User Guide for Virtual Coherence Scanning Interferometer (VCSI)

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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.

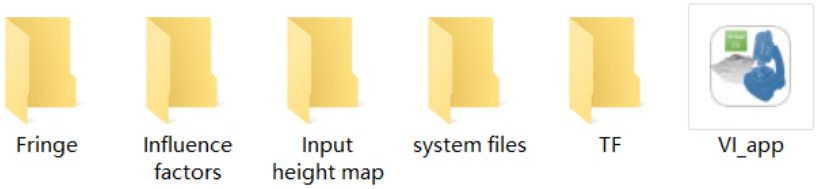
Acknowledgement Special thanks go to Matthew Thomas, Carlos Gomez and Joe Eastwood at the University of Nottingham for testing the software and providing feedback, Prof. Peter de Groot at Zygo Corporation and Prof. Jeremy Coupland at Loughborough University for fruitful technical discussions on optical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

1. Getting started

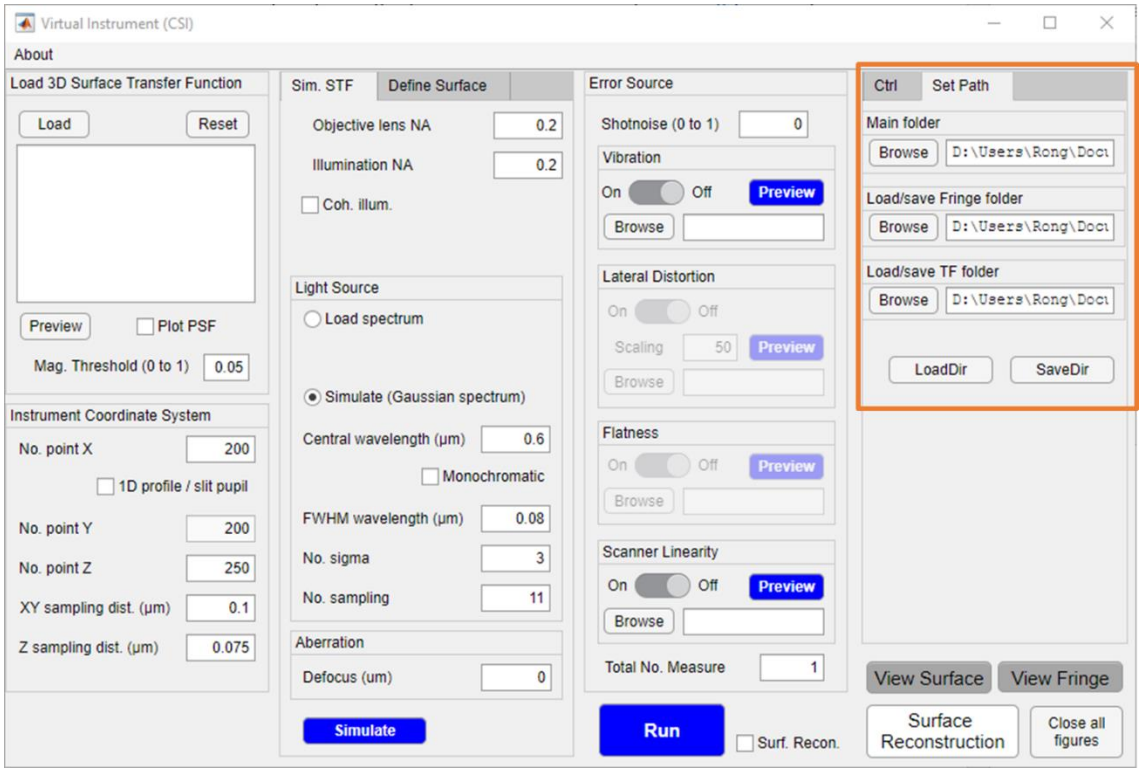
Verify that version 9.9 (R2020b) of the MATLAB Runtime is installed (for Windows). If not, download and install the Windows version of the MATLAB Runtime for R2020b from the following link on the MathWorks website:

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

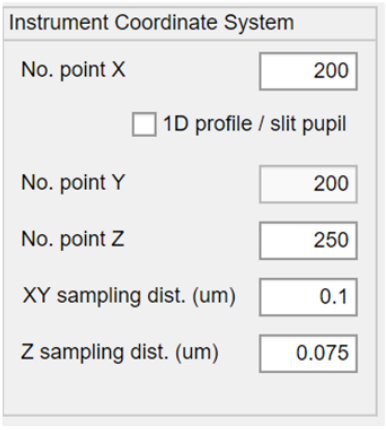
2. Setting up the virtual instrument

2.1 Define coordinate system

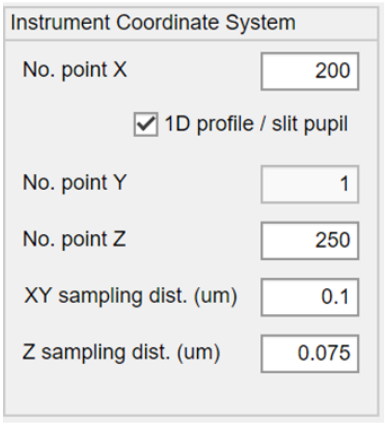
Set the number of sampling points for the x, y and z axes. For the quasi-3D case where a slit pupil and 1D surface profile is used, <No. point Y> will be set to be 1. Otherwise, <No. point Y> equals <No. point X>. The <XY sampling distance> should be at least smaller than $\lambda/2$ and the Nyquist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



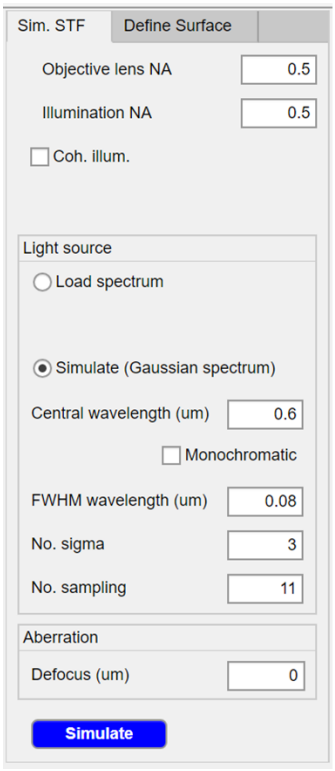
Once the 3D STF is generated and loaded (see section 0), the XY and Z sampling distances cannot be changed, but the number of points can be increased or decreased depending on the desired field of view (FOV) and scan length.

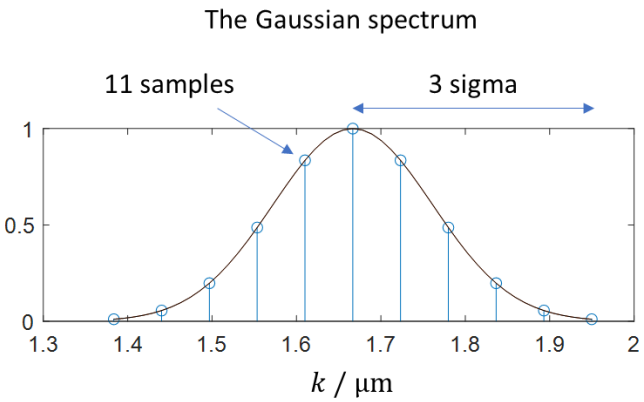
2.2 Simulate 3D STF

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/μm and the normalised strength "vSk" in arbitrary units. Both are (1×*N*) row vectors.

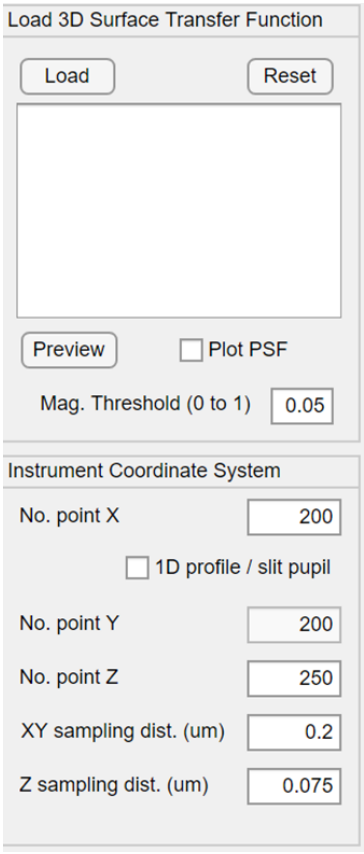
Click <Simulate> to generate the 3D STF and save the result to the "TF" folder.

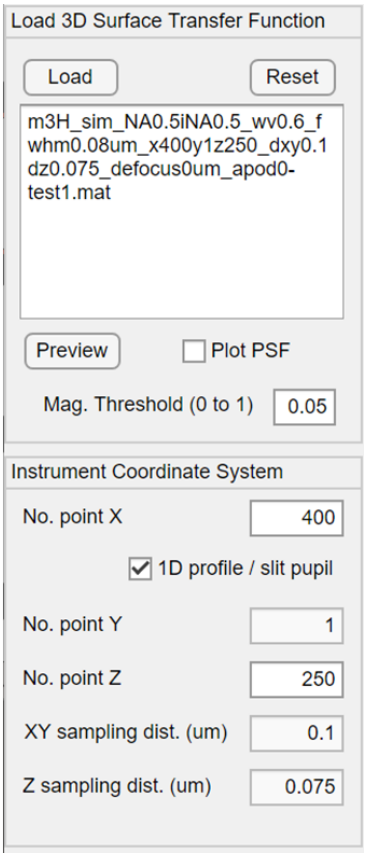




2.3 Loading the 3D STF

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.





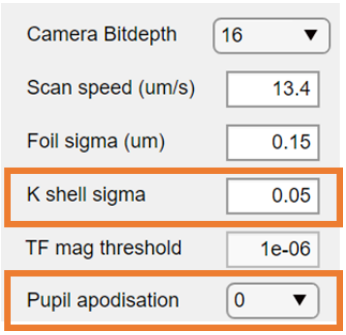
Click <Preview> to visualise the 3D STF. Tick <Plot PSF> to visualise the 3D point spread function (PSF).

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.



3. Defining a surface

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

3.1 Sampling parameters

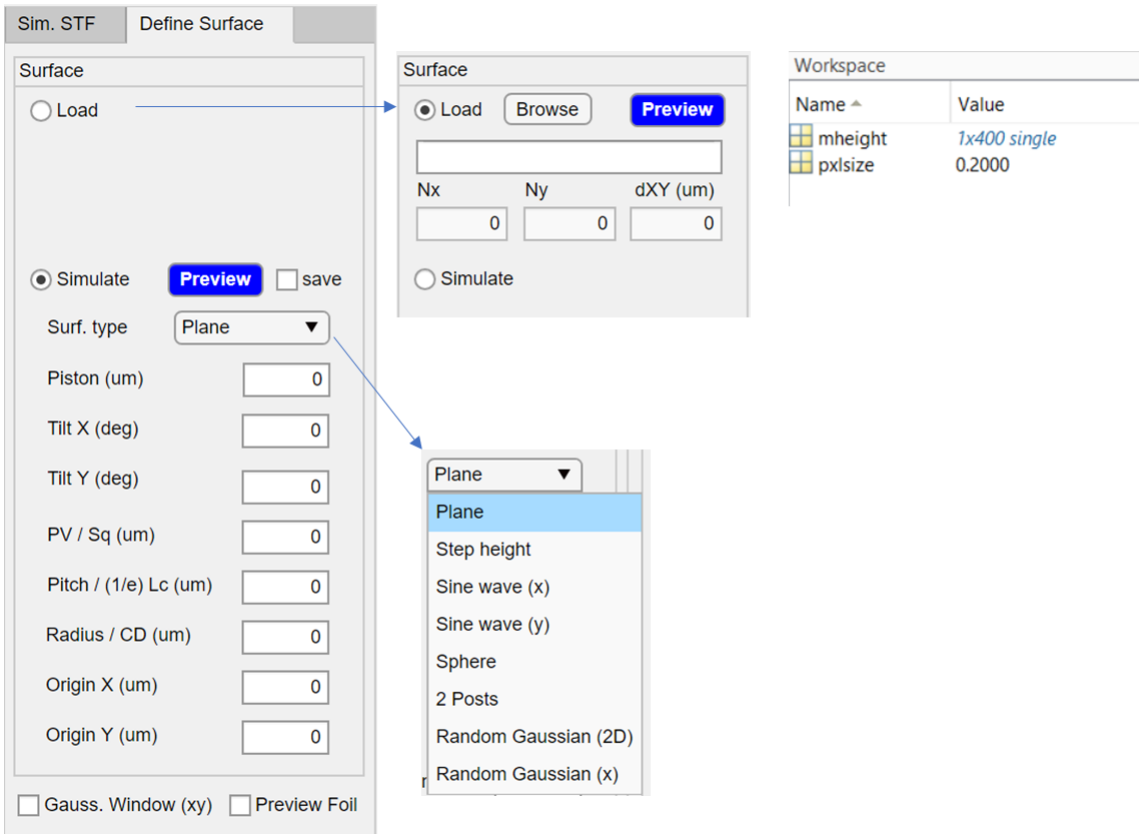
Note that after loading the 3D STF, the X, Y and Z sampling distances cannot be changed but the number of sampling points can. The product of <No. point Z> and <Z sampling distance> determines the total scan length, which should be larger than the total variation of the surface height. The product of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

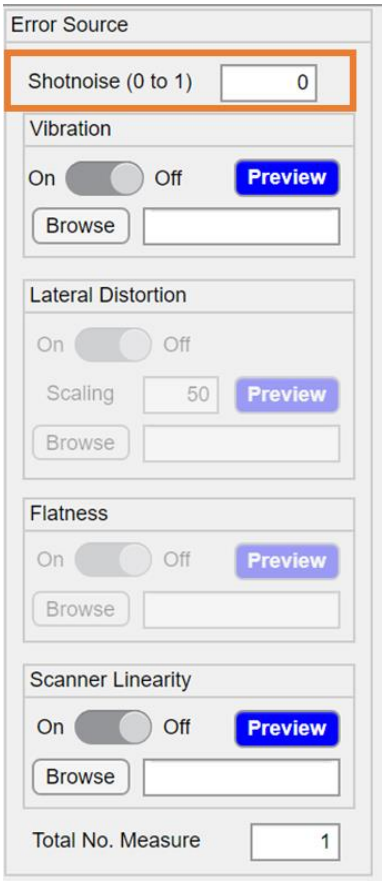
should be larger than the Z sampling distance. The default value is 0.15 μm.

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.

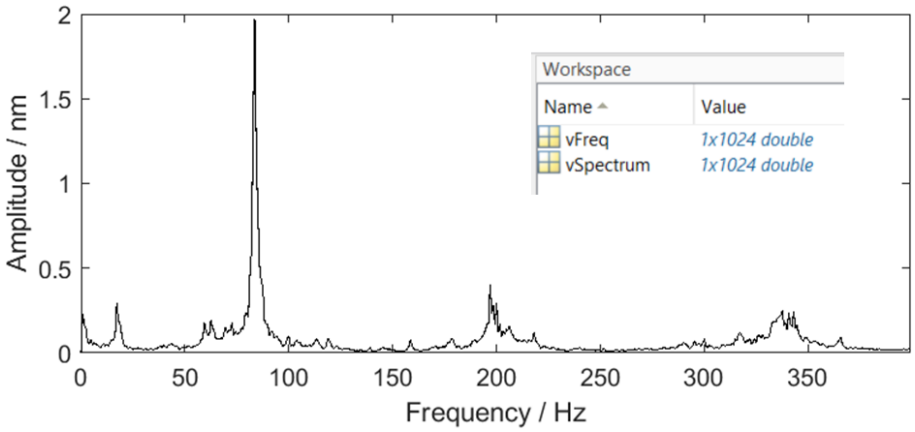
4.1 Camera noise

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.

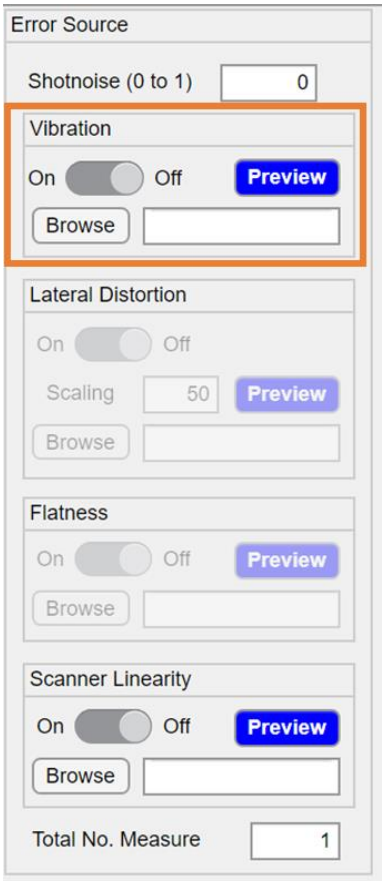


4.2 Vibration

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.

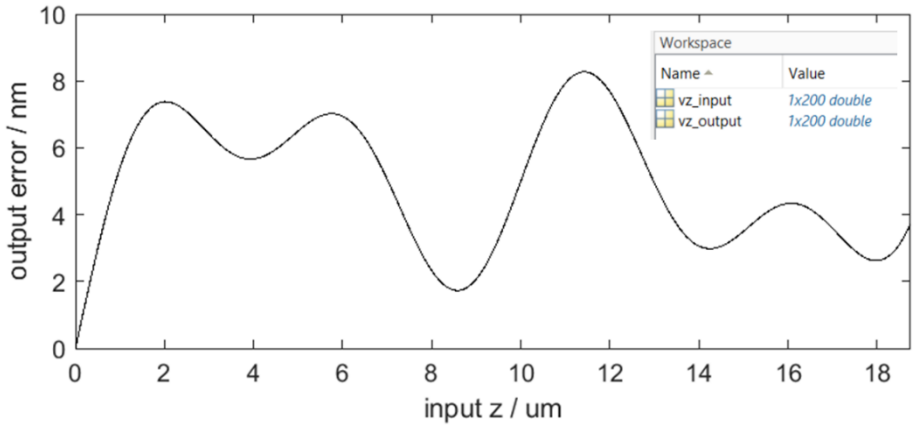


Click <Browse> to load the vibration spectrum data. Click <Preview> to visualise the spectrum. Switch on to enable the effect of vibration.

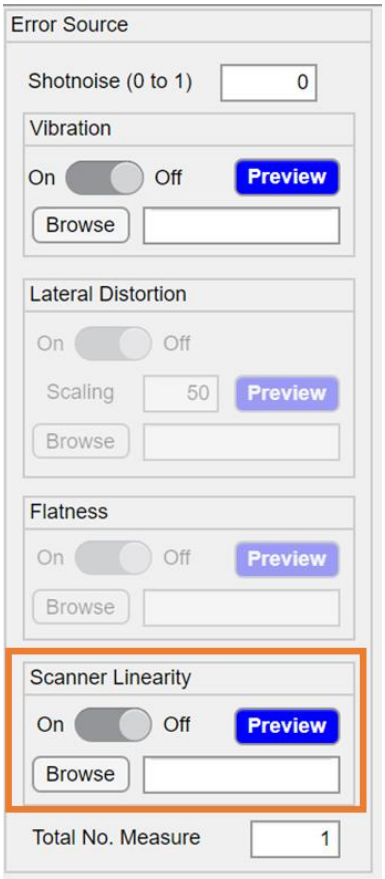


4.3 Actuator linearity

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.



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)

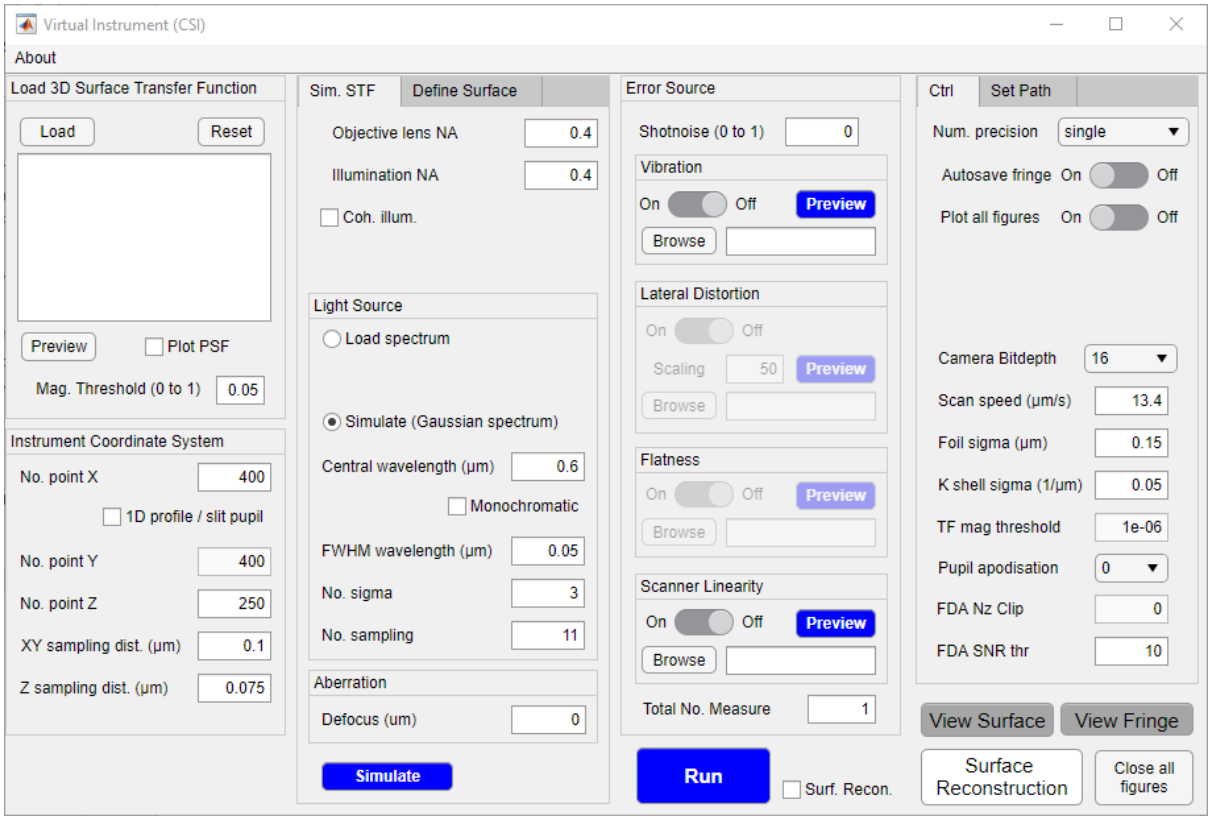
Start the measurement by clicking <Run>; the interferogram will be generated. Click <Surface Reconstruction> and select a saved interferogram to calculate the surface topography. The reconstruction algorithm is based on the frequency domain analysis method. Use <FDA SNR thr> to set the threshold of the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

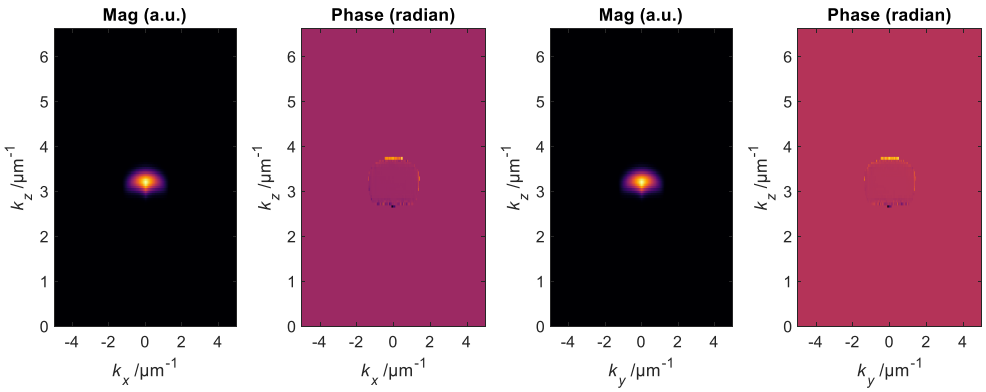
The measurement can be automatically repeated, and the number of repeats is controlled by <Total No. Measure>.

6. Example I

Simulate a 3D STF using the following settings:

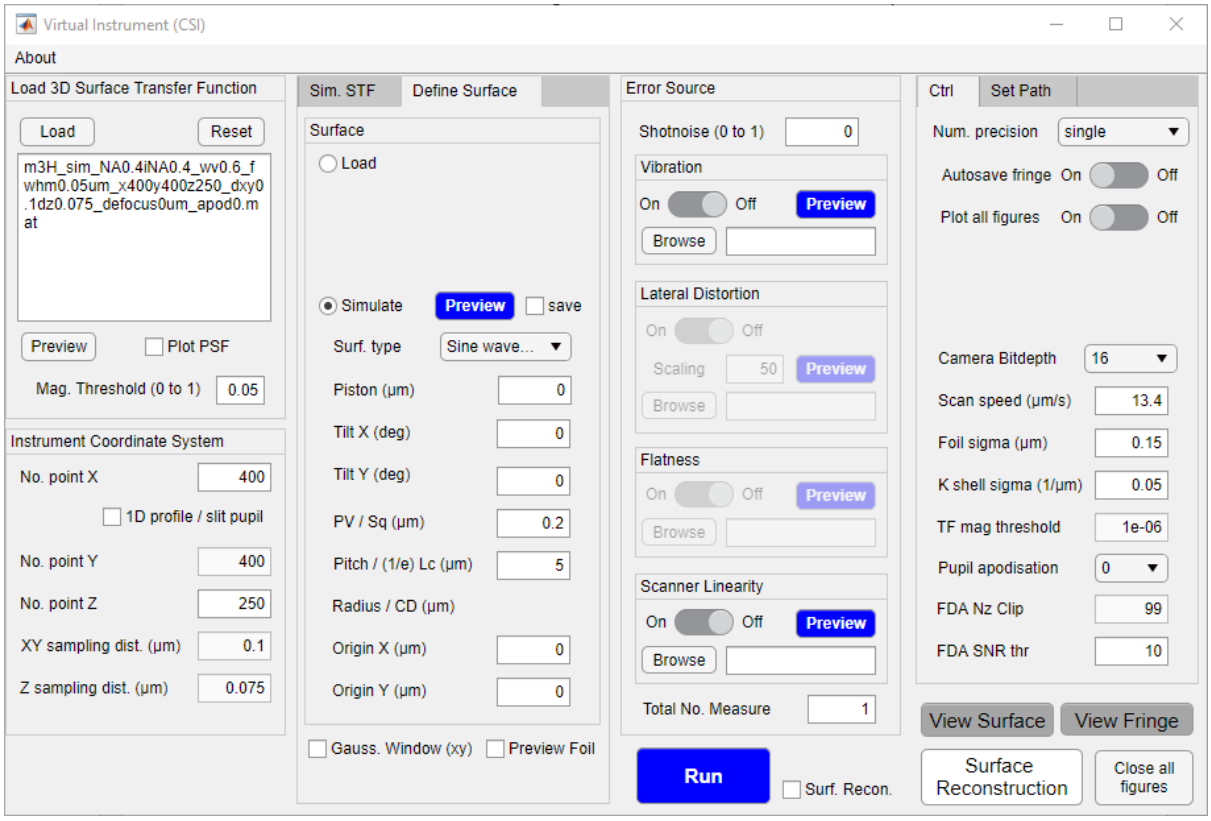


Save the 3D STF in the "TF" folder. Colour bar of the 3D STF plot can be switched on and off by the user.

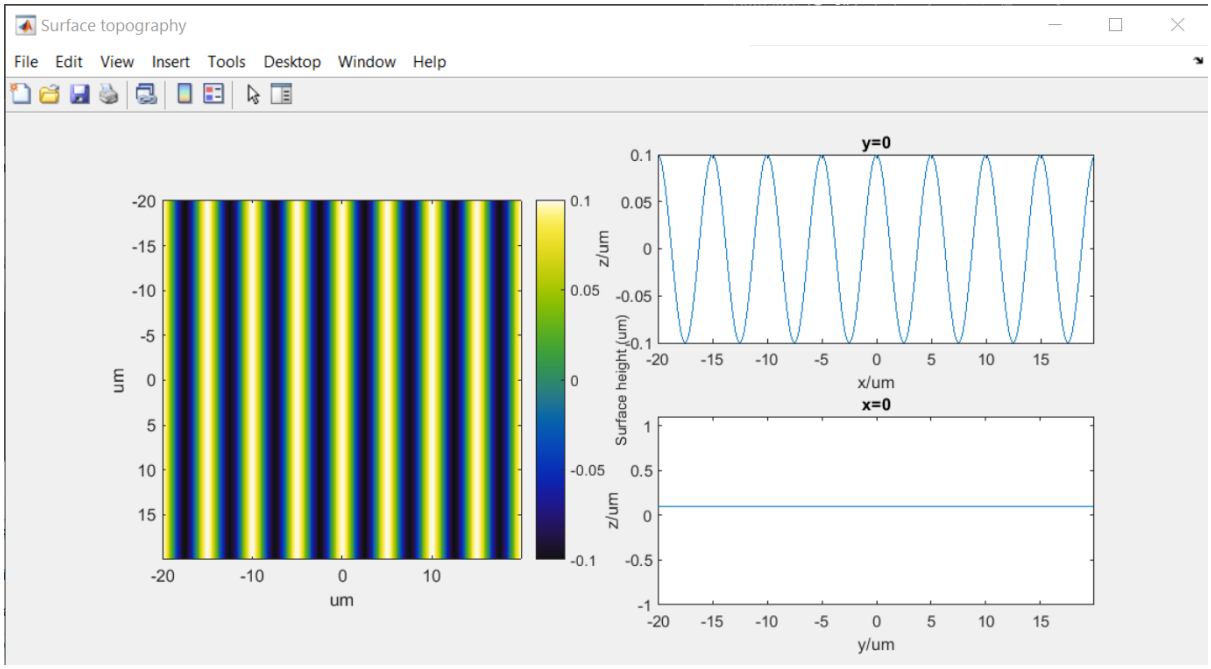


Load the saved 3D STF. Note that If a 3D STF is not named m3H*.mat (e.g. if the file is renamed by the user), it will not appear when browsing for 3D STFs to load. In that case, the user can change the filter to “all files”.

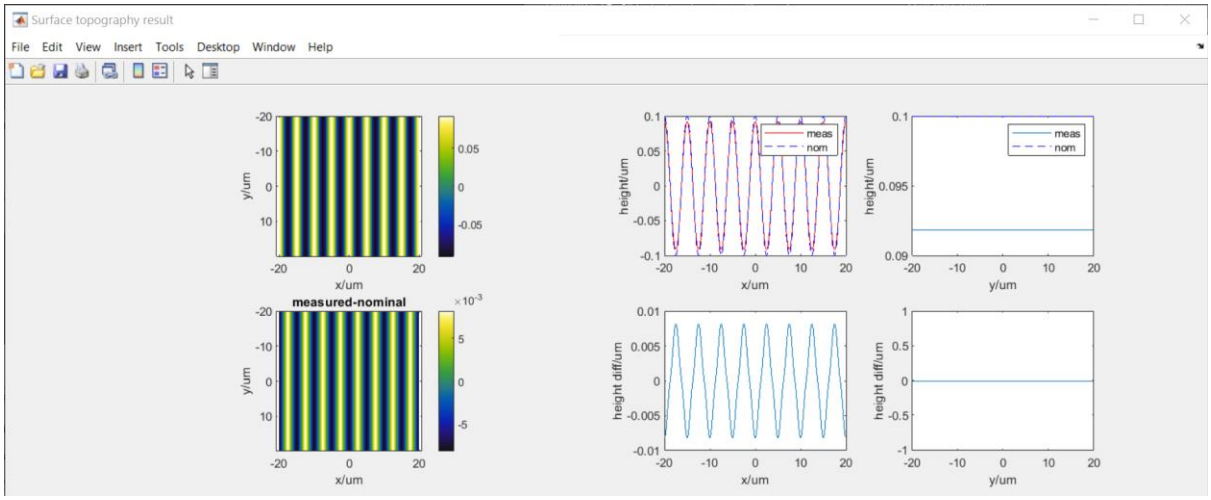
Then, define a sinusoidal surface by choosing “Sine wave (x)” from the drop-down list:



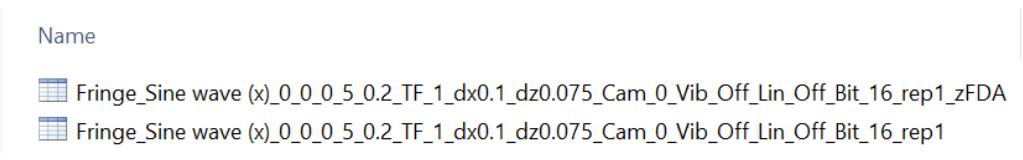
Preview the surface:



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

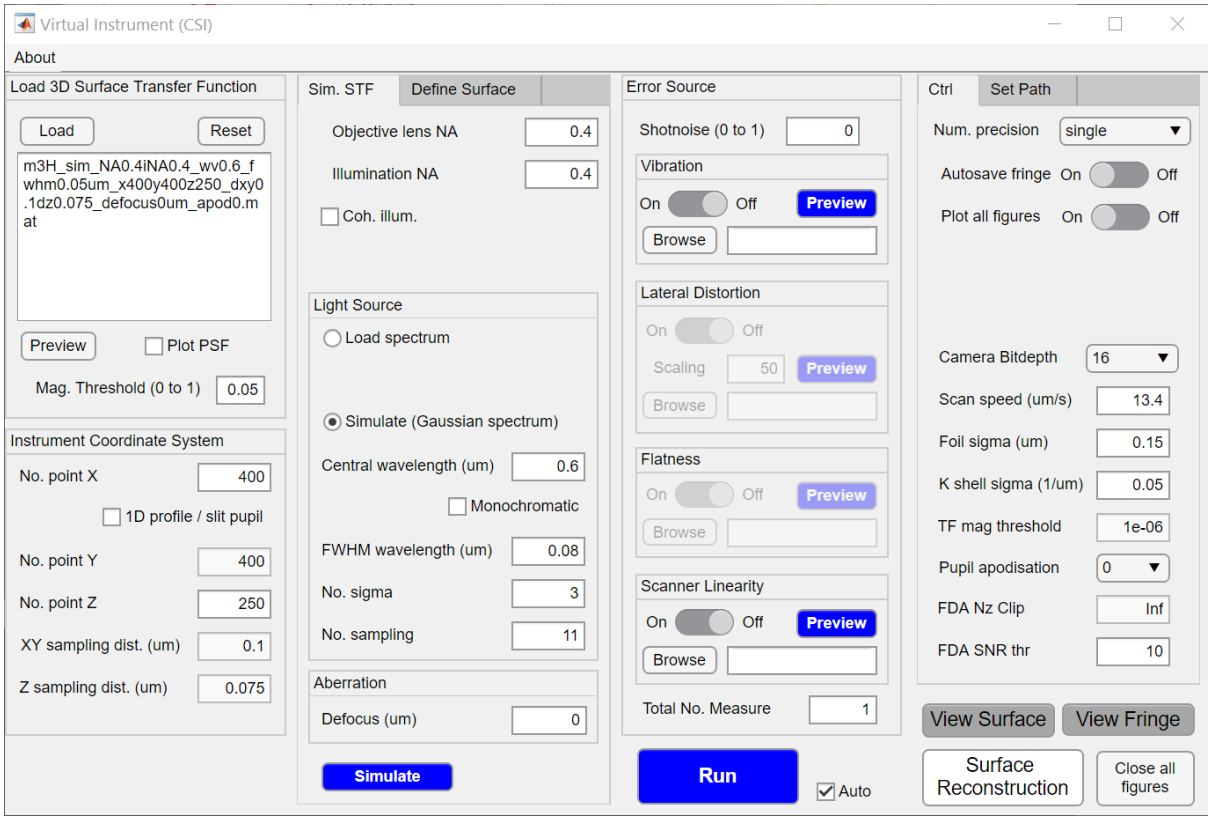


The fringe data and surface measurement result (file name ends with "_zFDA") are saved in the "Fringe" folder:

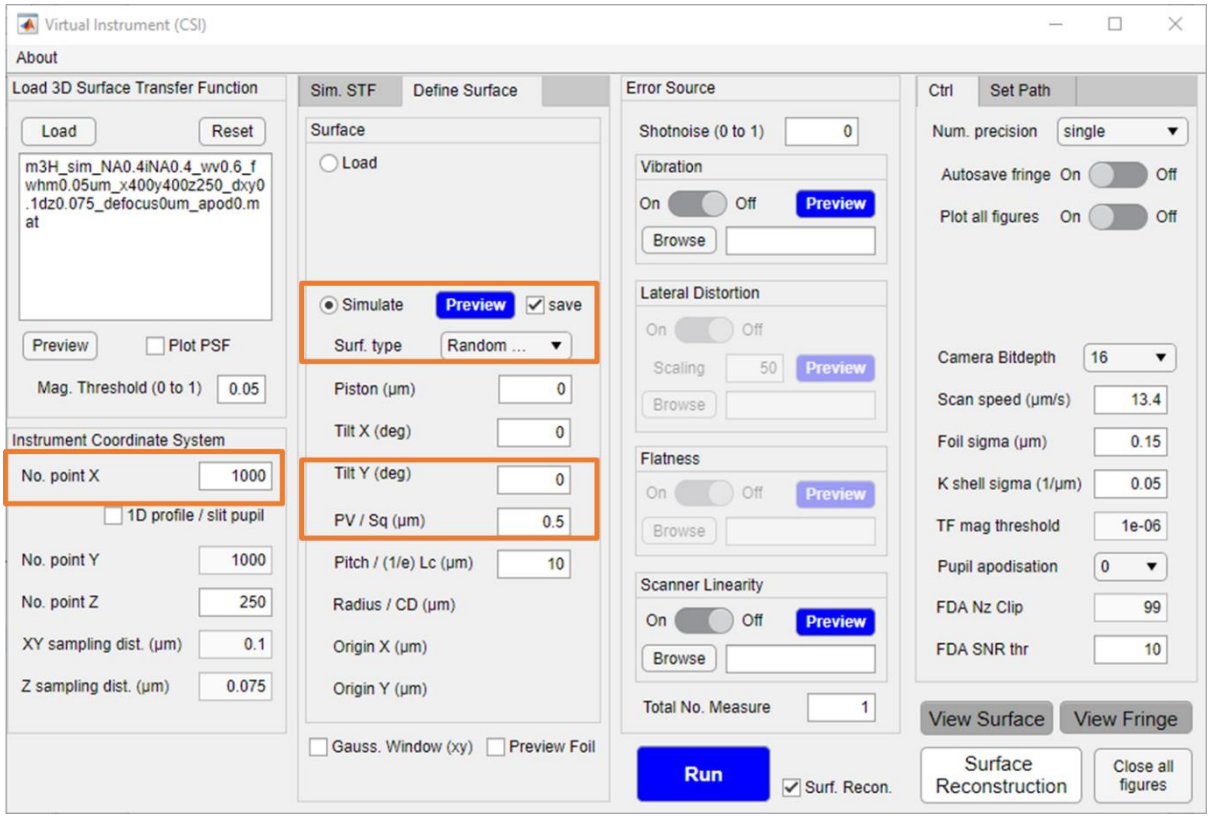


7. Example II

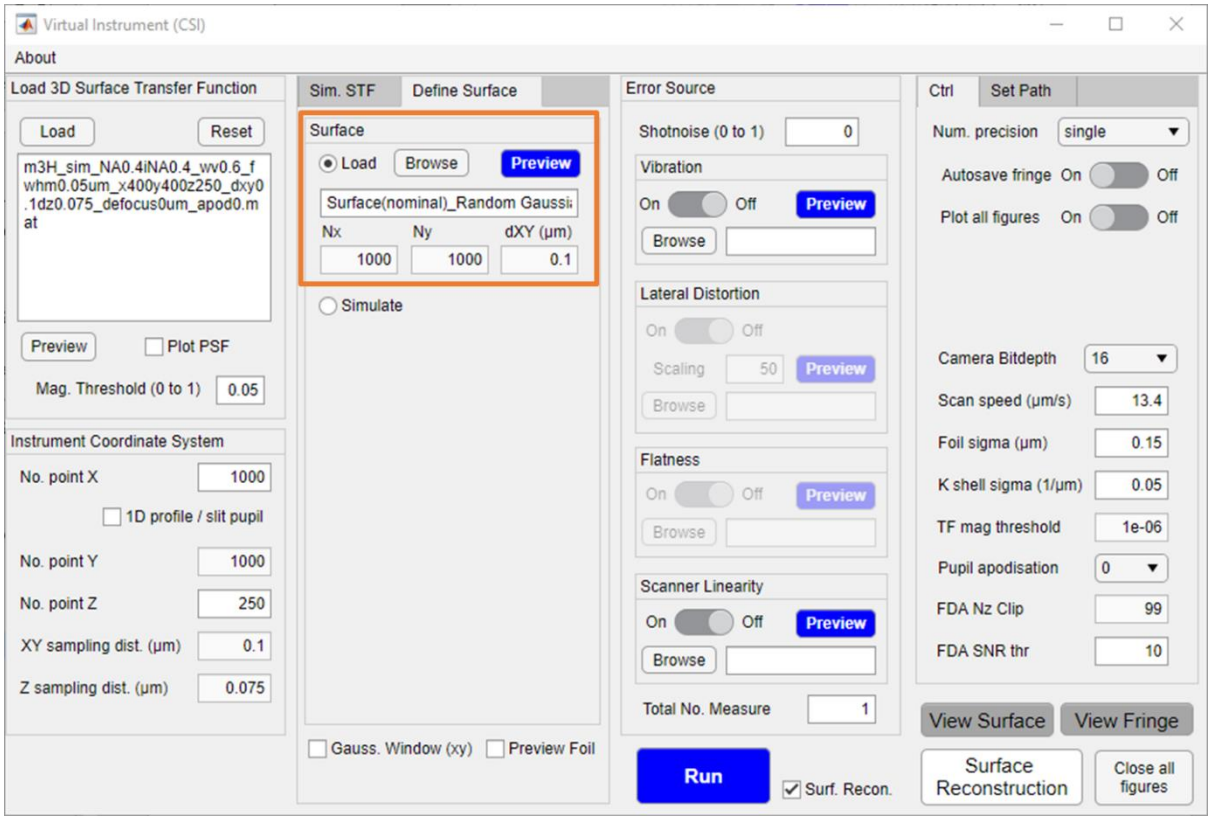
Load a saved 3D STF:



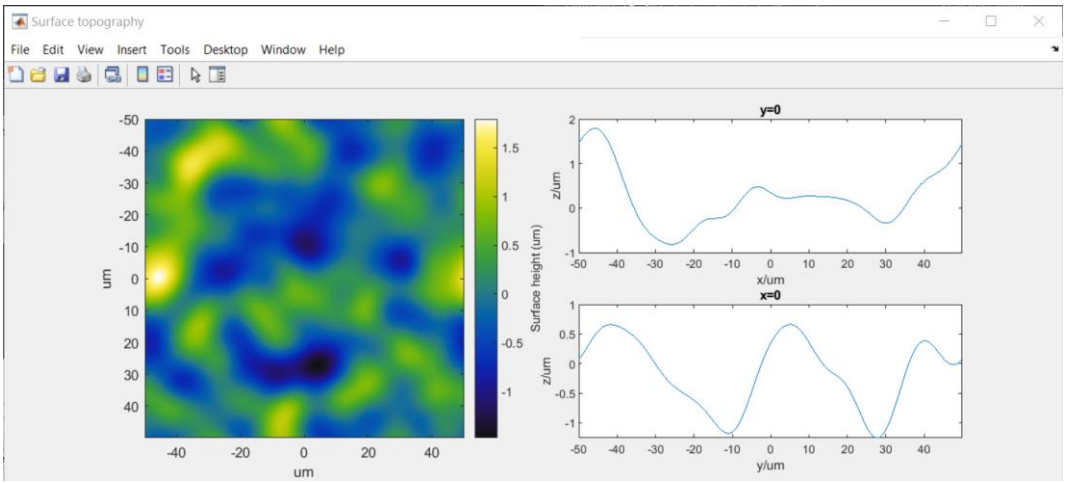
Go to <Define Surface> tab, choose Random Gaussian (2D) and set the Sq and Lc values, check <save> box, change <No. point X> to 1000, and click <Preview> to visualise and save the simulated surface data. Note that the 3D STF will be automatically resized to match the number of surface points.



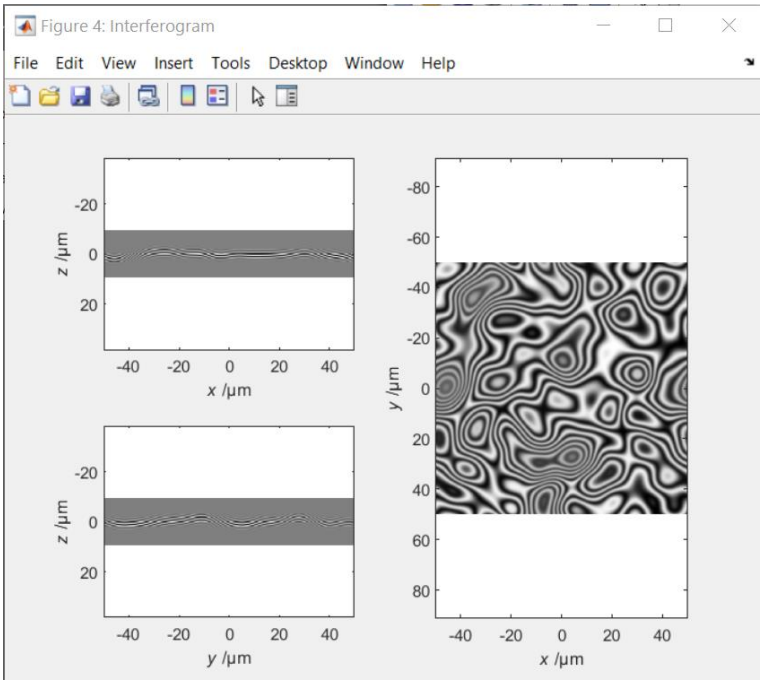
Select <Load> to load a saved surface.



Preview the surface:



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



and the measured surface and the error map.