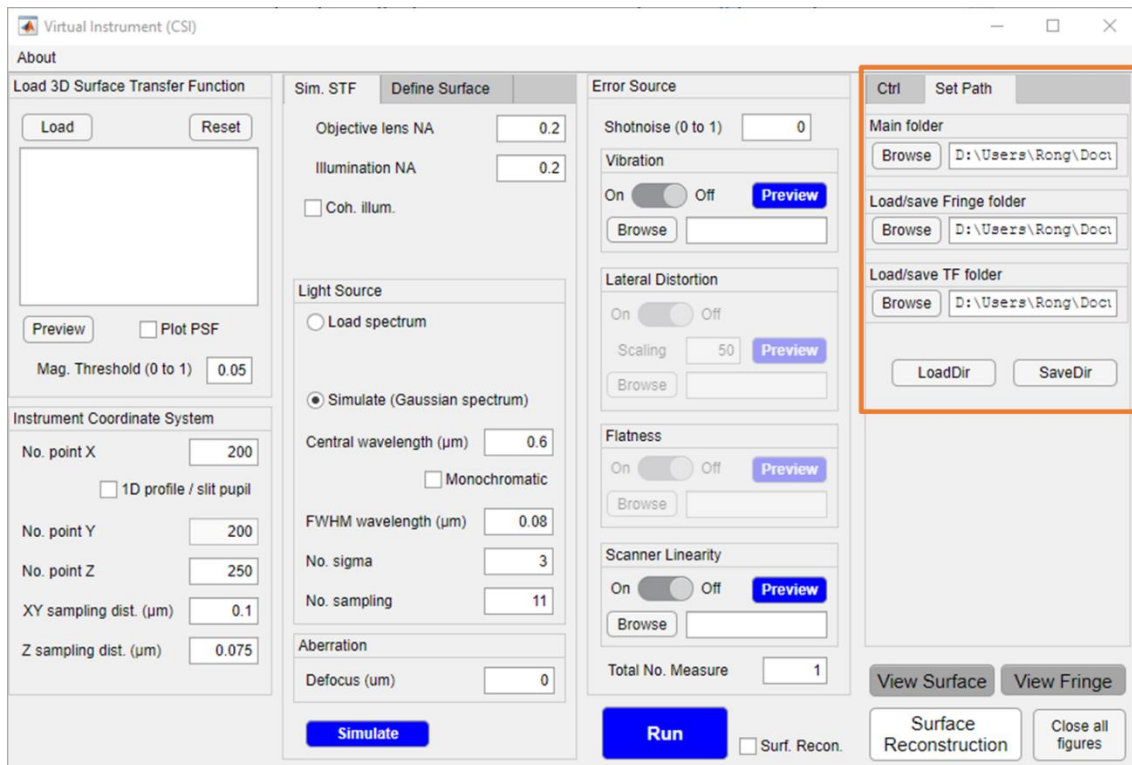
Verify that version 9.9 (R2020b) of the MATLAB Runtime is installed (for Windows). If not, download and install the Windows version of the MATLAB Runtime for R2020b from the following link on the MathWorks website:

https://ssd.mathworks.com/supportfiles/downloads/R2020b/Release/5/deployment_files/installer/complete/win64/MATLAB_Runtime_R2020b_Update_5_win64.zip

Put the following folders together with the VI app file in the same directory:



Open the VI app. The working directories are already set. If changing the main folder, make sure folder <system files> is located in the new main folder to allow saving and loading of the directories.



The general flow of a virtual CSI measurement is:

1. Generate and/or load a 3D surface transfer function (3D STF)
2. Define the surface to be measured
3. Define error sources
4. Run the virtual measurement

2. Setting up the virtual instrument

2.1 Define coordinate system

Set the number of sampling points for the x, y and z axes. For the quasi-3D case where a slit pupil and 1D surface profile is used, <No. point Y> will be set to be 1. Otherwise, <No. point Y> equals <No. point X>. The <XY sampling distance> should be at least smaller than $\lambda/2$ and the Nyquist sampling distance for the surface. The recommended <XY sampling distance> is 0.1 μm to start with. The default <Z sampling distance> is $\lambda/8$.

Caution: the RAM usage can be significant when making 3D simulations with large numbers of sampling points for x, y and z axes. It is easy to crash the program by using input values that are too large. Please use Task Manager to monitor the RAM usage.

3D case (circular pupil)	Quasi 3D case (slit pupil)
Instrument Coordinate System	
No. point X <input type="text" value="200"/>	No. point X <input type="text" value="200"/>
<input type="checkbox"/> 1D profile / slit pupil	<input checked="" type="checkbox"/> 1D profile / slit pupil
No. point Y <input type="text" value="200"/>	No. point Y <input type="text" value="1"/>
No. point Z <input type="text" value="250"/>	No. point Z <input type="text" value="250"/>
XY sampling dist. (um) <input type="text" value="0.1"/>	XY sampling dist. (um) <input type="text" value="0.1"/>
Z sampling dist. (um) <input type="text" value="0.075"/>	Z sampling dist. (um) <input type="text" value="0.075"/>

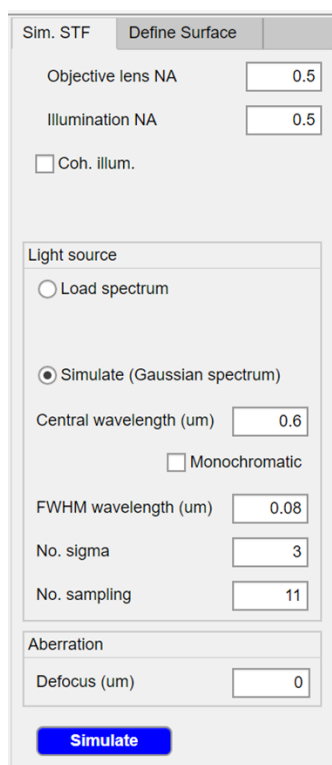
Once the 3D STF is generated and loaded (see section 0), the XY and Z sampling distances cannot be changed, but the number of points can be increased or decreased depending on the desired field of view (FOV) and scan length.

2.2 Simulate 3D STF

In the <Sim. STF> tab, parameters of the 3D STF can be set. For a fully filled pupil, the illumination NA is usually the same as the objective NA. Choose coherent illumination by ticking the box <Coh. Illum.>. A light source with a Gaussian spectrum can be generated. The parameters <No. sigma> and <No. sampling> controls the sampling of the spectrum. Defocus is expressed in terms of the axial offset of the reference mirror from its ideal position.

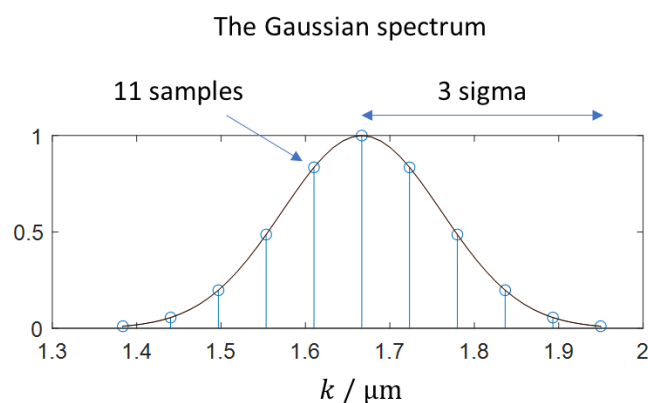
The spectrum data contained in a .mat file can also be loaded. This file must contain two variables: the wavenumber "vk0" in the unit of $1/\mu\text{m}$ and the normalised strength "vSk" in arbitrary units. Both are $(1 \times N)$ row vectors.

Click <Simulate> to generate the 3D STF and save the result to the "TF" folder.



The screenshot shows the 'Sim. STF' software interface with the following parameters:

- Objective lens NA: 0.5
- Illumination NA: 0.5
- ☐ Coh. illum.
- Light source:
 - ☐ Load spectrum
 - ☒ Simulate (Gaussian spectrum)
- Central wavelength (um): 0.6
- ☐ Monochromatic
- FWHM wavelength (um): 0.08
- No. sigma: 3
- No. sampling: 11
- Aberration:
 - Defocus (um): 0
- Simulate** button



2.3 Loading the 3D STF

If a 3D STF is ready for use, e.g. experimentally obtained or simulated, then load the 3D TF by clicking the <Load> button. The sampling parameters will be overwritten correspondingly.

The image displays two versions of the 'Load 3D Surface Transfer Function' dialog box. The left version is the initial state, and the right version is after loading a file.

Left Dialog (Initial State):

- Buttons: Load, Reset
- Text Area: (Empty)
- Buttons: Preview, ☐ Plot PSF
- Mag. Threshold (0 to 1): 0.05
- Instrument Coordinate System**
- No. point X: 200
- ☐ 1D profile / slit pupil
- No. point Y: 200
- No. point Z: 250
- XY sampling dist. (um): 0.2
- Z sampling dist. (um): 0.075

Right Dialog (After Loading):

- Buttons: Load, Reset
- Text Area: m3H_sim_NA0.5iNA0.5_wv0.6_f
whm0.08um_x400y1z250_dxy0.1
dz0.075_defocus0um_apod0-
test1.mat
- Buttons: Preview, ☐ Plot PSF
- Mag. Threshold (0 to 1): 0.05
- Instrument Coordinate System**
- No. point X: 400
- ☒ 1D profile / slit pupil
- No. point Y: 1
- No. point Z: 250
- XY sampling dist. (um): 0.1
- Z sampling dist. (um): 0.075

Click <Preview> to visualise the 3D STF. Tick <Plot PSF> to visualise the 3D point spread function (PSF).

Load a 3D STF before defining the surface. Do not change any parameters in the <Sim. STF> tab after the 3D STF is loaded.

2.4 Advanced settings

The generalised 3D pupil is a (partial) spherical shell in the spatial frequency domain. In theory, the shell is infinitely thin and expressed by a Dirac delta function. However, in a numerical calculation, the delta function is approximated by a Gaussian function with a sufficiently small standard deviation that is defined by the parameter <K shell sigma>. The value is automatically optimised.

The parameter <Pupil apodisation = 0> corresponds to a uniform angular apodisation (the Herschel condition); <Pupil apodisation = 0.5> corresponds to a perfect aplanatic case; <Pupil apodisation = 1> corresponds to a uniformly distributed 2D pupil.

Camera Bitdepth	16 ▼
Scan speed (um/s)	13.4
Foil sigma (um)	0.15
K shell sigma	0.05
TF mag threshold	1e-06
Pupil apodisation	0 ▼

3. Defining a surface

To define the surface, go to the <Define Surface> tab.

3.1 Sampling parameters

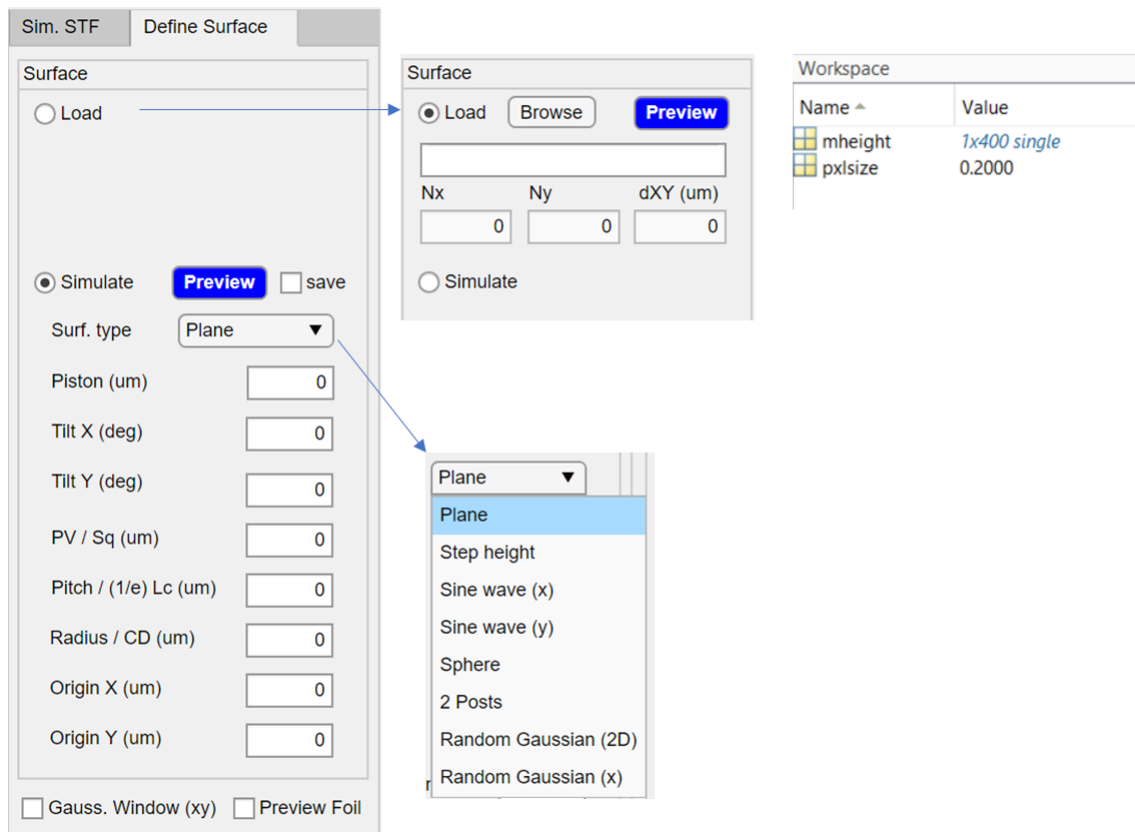
Note that after loading the 3D STF, the X, Y and Z sampling distances cannot be changed but the number of sampling points can. The product of <No. point Z> and <Z sampling distance> determines the total scan length, which should be larger than the total variation of the surface height. The product of <No. point X> and <XY sampling distance> determines the total field of view (FOV). Ideally, <XY sampling distance> should be smaller than the Nyquist sampling distance of the surface.

3.2 Simulate or load a surface

The surface can be either simulated or loaded.

Select <Simulate> and choose a surface type. There are eight selections:

- <Piston>: translationally shifts the surface along Z axis (applies to all surface types)
- <Tilt X or Y>: tilts the surface with respect to X/Y axes (applies to Plane, Sine wave and Gaussian surface)
- <PV / Sq>: the peak-to-valley (PV) of Sine wave, Step height, 2 Posts; or the Sq value of Random Gaussian surface
- <Pitch / (1/e) Lc>: the pitch of Sine wave and 2 Posts; or the 1/e correlation length of Random Gaussian surface
- <Radius / CD>: the radius of Sphere; or the critical dimension of 2 Posts
- <Origin X or Y>: translationally shifts the surface along X/Y axes (applies to all surface types)



Choose an appropriate value for <No. point X>; click <Preview> to visualise the surface topography/profile. Tick <save> to save the visualised surface data. Tick <Preview Foil> to visualise the foil model of the surface and the corresponding spectrum. Tick <Gauss. Window (xy)> to add a lateral Gaussian window on the foil model to reduce its amplitude to nearly zero at the end of the FOV.

To load existing surface data, select <Load> and use <Browse> to choose the surface data. The surface data must be a .mat file that contains two variables: "mheight" and "pxlsize". "mheight" is a ($M \times N$) matrix where M equals 1 or N ; "pxlsize" and the XY sampling distance must be equal.

3.3 Advanced settings

The foil model of the surface is expressed by a Dirac delta function. In the numerical calculation, the delta function is approximated by a Gaussian function which has a standard deviation of <Foil sigma>. This parameter

should be larger than the Z sampling distance. The default value is 0.15 μm .

4. Error sources

In this version of the software, the user can simulate the effects of the camera noise, vibration and actuator linearity. The effects of these influence factors are directly incorporated into the 3D interferogram. A Monte Carlo method is used for repeated measurements.

4.1 Camera noise

The parameter to control the shot noise level is a weighting factor, taking a value in the range $[0,1]$. The noise value is usually smaller than 10 % of the signal, corresponding to a weighting factor of 0.1.

Error Source

Shotnoise (0 to 1)

Vibration

On ☐ Off

Lateral Distortion

On ☐ Off

Scaling

Flatness

On ☐ Off

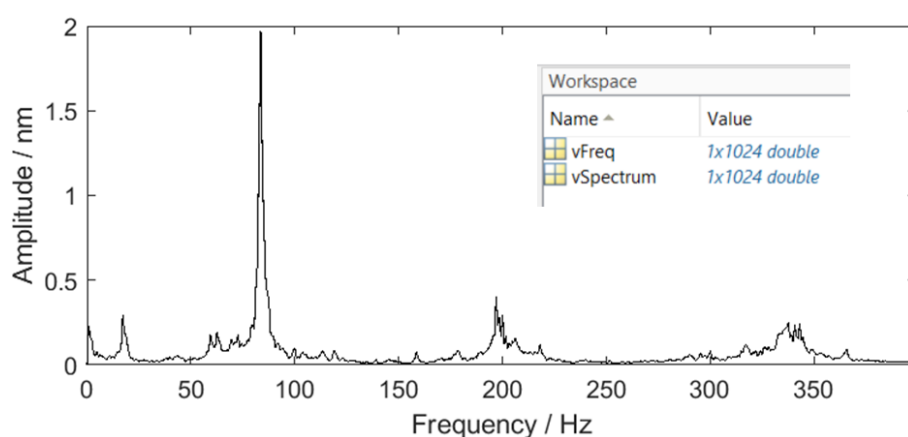
Scanner Linearity

On ☐ Off

Total No. Measure

4.2 Vibration

To incorporate the effect of vibration, the amplitude spectrum of the vibration is required. The spectrum data should be saved in a .mat file which contains two variables named *vFreq* (temporal frequency in hertz) and *vSpectrum* (amplitude spectrum in nanometres), respectively. Both variables are row vectors. The <Scan speed> parameter in the Ctrl panel needs to be specified.



Click <Browse> to load the vibration spectrum data. Click <Preview> to visualise the spectrum. Switch on to enable the effect of vibration.

Error Source

Shotnoise (0 to 1)

0

Vibration

On

Off

Preview

Browse

Lateral Distortion

On

Off

Preview

Scaling

50

Preview

Browse

Flatness

On

Off

Preview

Browse

Scanner Linearity

On

Off

Preview

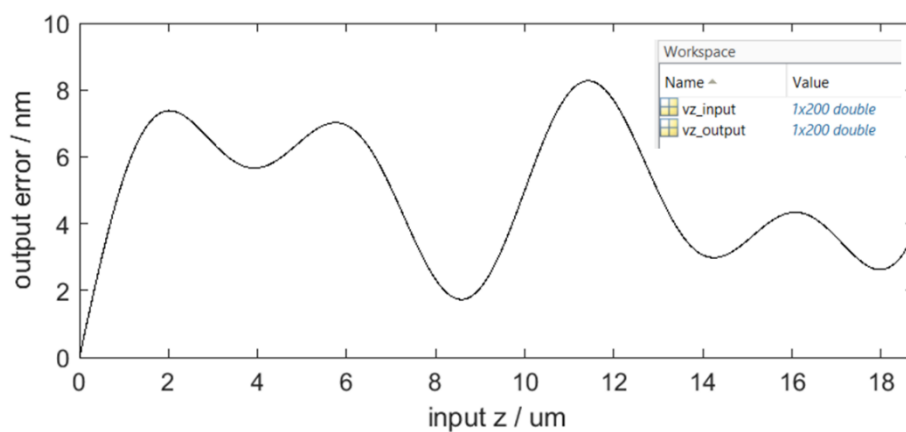
Browse

Total No. Measure

1

4.3 Actuator linearity

To incorporate the effect of actuator linearity, the linearity information should be saved in a .mat file which contains two variables named `vz_input` (nominal scan position in micrometre) and `vz_output` (actual scan position in micrometre), respectively. Both variables are row vectors.



Click <Browse> to load the linearity data. Click <Preview> to visualise the linearity error. Switch on to enable the effect of linearity.

The screenshot shows the 'Error Source' configuration window. It contains several sections for different error types:

- Shotnoise (0 to 1)**: A text input field with the value '0'.
- Vibration**: A toggle switch set to 'Off', a 'Preview' button, and a 'Browse' button for file selection.
- Lateral Distortion**: A toggle switch set to 'Off', a 'Scaling' input field with the value '50', a 'Preview' button, and a 'Browse' button.
- Flatness**: A toggle switch set to 'Off', a 'Preview' button, and a 'Browse' button.
- Scanner Linearity**: This section is highlighted with an orange border. It features a toggle switch set to 'Off', a 'Preview' button, and a 'Browse' button.
- Total No. Measure**: A text input field with the value '1'.

4.4 Lateral distortion and flatness

The effects of lateral distortion and residual flatness can usually be added to the final measured surface topography. Therefore, the modelling of lateral distortion and residual flatness is disabled in the current version of the VCSI software.

5. Measure

The virtual measurement can be carried out if:

- 1) The 3D STF is loaded
- 2) The surface is defined
- 3) Error sources are specified (optional)

Start the measurement by clicking <Run>; the interferogram will be generated. Click <Surface Reconstruction> and select a saved interferogram to calculate the surface topography. The reconstruction algorithm is based on the frequency domain analysis method. Use <FDA SNR thr> to set the threshold of the SNR for valid fringe data.

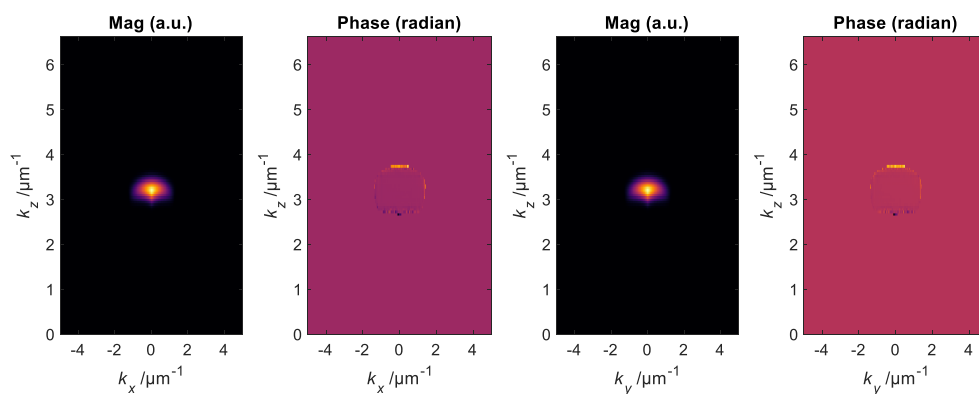
If the tick box <Surf. Recon.> is checked when clicking <Run>, the surface topography will be reconstructed from the interferogram.

The measurement can be automatically repeated, and the number of repeats is controlled by <Total No. Measure>.

6. Example I

Simulate a 3D STF using the following settings:

Save the 3D STF in the "TF" folder. Colour bar of the 3D STF plot can be switched on and off by the user.



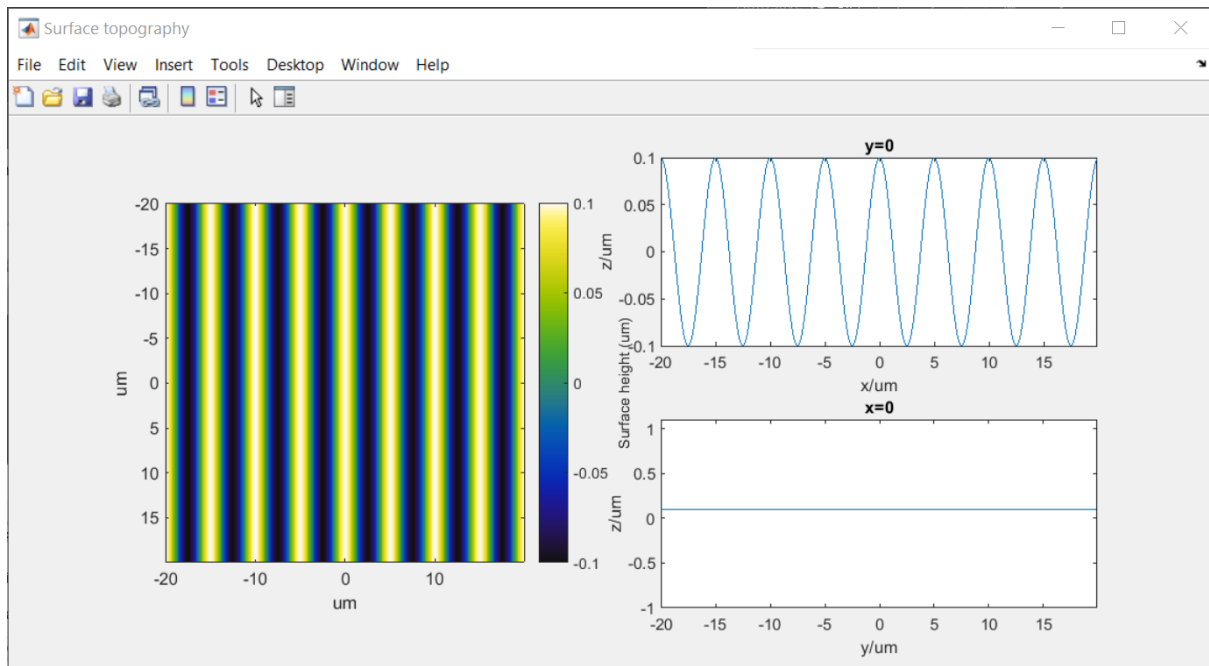
Load the saved 3D STF. Note that If a 3D STF is not named m3H*.mat (e.g. if the file is renamed by the user), it will not appear when browsing for 3D STF to load. In that case, the user can change the filter to “all files”.

Then, define a sinusoidal surface by choosing “Sine wave (x)” from the drop-down list:

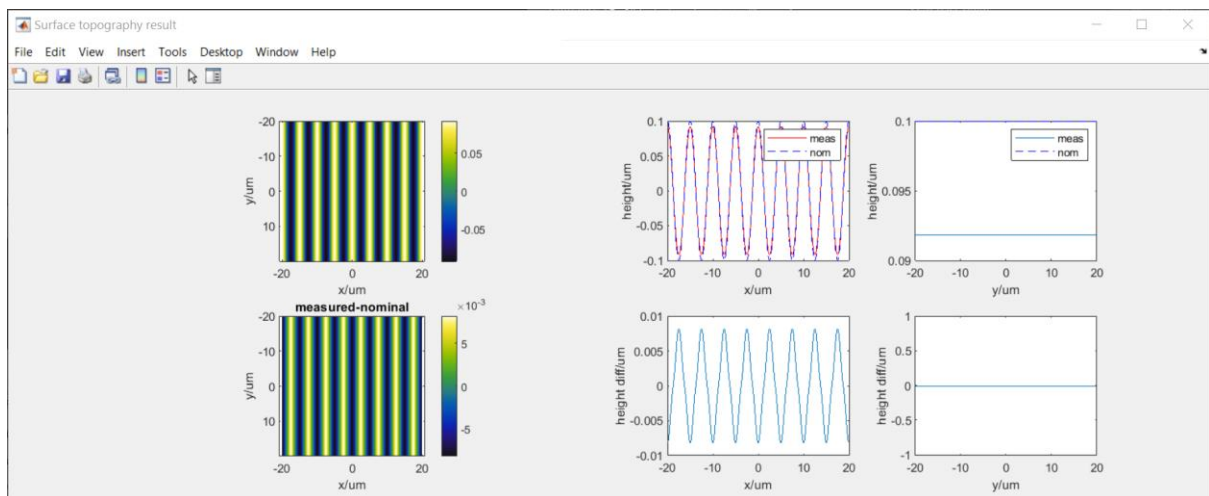
The screenshot shows the 'Virtual Instrument (CSI)' window with the 'Define Surface' tab selected. The interface is divided into several sections:

- Load 3D Surface Transfer Function:** Includes 'Load' and 'Reset' buttons. A text box contains the file path: `m3H_sim_NA0.4iNA0.4_wv0.6_fwhm0.05um_x400y400z250_dxy0.1dz0.075_defocus0um_apod0.mat`. Below are 'Preview' and 'Plot PSF' buttons, and a 'Mag. Threshold (0 to 1)' slider set to 0.05.
- Instrument Coordinate System:** Contains input fields for 'No. point X' (400), 'No. point Y' (400), 'No. point Z' (250), 'XY sampling dist. (μm)' (0.1), and 'Z sampling dist. (μm)' (0.075). There is a checkbox for '1D profile / slit pupil'.
- Sim. STF / Define Surface:** The 'Surface' section has 'Load' and 'Simulate' radio buttons. 'Simulate' is selected, with 'Preview' and 'save' buttons. A dropdown menu shows 'Sine wave...'. Below are input fields for 'Piston (μm)', 'Tilt X (deg)', 'Tilt Y (deg)', 'PV / Sq (μm)', 'Pitch / (1/e) Lc (μm)', 'Radius / CD (μm)', 'Origin X (μm)', and 'Origin Y (μm)'. At the bottom are checkboxes for 'Gauss. Window (xy)' and 'Preview Foil'.
- Error Source:** Contains sections for 'Shotnoise (0 to 1)' (0), 'Vibration' (On/Off toggle, 'Preview' button, 'Browse' button), 'Lateral Distortion' (On/Off toggle, 'Preview' button, 'Browse' button), 'Flatness' (On/Off toggle, 'Preview' button, 'Browse' button), and 'Scanner Linearity' (On/Off toggle, 'Preview' button, 'Browse' button). A 'Total No. Measure' input field is set to 1.
- Ctrl / Set Path:** Includes 'Num. precision' (single), 'Autosave fringe' (On/Off toggle), 'Plot all figures' (On/Off toggle), 'Camera Bitdepth' (16), 'Scan speed (μm/s)' (13.4), 'Foil sigma (μm)' (0.15), 'K shell sigma (1/μm)' (0.05), 'TF mag threshold' (1e-06), 'Pupil apodisation' (0), 'FDA Nz Clip' (99), and 'FDA SNR thr' (10).
- Bottom Section:** Features a large blue 'Run' button, a 'Surf. Recon.' checkbox, and buttons for 'View Surface', 'View Fringe', 'Surface Reconstruction', and 'Close all figures'.

Preview the surface:



Tick <Surf. Recon.> and Click <Run> to get the measured surface and the error map:



The fringe data and surface measurement result (file name ends with "_zFDA") are saved in the "Fringe" folder:

Name
Fringe_Sine wave (x)_0_0_0_5_0.2_TF_1_dx0.1_dz0.075_Cam_0_Vib_Off_Lin_Off_Bit_16_rep1_zFDA
Fringe_Sine wave (x)_0_0_0_5_0.2_TF_1_dx0.1_dz0.075_Cam_0_Vib_Off_Lin_Off_Bit_16_rep1

7. Example II

Load a saved 3D STF:

The screenshot displays the 'Virtual Instrument (CSI)' software window. The 'Define Surface' tab is active, showing various parameters for surface definition. The 'Load 3D Surface Transfer Function' section on the left contains a text box with a file path and buttons for 'Load', 'Reset', 'Preview', and 'Plot PSF'. The 'Instrument Coordinate System' section below it has input fields for 'No. point X' (400), 'No. point Y' (400), 'No. point Z' (250), 'XY sampling dist. (um)' (0.1), and 'Z sampling dist. (um)' (0.075). The 'Sim. STF' section includes 'Objective lens NA' (0.4), 'Illumination NA' (0.4), a 'Coh. illum.' checkbox, and a 'Light Source' section with 'Load spectrum' and 'Simulate (Gaussian spectrum)' options. The 'Define Surface' section has 'Central wavelength (um)' (0.6), 'FWHM wavelength (um)' (0.08), 'No. sigma' (3), 'No. sampling' (11), and 'Aberration' (Defocus (um) 0). The 'Error Source' section on the right includes 'Shotnoise (0 to 1)' (0), 'Vibration' (On/Off), 'Lateral Distortion' (On/Off), 'Flatness' (On/Off), and 'Scanner Linearity' (On/Off), each with a 'Preview' button. The 'Ctrl' section on the far right has 'Num. precision' (single), 'Autosave fringe' (On/Off), 'Plot all figures' (On/Off), 'Camera Bitdepth' (16), 'Scan speed (um/s)' (13.4), 'Foil sigma (um)' (0.15), 'K shell sigma (1/um)' (0.05), 'TF mag threshold' (1e-06), 'Pupil apodisation' (0), 'FDA Nz Clip' (Inf), and 'FDA SNR thr' (10). At the bottom, there are 'Simulate' and 'Run' buttons, an 'Auto' checkbox, and 'View Surface', 'View Fringe', 'Surface Reconstruction', and 'Close all figures' buttons.

Go to <Define Surface> tab, choose Random Gaussian (2D) and set the Sq and Lc values, check <save> box, change <No. point X> to 1000, and click <Preview> to visualise and save the simulated surface data. Note that the 3D STF will be automatically resized to match the number of surface points.

Virtual Instrument (CSI)

About

Load 3D Surface Transfer Function

Load Reset

m3H_sim_NA0.4iNA0.4_vw0.6_f
whm0.05um_x400y400z250_dxy0
.1dz0.075_defocus0um_apod0.m
at

Preview ☐ Plot PSF

Mag. Threshold (0 to 1) 0.05

Instrument Coordinate System

No. point X 1000 ☐ 1D profile / slit pupil

No. point Y 1000

No. point Z 250

XY sampling dist. (μm) 0.1

Z sampling dist. (μm) 0.075

Sim. STF Define Surface

Surface

☐ Load

☒ Simulate Preview ☒ save

Surf. type Random ...

Piston (μm) 0

Tilt X (deg) 0

Tilt Y (deg) 0

PV / Sq (μm) 0.5

Pitch / (1/e) Lc (μm) 10

Radius / CD (μm)

Origin X (μm)

Origin Y (μm)

☐ Gauss. Window (xy) ☐ Preview Foil

Error Source

Shotnoise (0 to 1) 0

Vibration

On Off Preview

Browse

Lateral Distortion

On Off

Scaling 50 Preview

Browse

Flatness

On Off Preview

Browse

Scanner Linearity

On Off Preview

Browse

Total No. Measure 1

Run ☒ Surf. Recon.

Ctrl Set Path

Num. precision single

Autosave fringe On Off

Plot all figures On Off

Camera Bitdepth 16

Scan speed (μm/s) 13.4

Foil sigma (μm) 0.15

K shell sigma (1/μm) 0.05

TF mag threshold 1e-06

Pupil apodisation 0

FDA Nz Clip 99

FDA SNR thr 10

View Surface View Fringe

Surface Reconstruction Close all figures

Select <Load> to load a saved surface.

Virtual Instrument (CSI)

About

Load 3D Surface Transfer Function

Load Reset

m3H_sim_NA0.4iNA0.4_vw0.6_f
whm0.05um_x400y400z250_dxy0
.1dz0.075_defocus0um_apod0.m
at

Preview ☐ Plot PSF

Mag. Threshold (0 to 1) 0.05

Instrument Coordinate System

No. point X 1000 ☐ 1D profile / slit pupil

No. point Y 1000

No. point Z 250

XY sampling dist. (μm) 0.1

Z sampling dist. (μm) 0.075

Sim. STF Define Surface

Surface

☒ Load Browse Preview

Surface(nominal)_Random Gaussii

Nx Ny dXY (μm)

1000 1000 0.1

☐ Simulate

☐ Gauss. Window (xy) ☐ Preview Foil

Error Source

Shotnoise (0 to 1) 0

Vibration

On Off Preview

Browse

Lateral Distortion

On Off

Scaling 50 Preview

Browse

Flatness

On Off Preview

Browse

Scanner Linearity

On Off Preview

Browse

Total No. Measure 1

Run ☒ Surf. Recon.

Ctrl Set Path

Num. precision single

Autosave fringe On Off

Plot all figures On Off

Camera Bitdepth 16

Scan speed (μm/s) 13.4

Foil sigma (μm) 0.15

K shell sigma (1/μm) 0.05

TF mag threshold 1e-06

Pupil apodisation 0

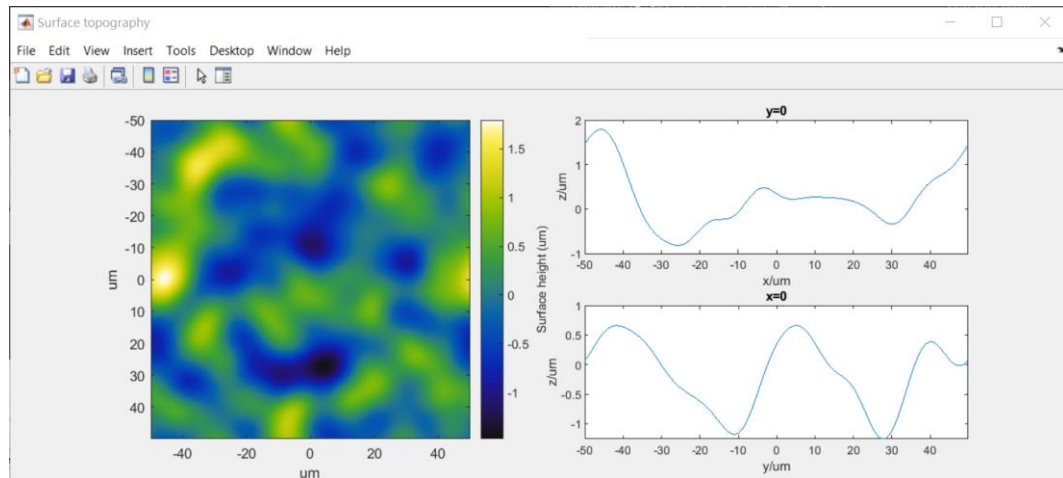
FDA Nz Clip 99

FDA SNR thr 10

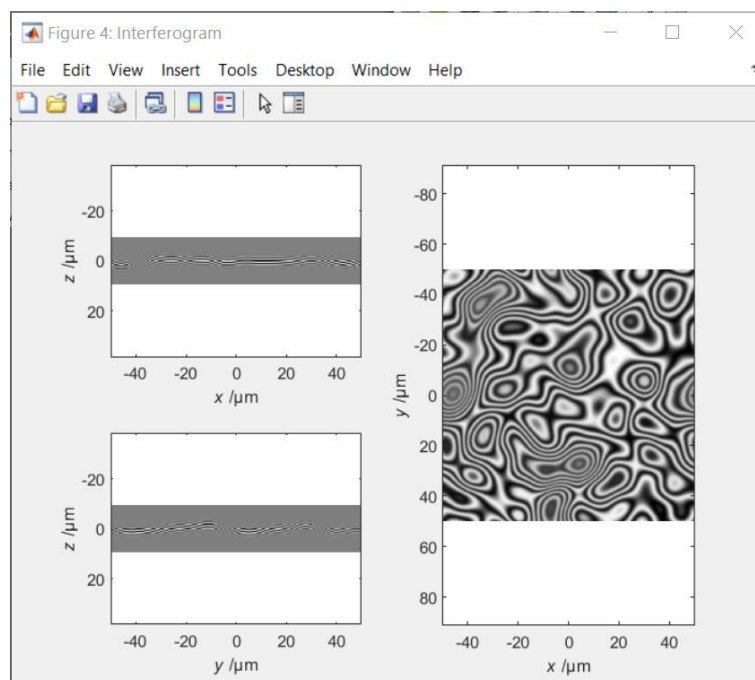
View Surface View Fringe

Surface Reconstruction Close all figures

Preview the surface:



Tick <Surf. Recon.> and Click <Run> to get the 3D interferogram



and the measured surface and the error map.

