INSTITUT FRESNEL MARSEILLE

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Theoretical modeling and experimental characterization of the light fields retro-reflected and/or backscattered by optical components

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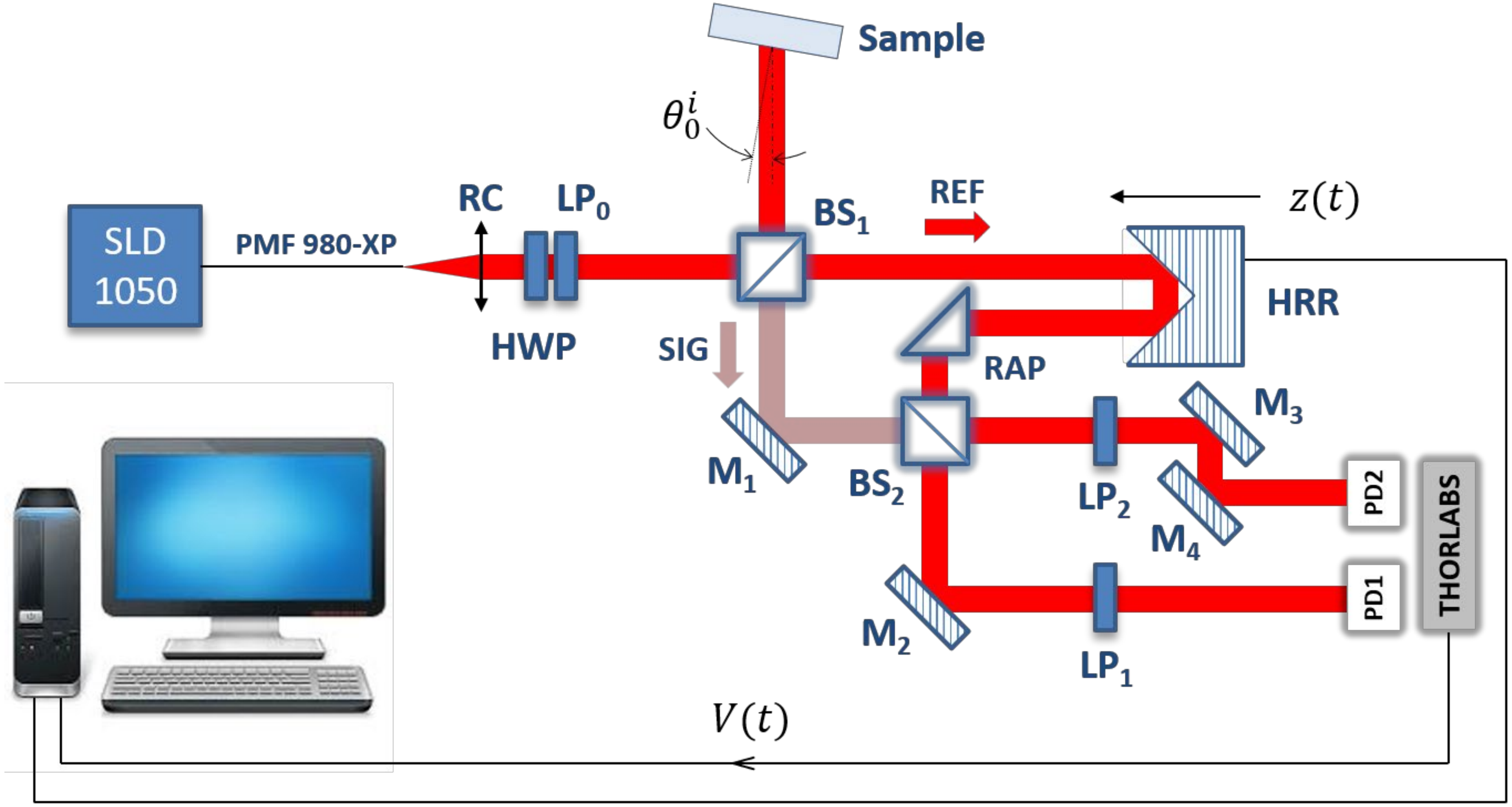
Introduction

- **Light scattering perturbation is a coherent effect in gravitational wave interferometric detectors**
  - *Amplitude and phase of the scattered field*
- **Only the part that can be coherently mixed with the main beam is relevant**
  - *State of polarization of the scattered field*
- **Surface roughness and point defects are the main sources of light scattering**
  - *Fast angular variations of the scattered field (speckle grains, Airy patterns)*

Introduction

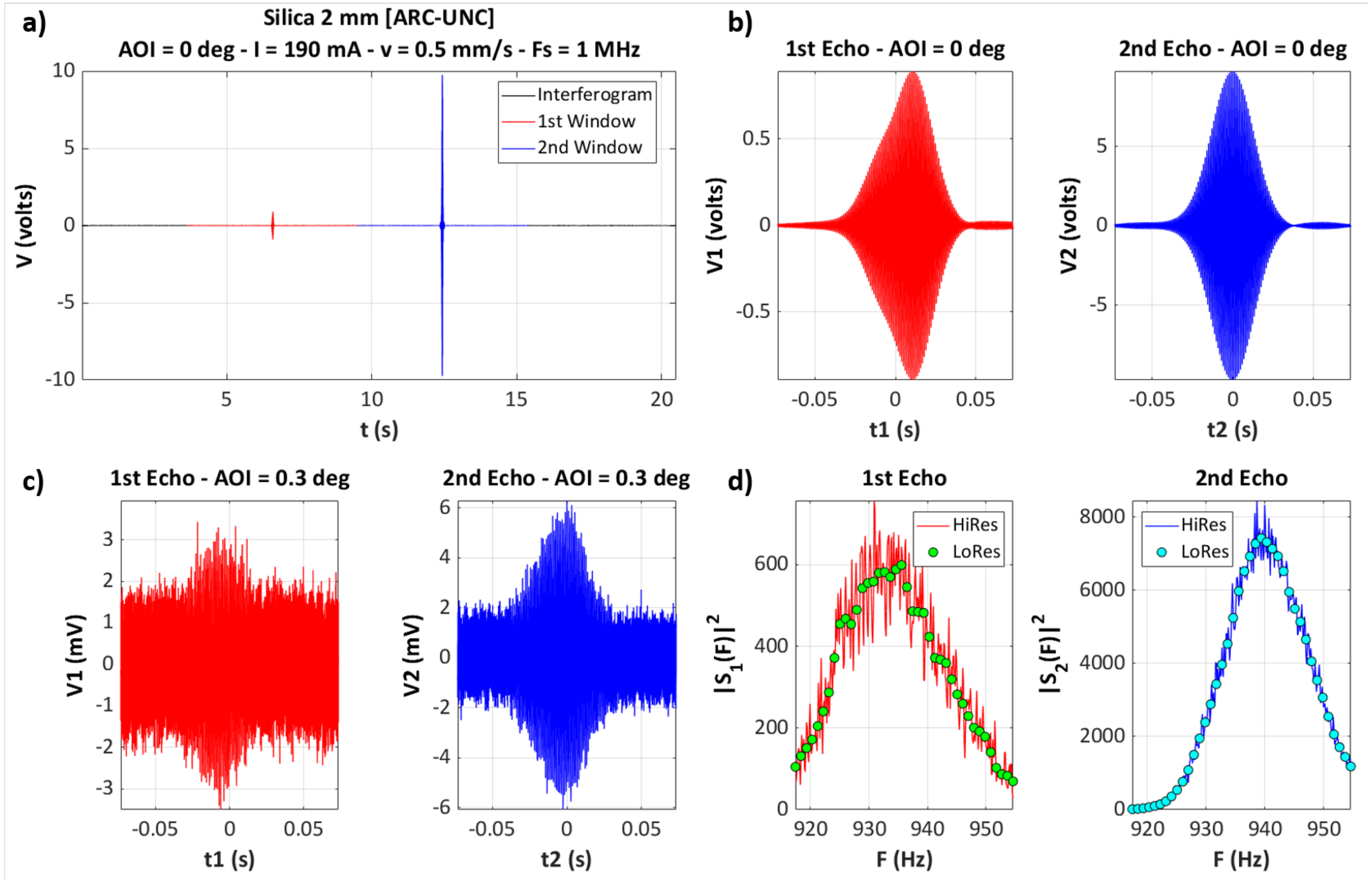
- **f_{sc} approaches are mainly based on incoherent measurements**
  - ***Angle Resolved Scattering (SALSA, CASIX)***
- **Development of coherent tools**
  - ***LAPP – Homodyne detection in monochromatic lightning (component mounted on an oscillating breadboard)***
  - ***ARTEMIS – FMCW scheme with ranging capability (characterization of a set of components in a fixed configuration)***
  - ***Institut FRESNEL – BARRITON (low-coherence interferometry with ranging capability and spectrally resolved amplitude/phase measurement)***
    - ✓ *Measurement of the wavelength dependence of the retroreflection of high efficiency AR coatings*
    - ✓ *Recording of speckle and Airy patterns in a backscatter configuration*

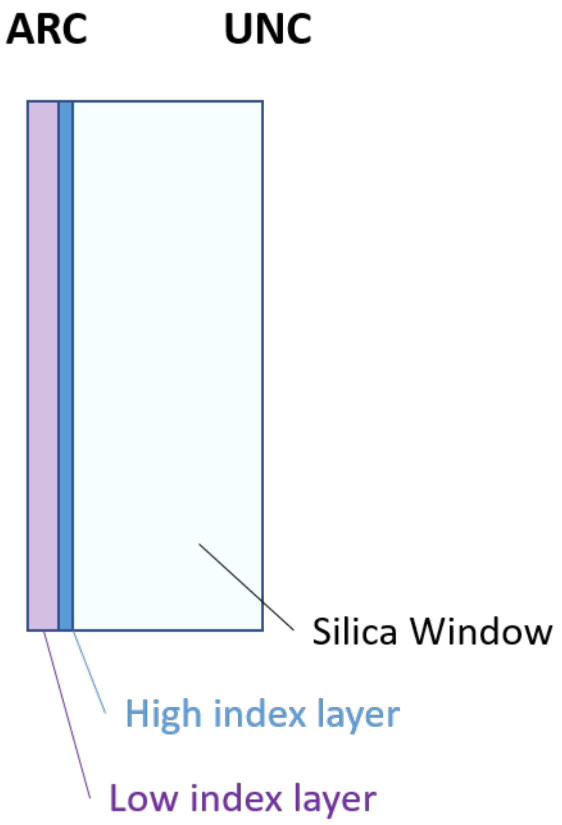
BARRITON



Angular resolution: 0.1 mdeg

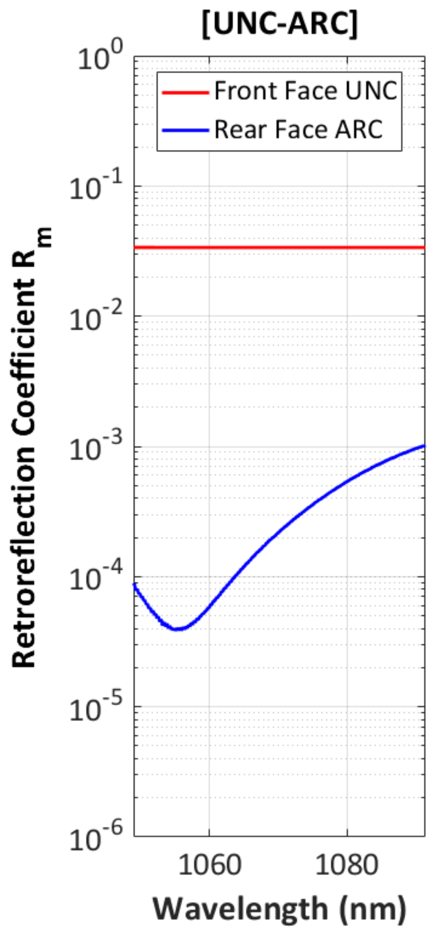
BARRITON



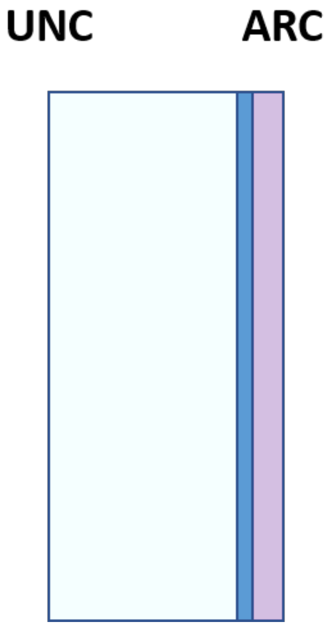


$$\lambda = \frac{2v}{F}$$

Experimental characterization

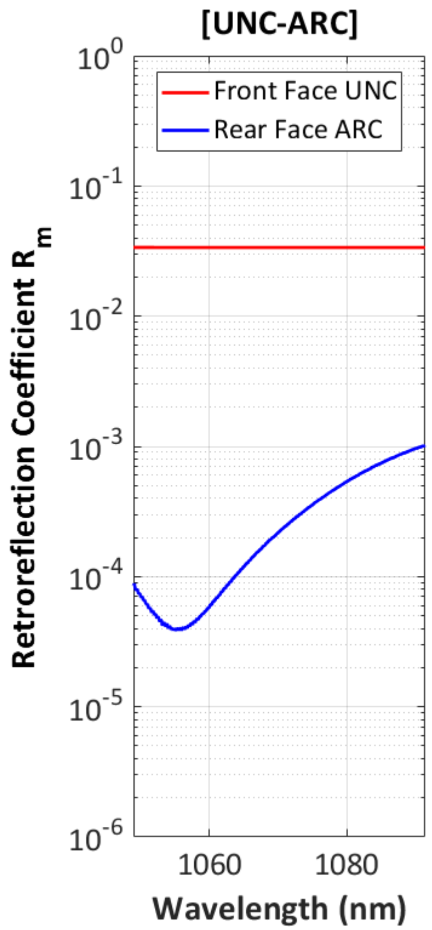


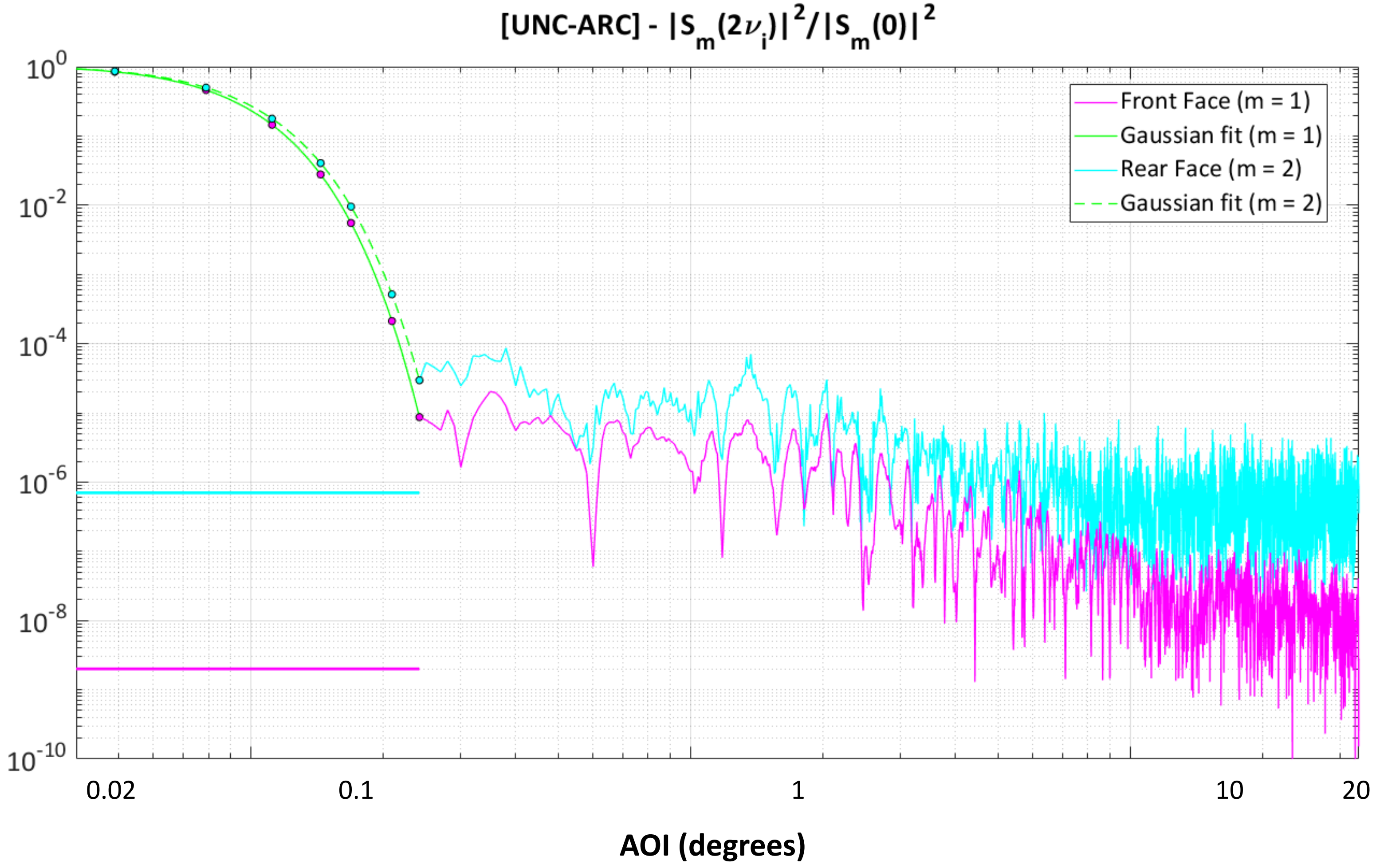
$$\mathrm{ARS}_m(\lambda,\nu) = \frac{\pi w_s^2}{\lambda^2} R_m(\lambda) \frac{|S_m(\nu)|^2}{|S_m(0)|^2}$$

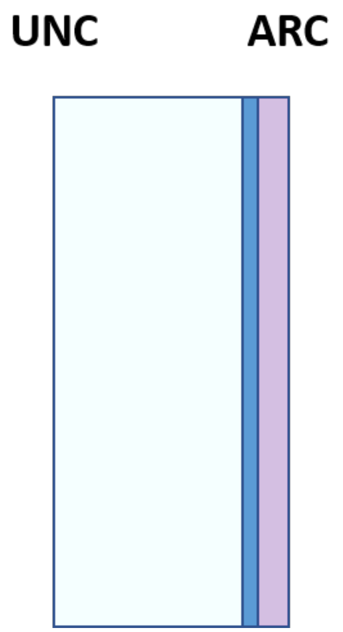


Experimental characterization

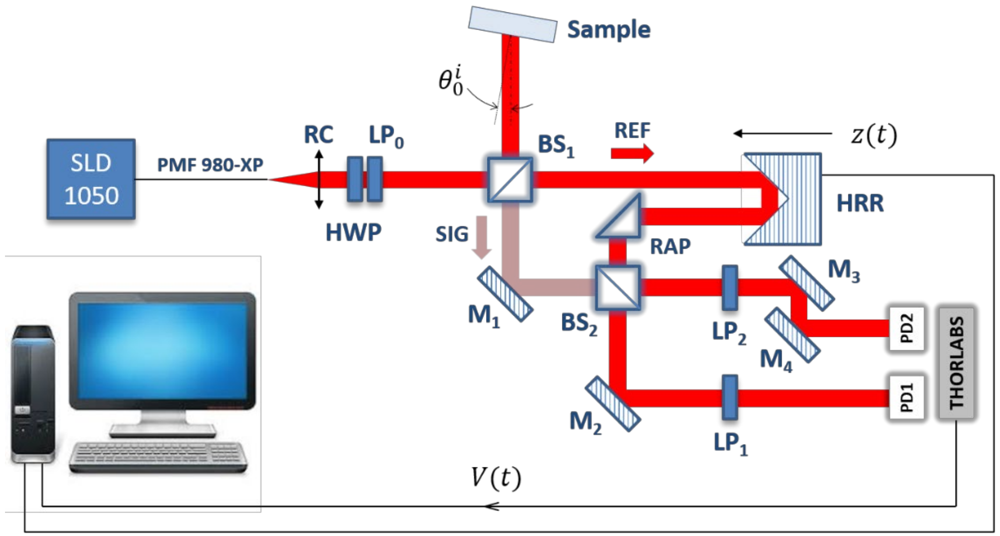
Polarization TE
Noise floor ~ 10^{-11}







Theoretical modeling



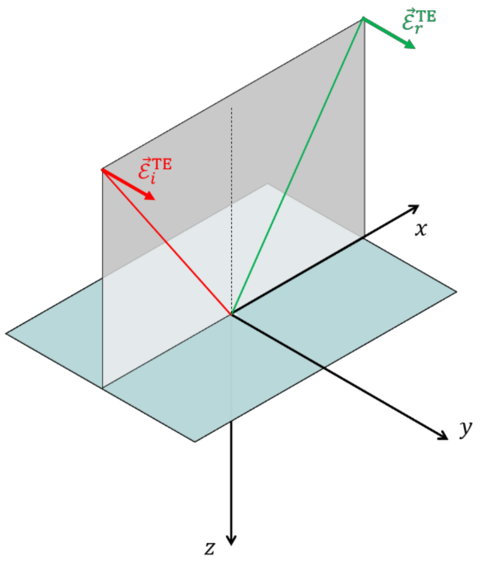
- **Lightning beam**
  - ***Gaussian beam with a waist located in the image focal plane of RC*** $(w_f = 0.7\ \text{mm})$
- **Interferometer**
  - ***Free space propagation of the reference beam to the photodiodes (Fresnel approximation)***

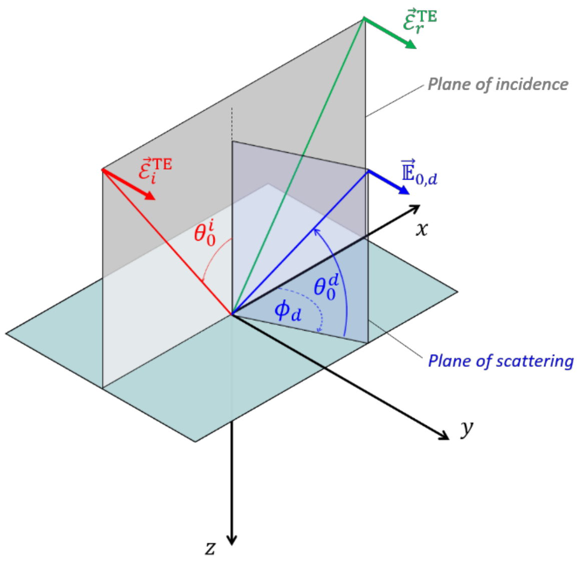
$$\vec{\mathcal{E}}_{ref,1}(x,y,z;f) = t_1 t_2 \frac{e^{ikz}}{1 + i\, z/z_R}\, e^{-\frac{x^2+y^2}{w_f^2(1+iz/z_R)}}\, \vec{\mathcal{E}}_i$$

  - ***Free space propagation of the signal beam to the sample***
  - ***Reflection/Scattering of the signal beam at the sample surface (AOI*** θ_0^i***)***
  - ***Free space propagation of the reflected/backscattered fields from the sample to the photodiodes***

Theoretical modeling

- **At the sample surface**
  - ***Decomposition of the incident field spatial repartition into elementary plane waves***
  - ***Calculation of the plane waves reflected and scattered from the sample surface***





  - ***Coherent mixing with the reference beam***

Theoretical modeling

- **Scattered field**

$$\propto \hat{\boldsymbol{h}}_S^i(\vec{\boldsymbol{v}}_d) \qquad \vec{v}_d = \begin{bmatrix} (n_0/\lambda)\sin\theta_0^d \cos\phi_d \\ (n_0/\lambda)\sin\theta_0^d \sin\phi_d \end{bmatrix} \qquad \vec{v}_i = \begin{bmatrix} (n_0/\lambda)\sin\theta_0^i \\ 0 \end{bmatrix}$$

$$h_S^i(x,y) = h(x,y)\, S_i(x,y)$$

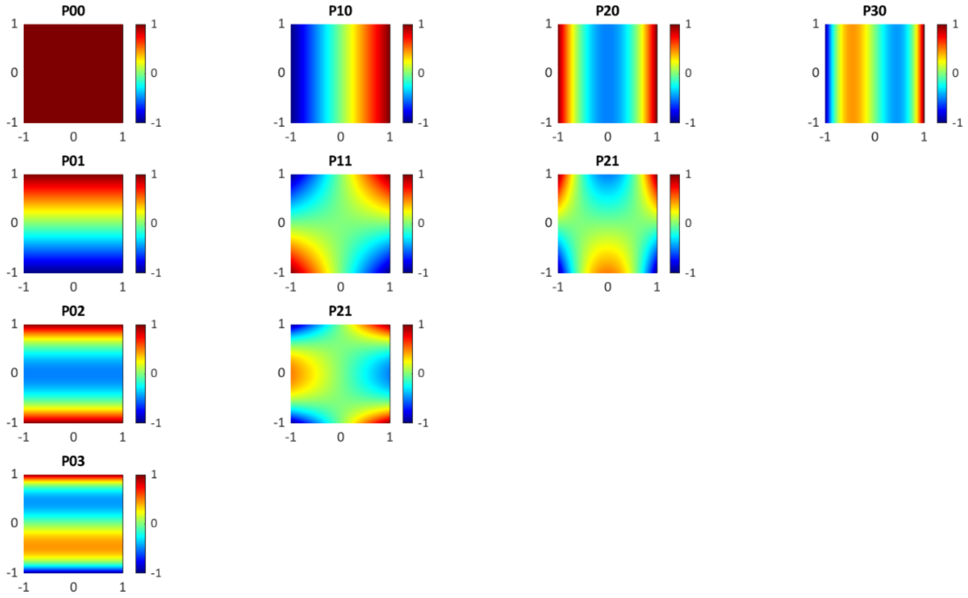
$$S_i(x,y) = \frac{1}{1 + i\, d/z_R} e^{-\frac{(x\cos\theta_0^i)^2 + y^2}{w_f^2(1+id/z_R)}} e^{ik_0(d + x\sin\theta_0^i)}$$

- **Backscattered field** $\theta_0^d = \theta_0^i\ ;\ \phi_d = \pi \implies \propto \hat{h}_S^i(-\nu_i, 0)$

Theoretical modeling

▪ Method

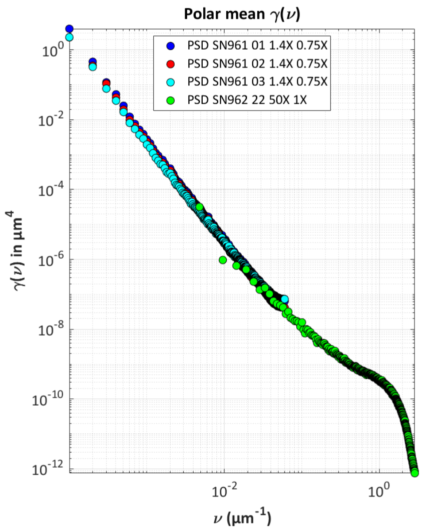
- ***To define a realistic representation of a surface with both waviness and roughness***
  - ✓ *Either directly derived or numerically generated from experimental results*
  - ✓ *Waviness : generated on the basis of 2D Legendre polynomials*

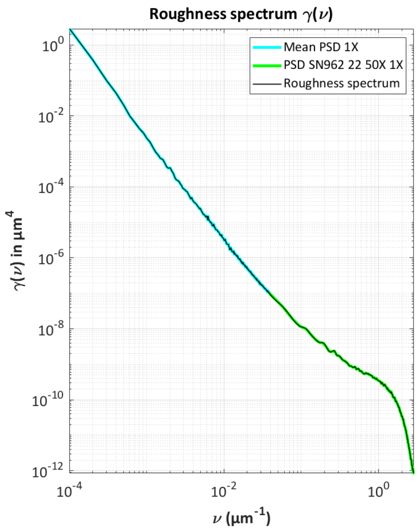


Theoretical modeling

▪ Method

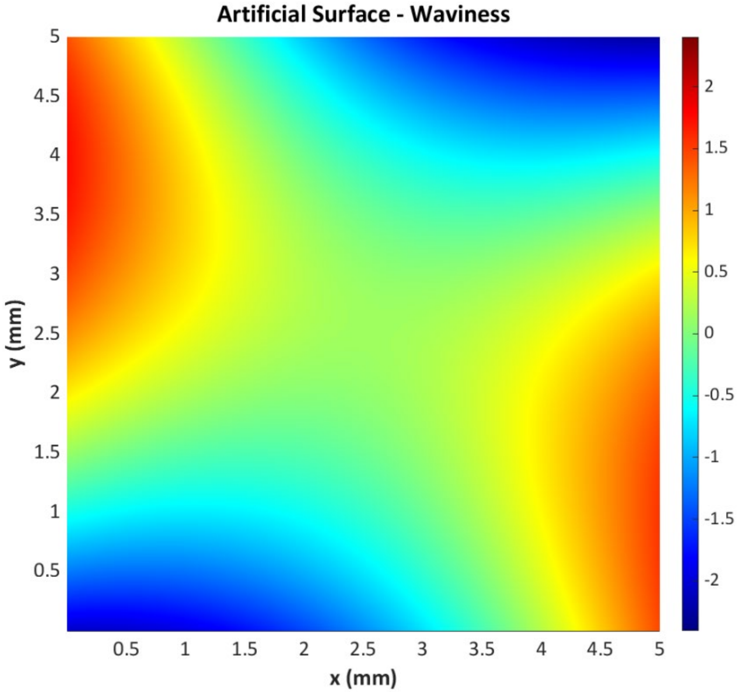
- ***To define a realistic representation of a surface with both waviness and roughness***
  - ✓ *Either directly derived or numerically generated from experimental results*
  - ✓ *Waviness : generated on the basis of 2D Legendre polynomials*
  - ✓ *Roughness : generated from polar averaging of an experimental PSD*



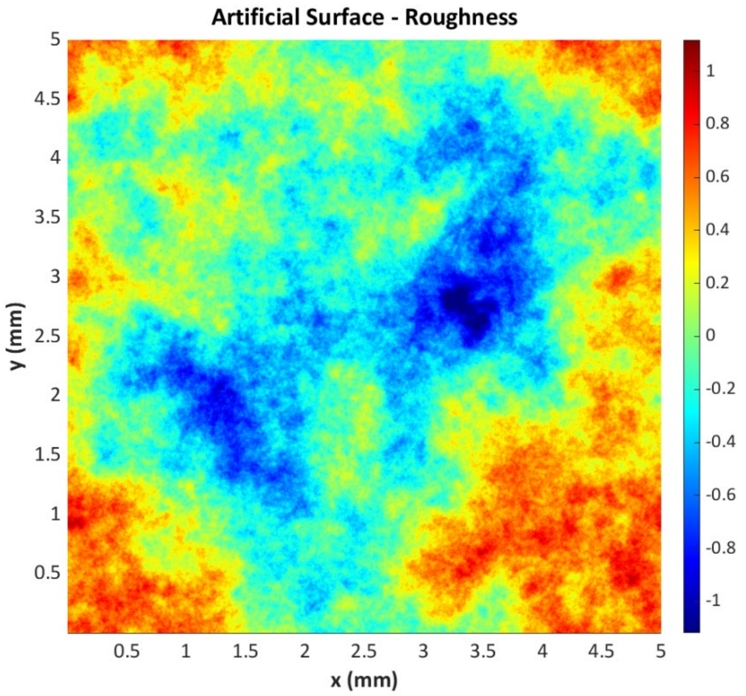


$$h(x,y) = FT^{-1}\left[\sqrt{S\bar{\gamma}(\nu)}\, e^{i\phi(\nu_x,\nu_y)}\right] \quad \text{where} \quad \nu = \sqrt{\nu_x^2 + \nu_y^2}$$

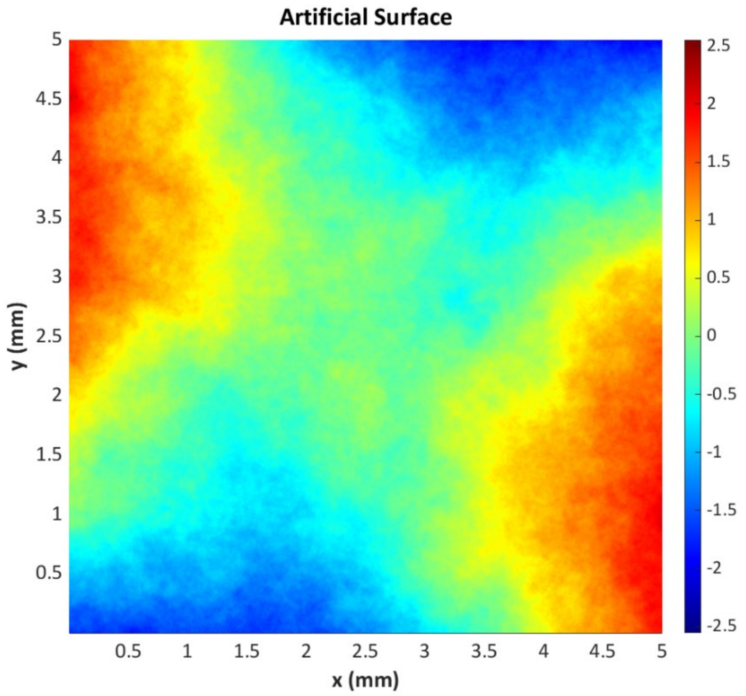
High quality surface



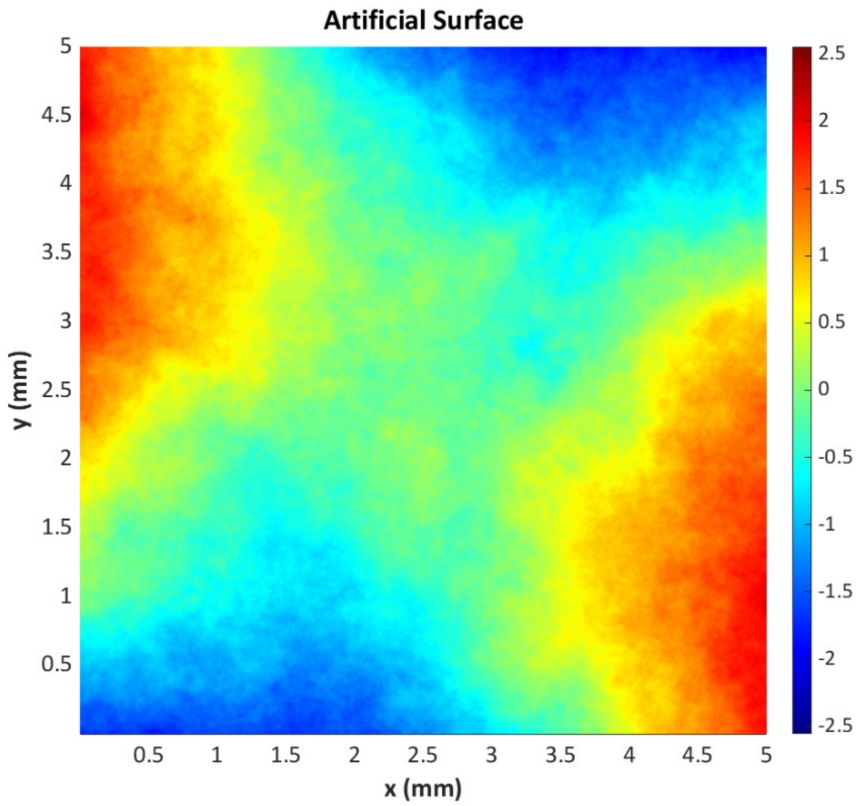
$\sigma_w = 2.1$ nm



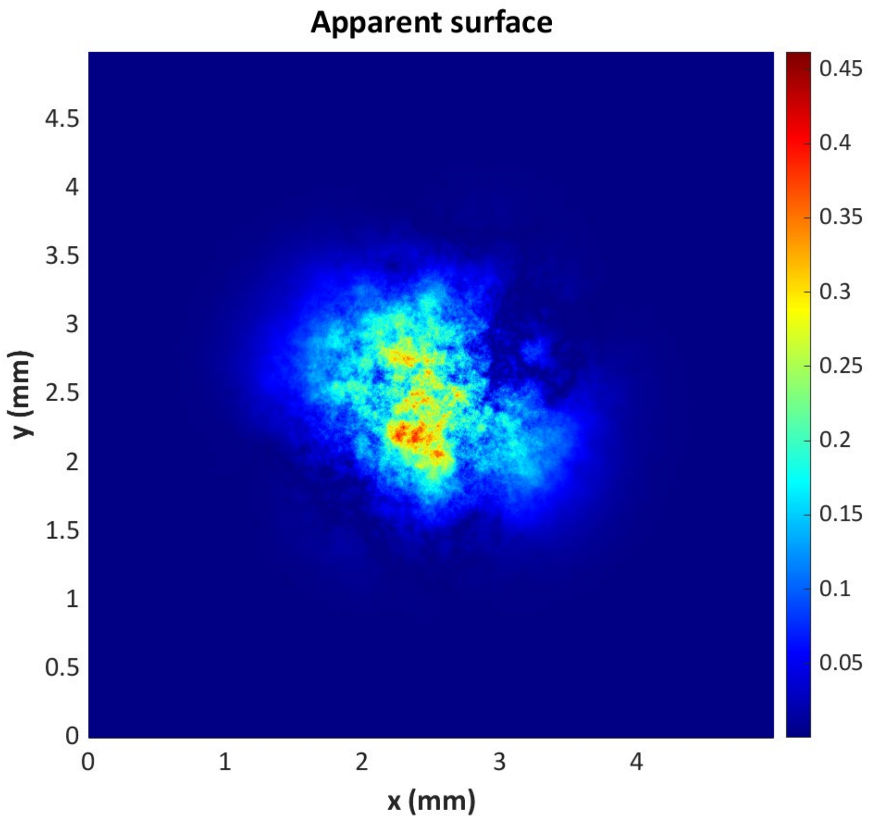
$\sigma_r = 0.3$ nm



High quality surface

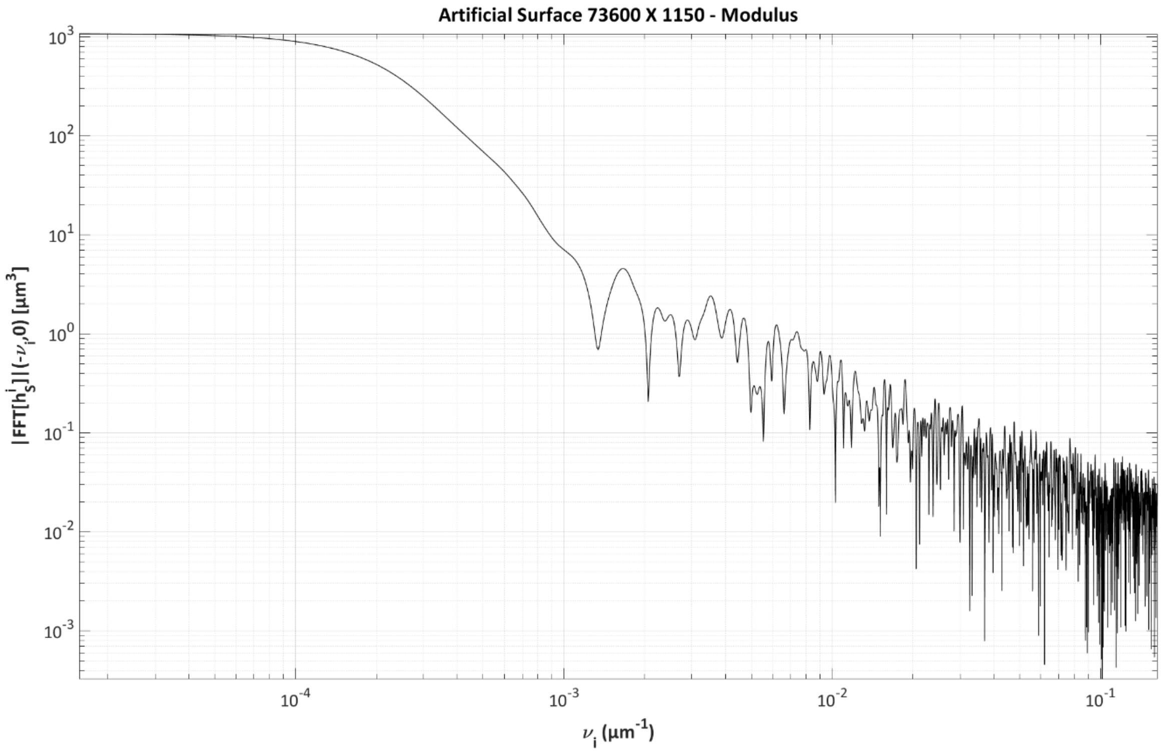


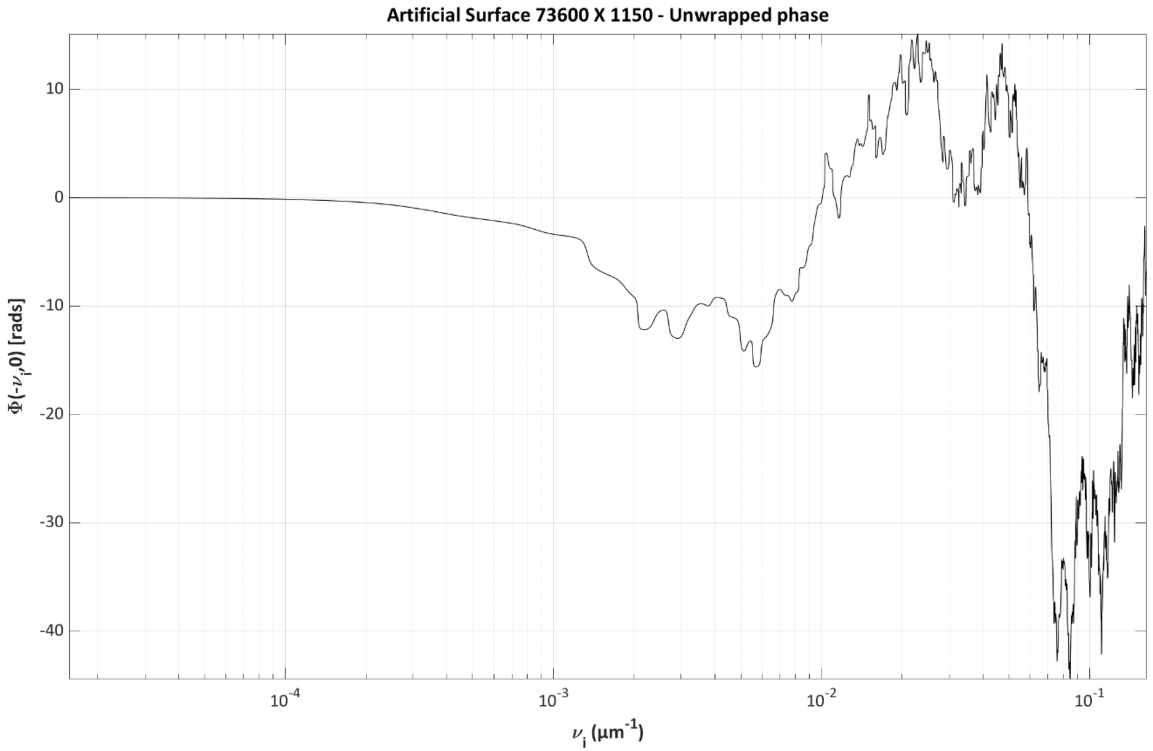
$h(x, y)$



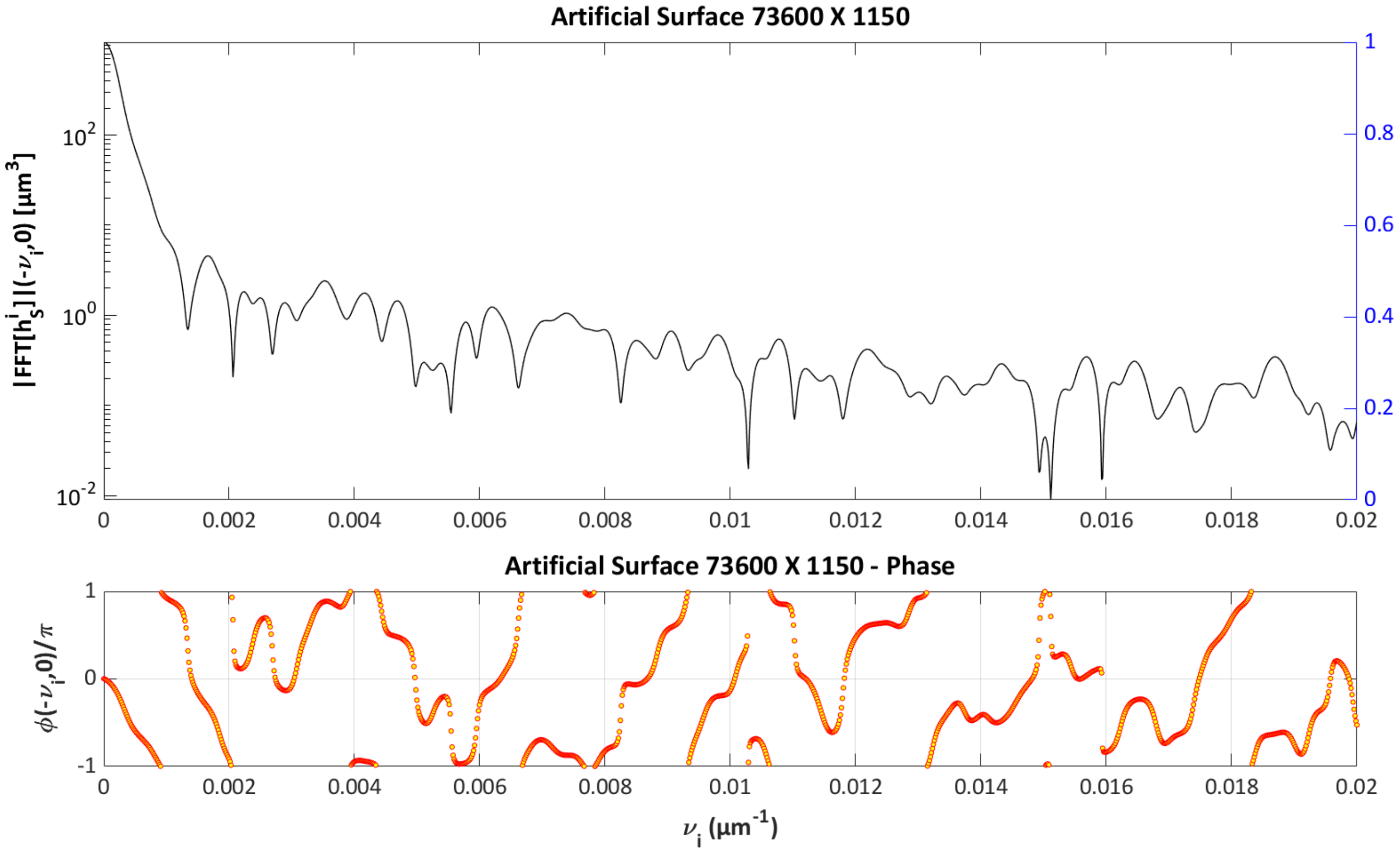
$h_S^i(x, y) = h(x, y)S_i(x, y)$

High quality surface

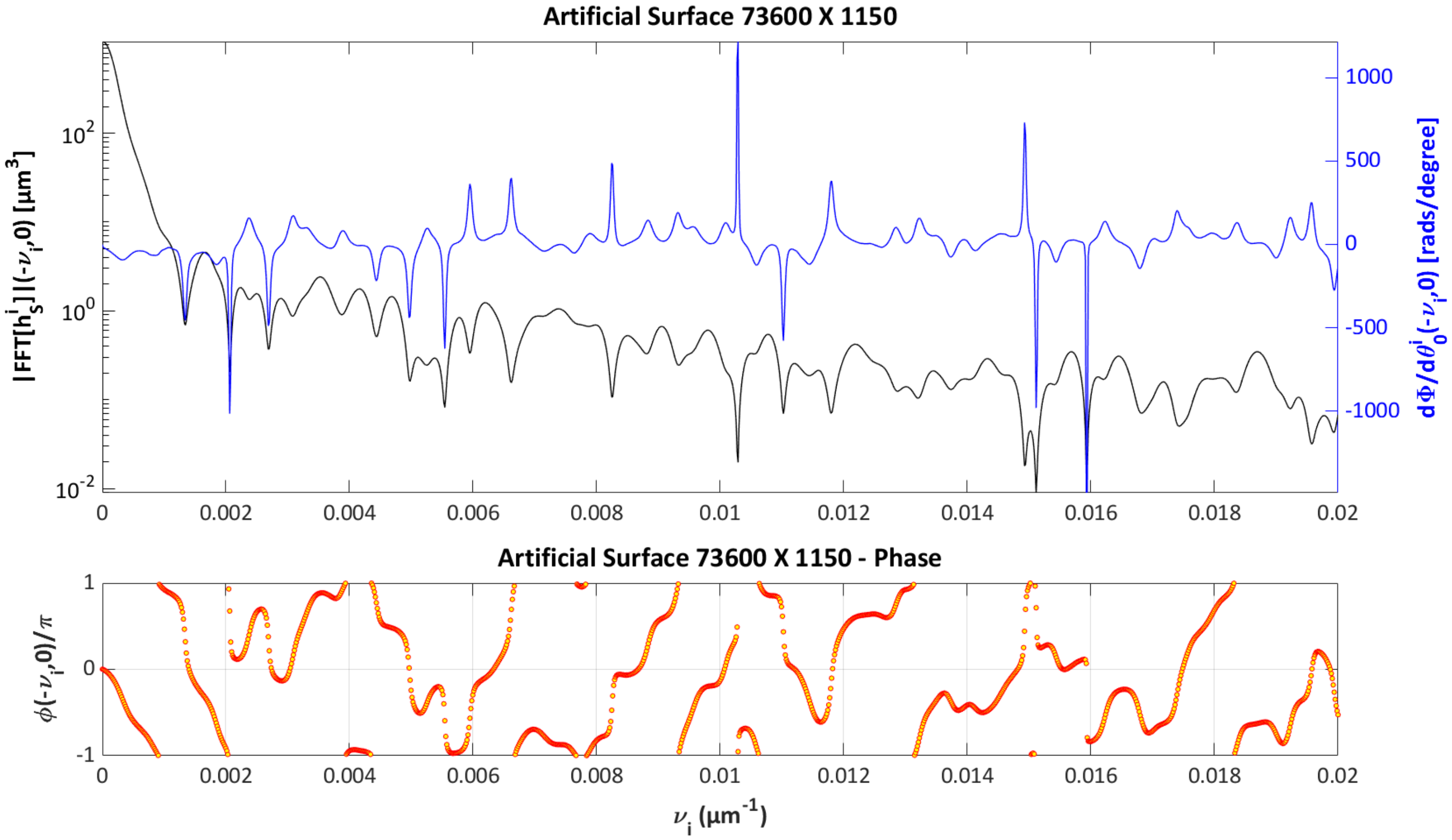




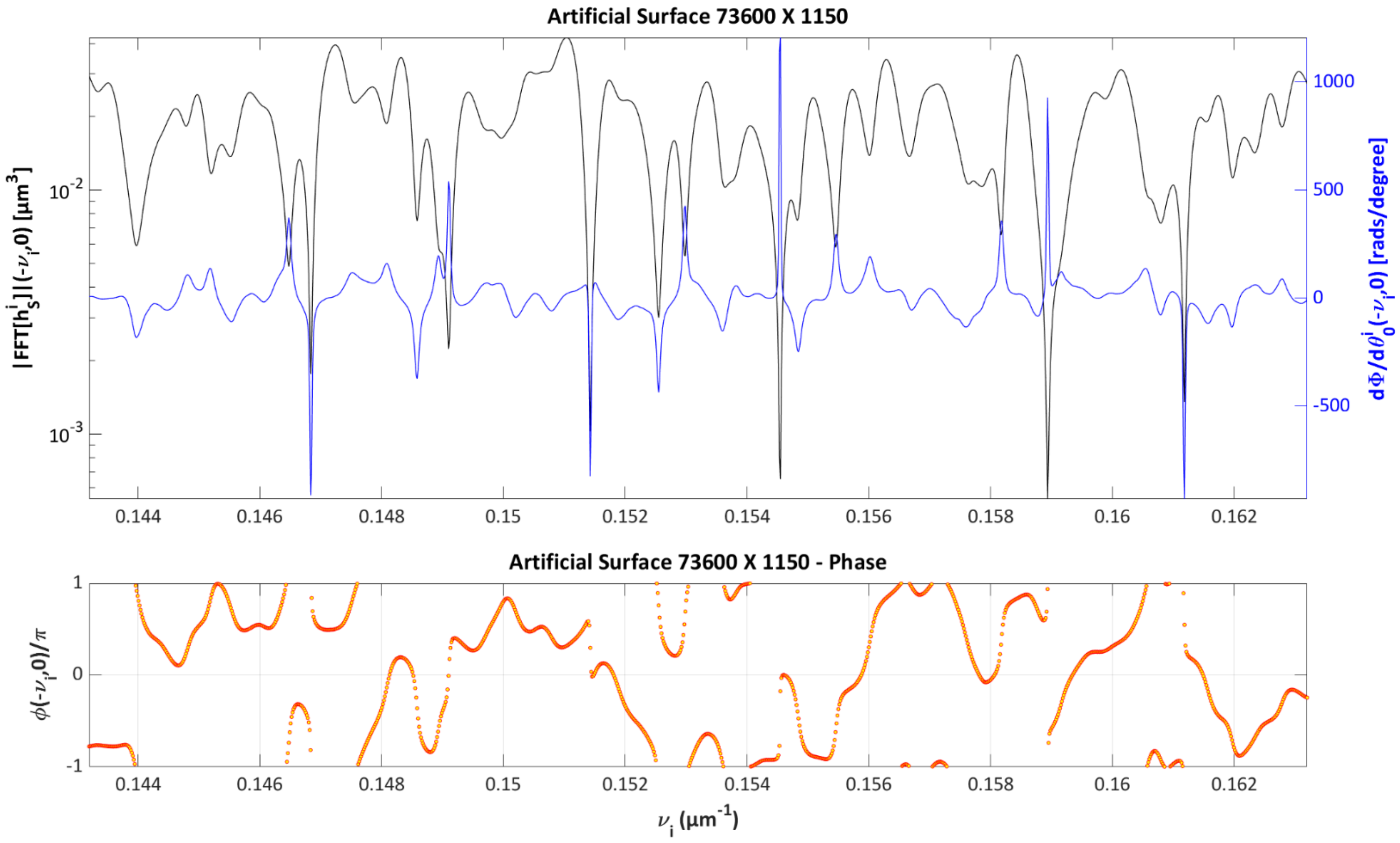
High quality surface



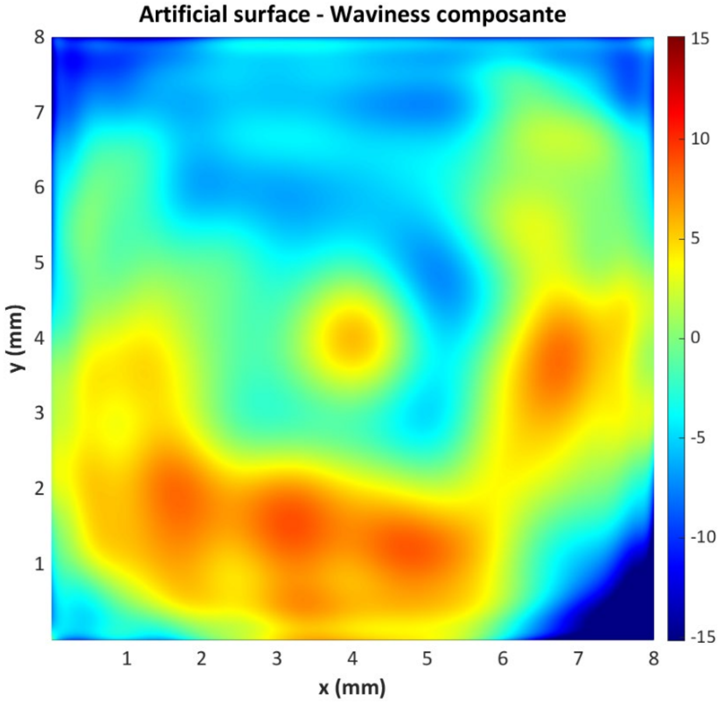
High quality surface



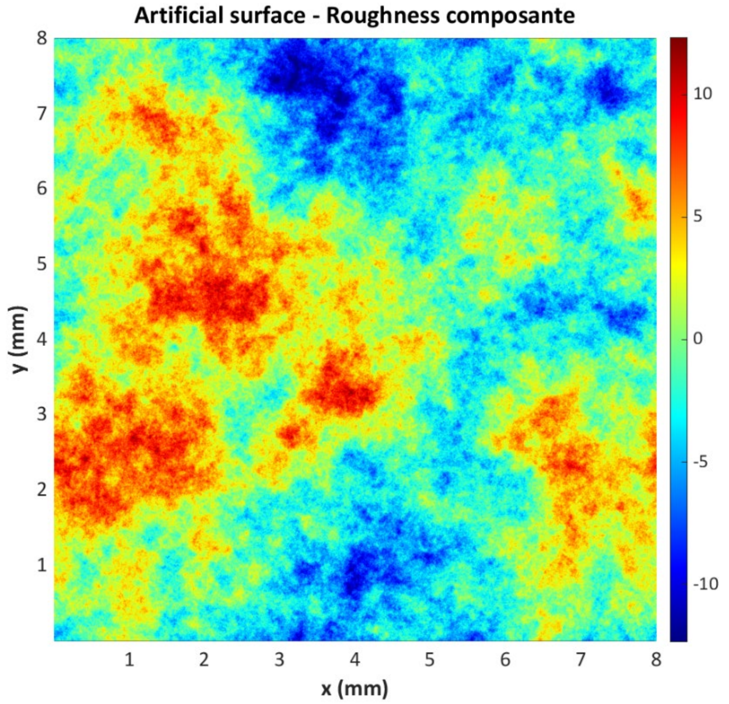
High quality surface



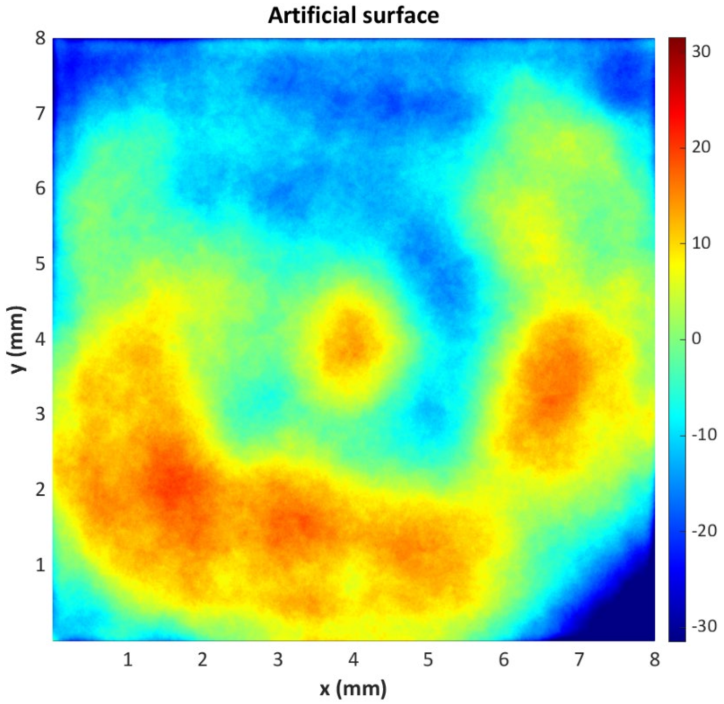
Low quality surface



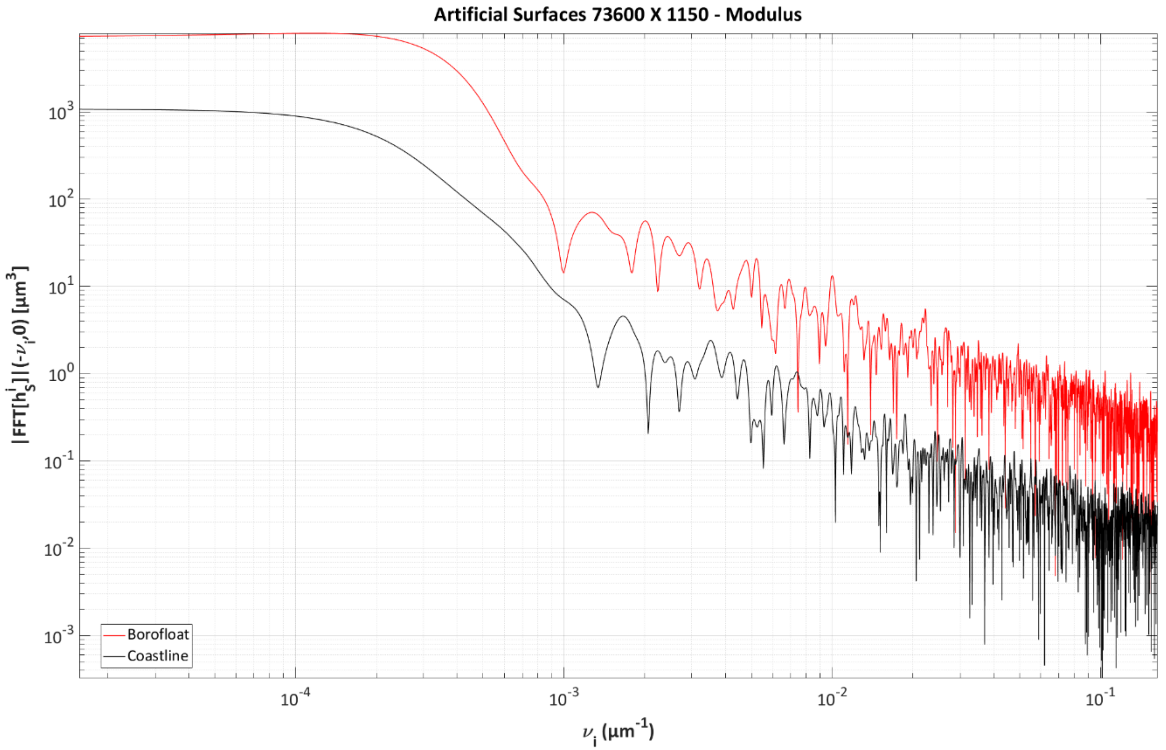
$\sigma_w = 10.1$ nm

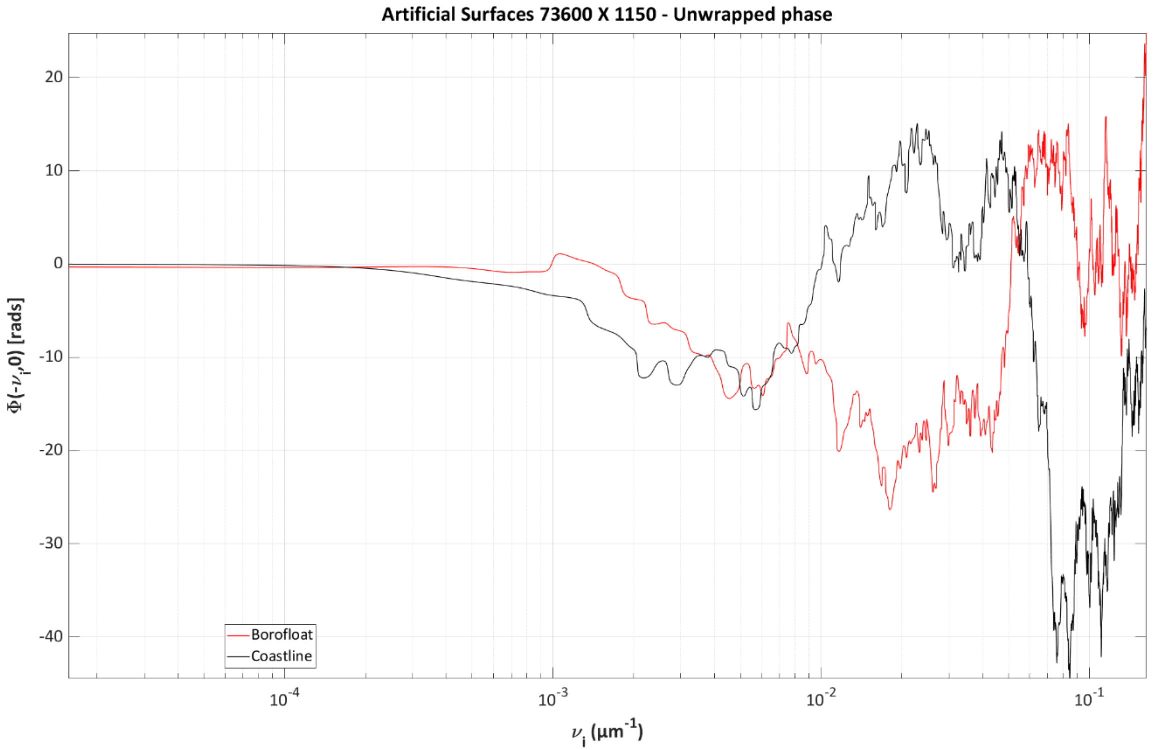


$\sigma_r = 2.1$ nm

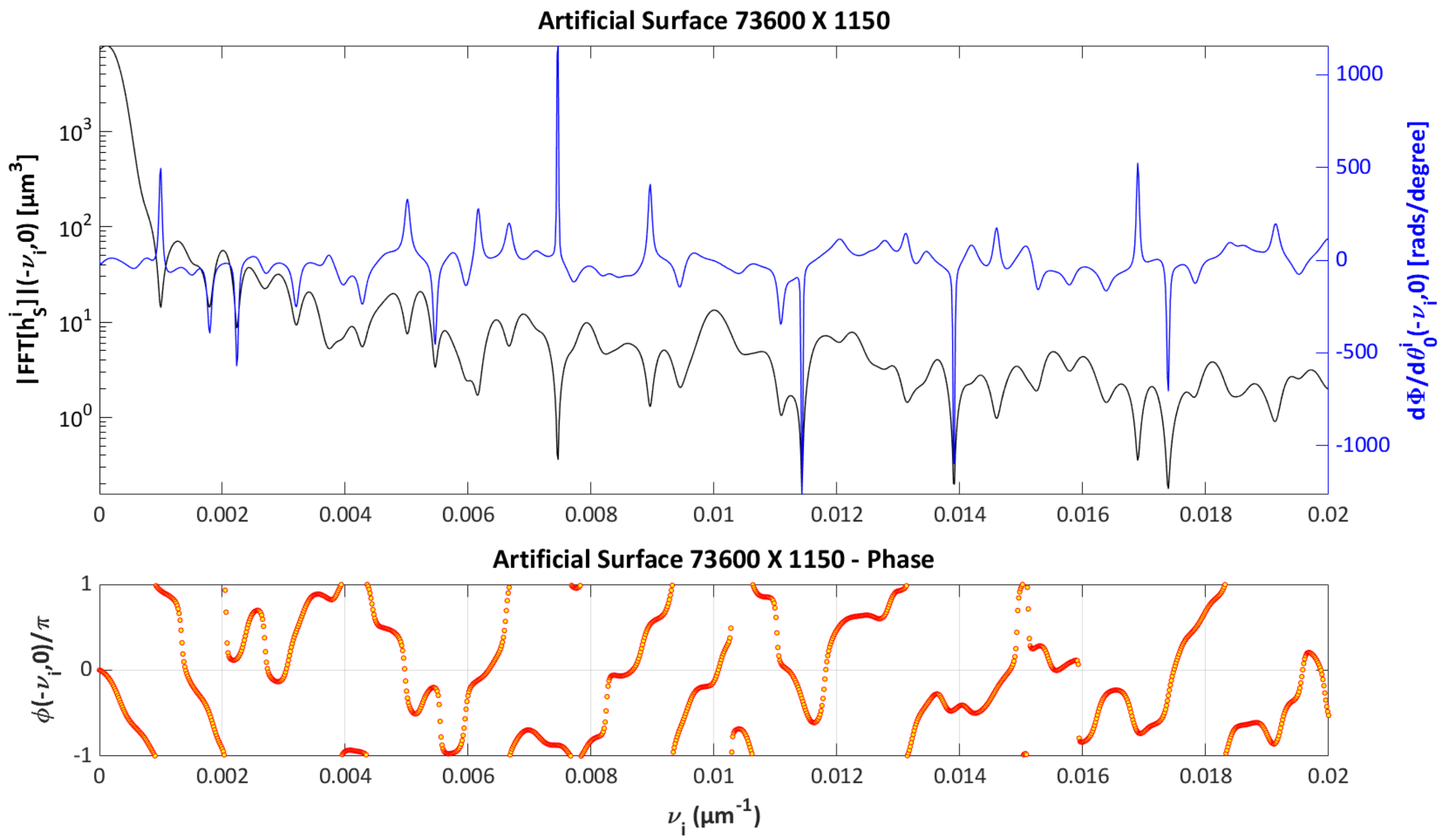


Low quality surface





Low quality surface



Conclusion

- ## Main achievements
  - ***Generation of artificial surfaces with realistic waviness and roughness features***
  - ***Good agreement between experimental results and theoretical modelling of coherent backscattering from a surface***
  - ***Very fast dependence of the phase of the scattered field with respect to small change in the angular position of the surface***
    - ✓ *To be considered in the perturbation budget induced by light scattering*
- ## Further activities
  - ***Integration and qualification of BARRITON 2 (expected noise floor*** $\sim 3 \times 10^{-14}$***)***
  - ***Phase measurement of the field backscattered by a surface***

Thanks a lot for your kind attention!