

ERATO Meeting Nov.17.2015

High-precision 3-D surface measurement  
using multi-wavelength digital holography  
referenced by optical frequency comb

By

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# Principle

## Merits:

- 1- High-precision (referenced to the FC of the fiber laser which is stabilized to the Rb atomic clock of  $10^{-12}$  uncertainty)
- 2- Large stepped structures (by varying the repetition rate of femtosecond pulses)
- 3- Does not need phase unwrapping

## Demerits:

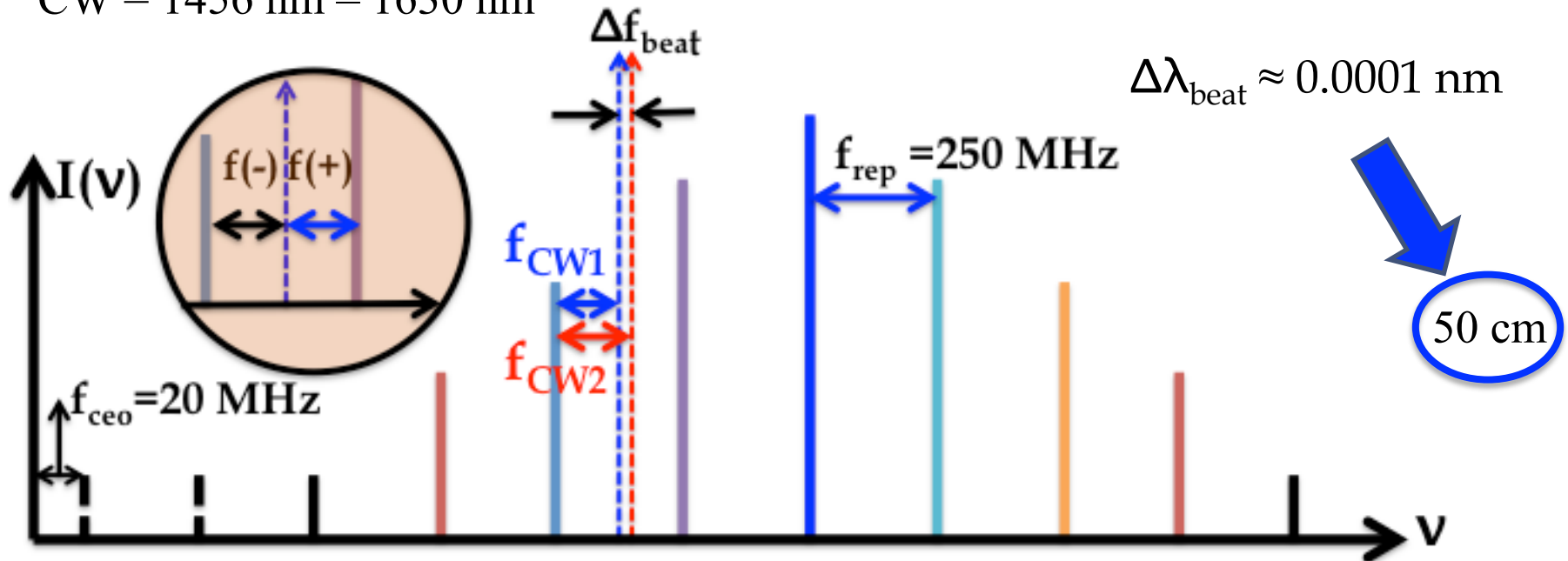
- 1-Not in real-time

$$\nu_n = n_0 f_{\text{rep}1} \pm f_{\text{ceo}} \pm f_{\text{beat}}$$

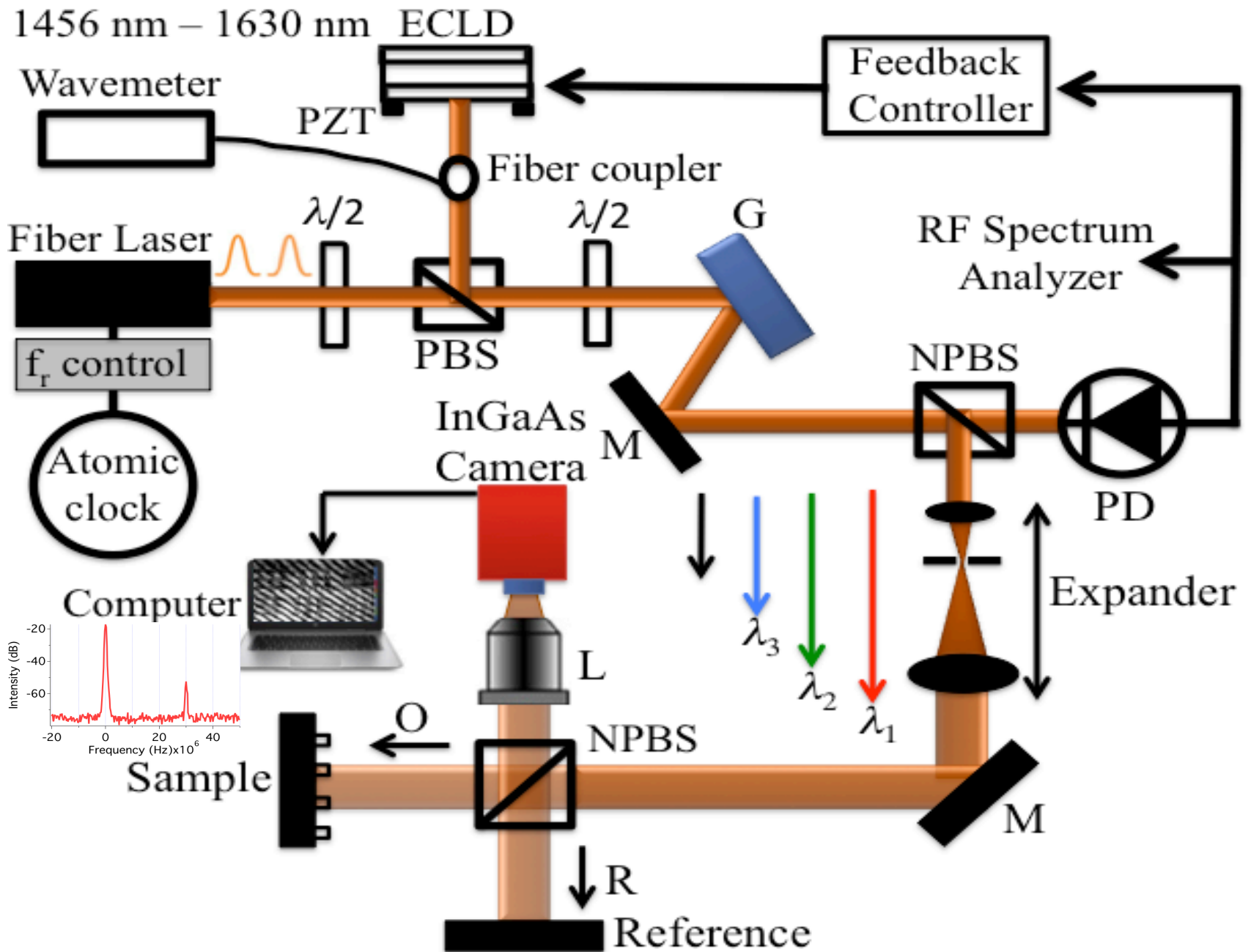
$$\nu_{n+1} = n_0 f_{\text{rep}2} \pm f_{\text{ceo}} \pm f_{\text{beat}}$$

$$\nu_{n+1} - \nu_n = c / \Delta\lambda_{\text{beat}}$$

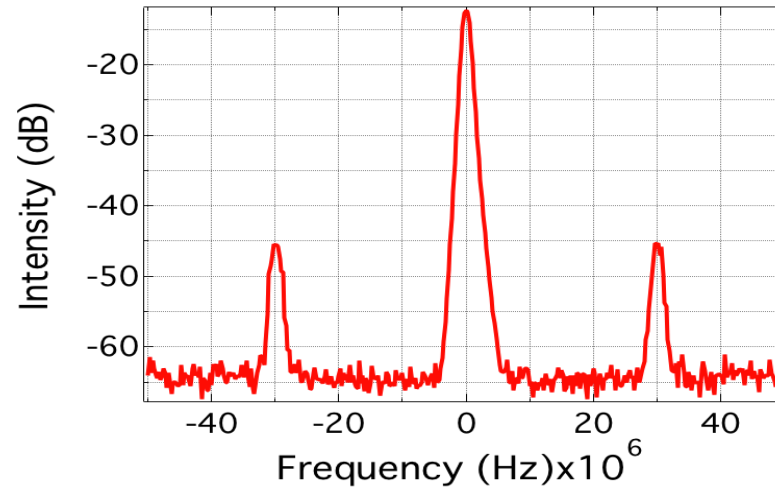
CW = 1456 nm – 1630 nm



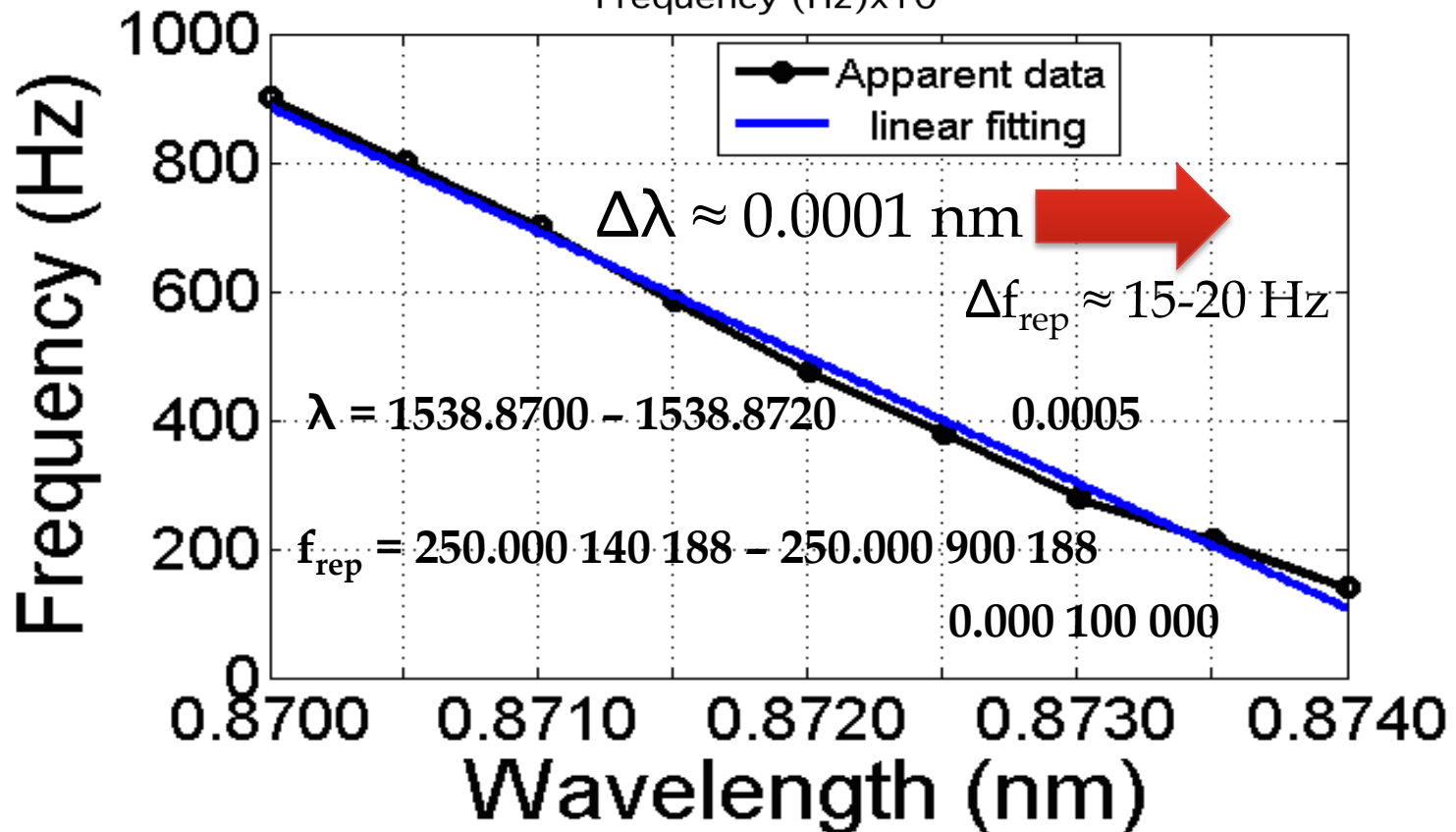
# Optical setup



# Results: calibration, wavelength vs. $f_{\text{rep}}$



Stabilized by PID  
at 30 MHz



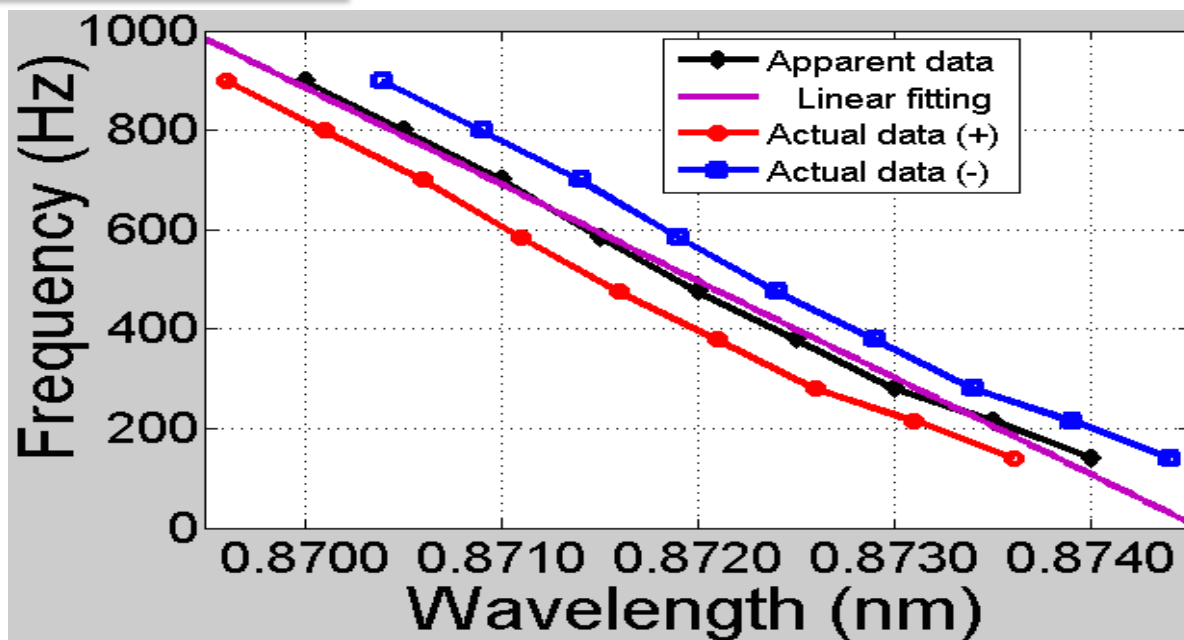
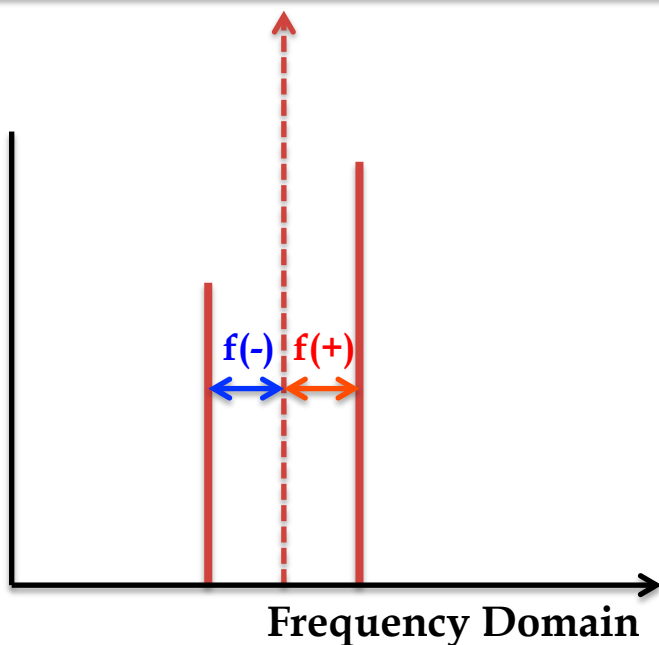


# Actual and apparent values of wavelengths (0.0005)

App. (nm)	1538.8700	1538.8705	1538.8710	1538.8715	1538.8720	1538.8725	1538.8730
Actual (+nm)	1538.8696	1538.8701	1538.8706	1538.8711	1538.8716	1538.8721	1538.8726
Actual (-nm)	1538.8704	1538.8709	1538.8714	1538.8719	1538.8724	1538.8729	1538.8734
$f_{\text{rep}}$ (MHz)	250.000						
	900 188	800 188	700 188	585 188	475 188	380 188	280 188
App. (nm)	1538.8735	1538.8740					
Actual (+nm)	1538.8731	1538.8736					
Actual (-nm)	1538.8739	1538.8744					
$f_{\text{rep}}$ (MHz)	250.000 215 188	250.000 140 188					

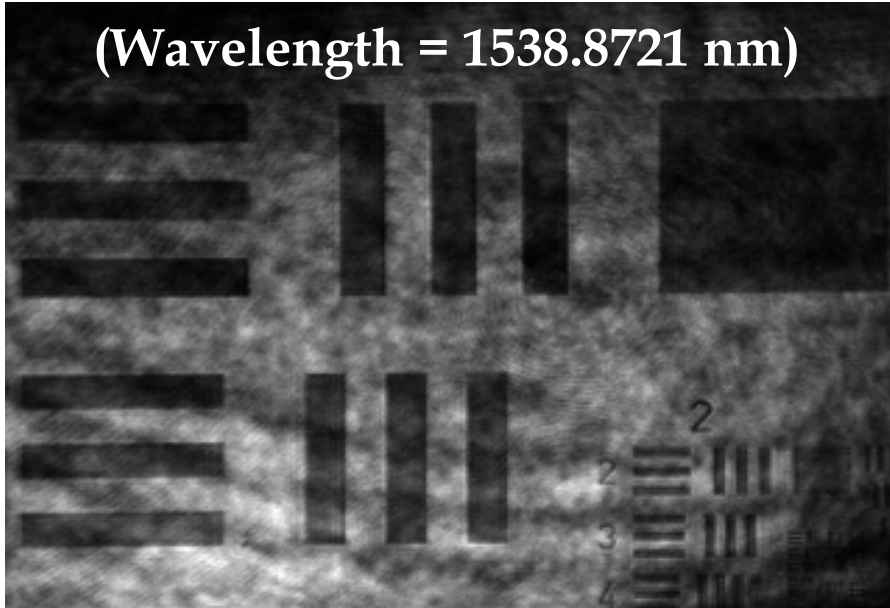
Diff. =  $\pm 0.0004$  nm

$$f(\pm) = n_0 f_{\text{rep}} \pm f_{\text{ceo}} \pm f_{\text{beat}}$$

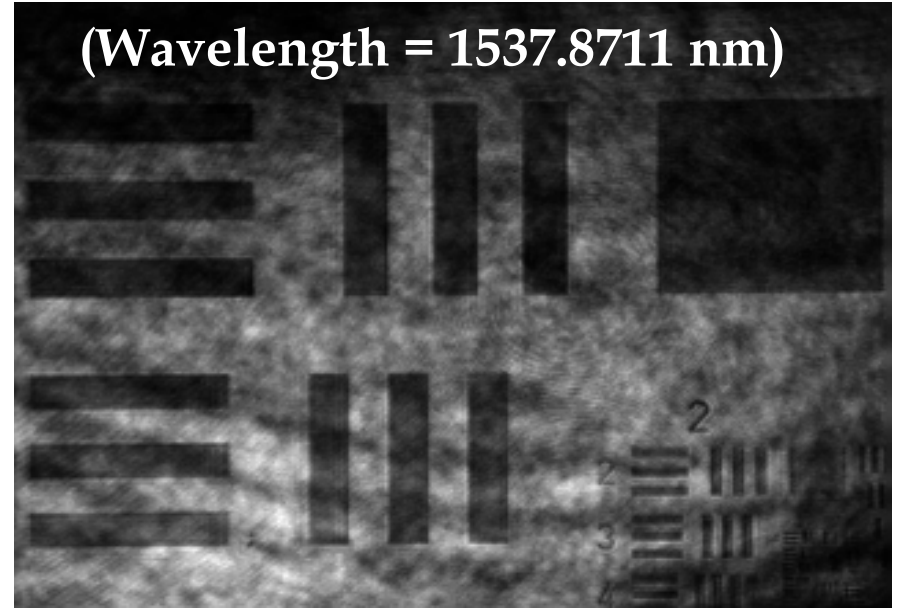


# 1-1. USF object

(Wavelength = 1538.8721 nm)



(Wavelength = 1537.8711 nm)



Corrected

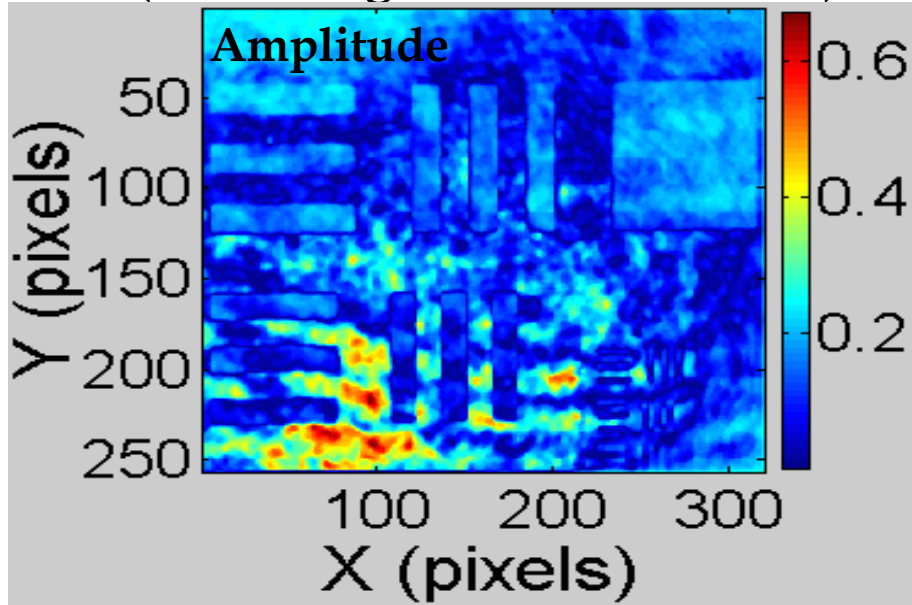


Corrected

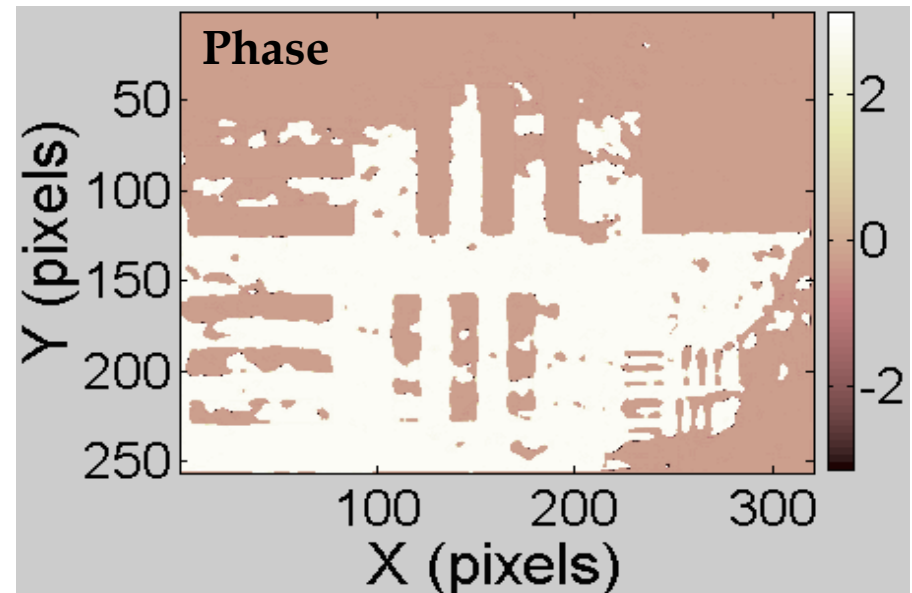
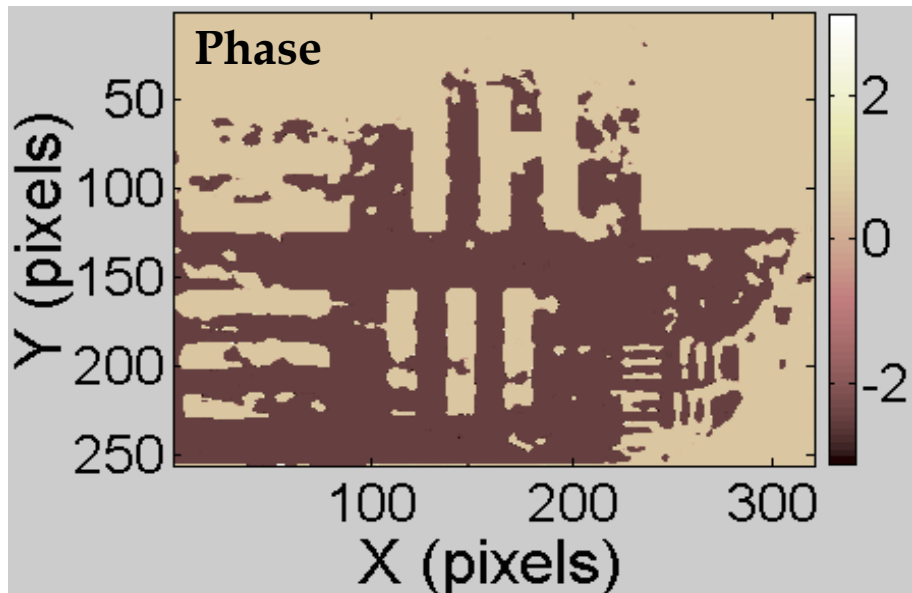
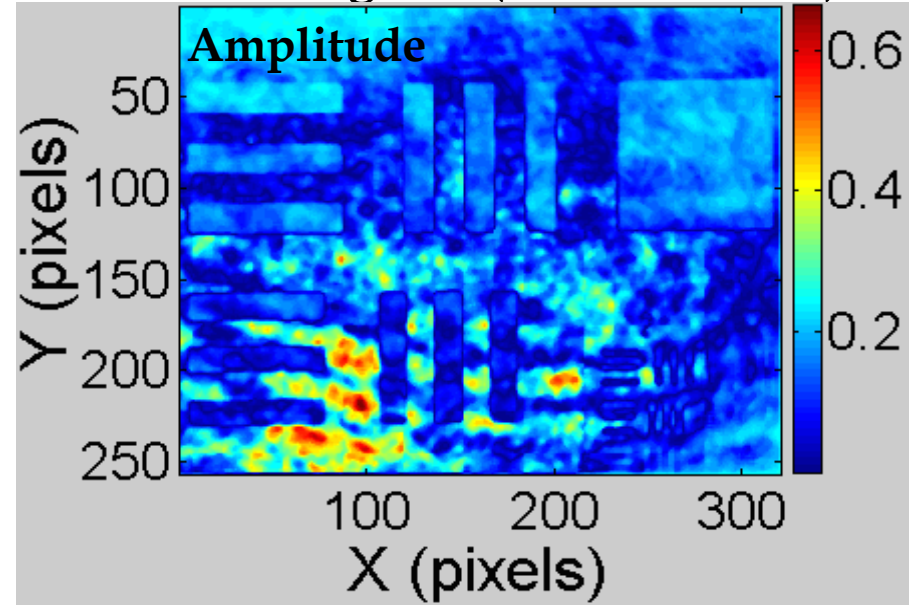


# 1-1. Reconstruction (original)

(Wavelength = 1538.8721 nm)

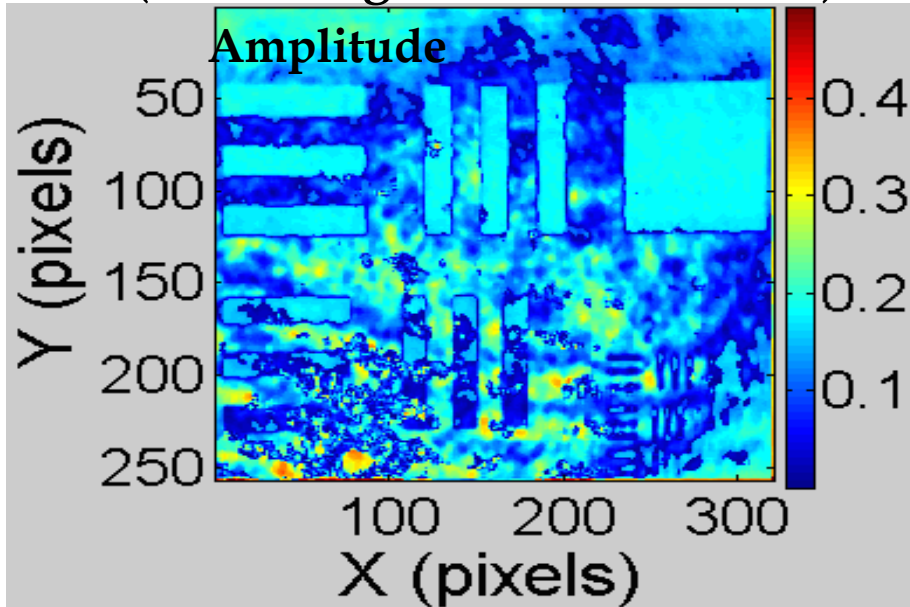


Wavelength = (1537.8711 nm)

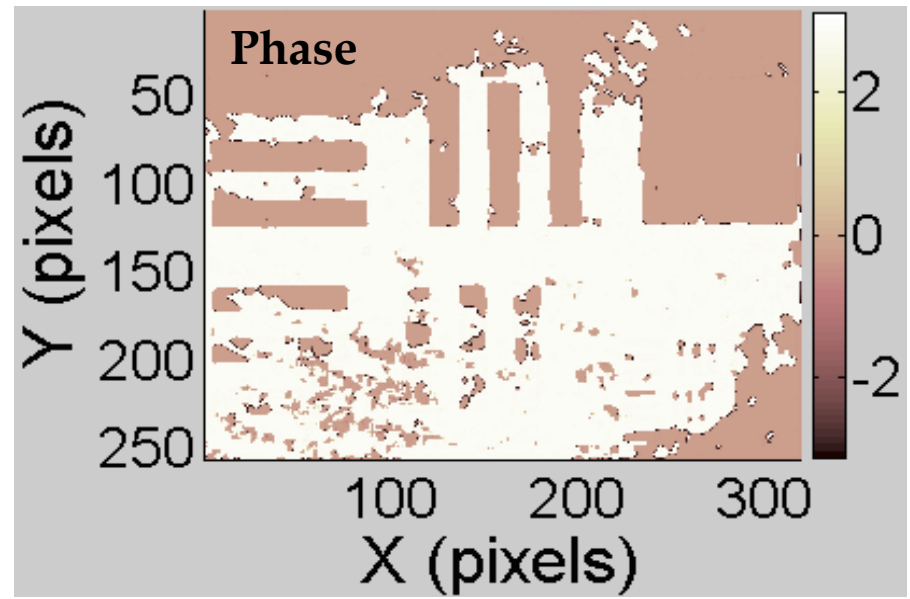
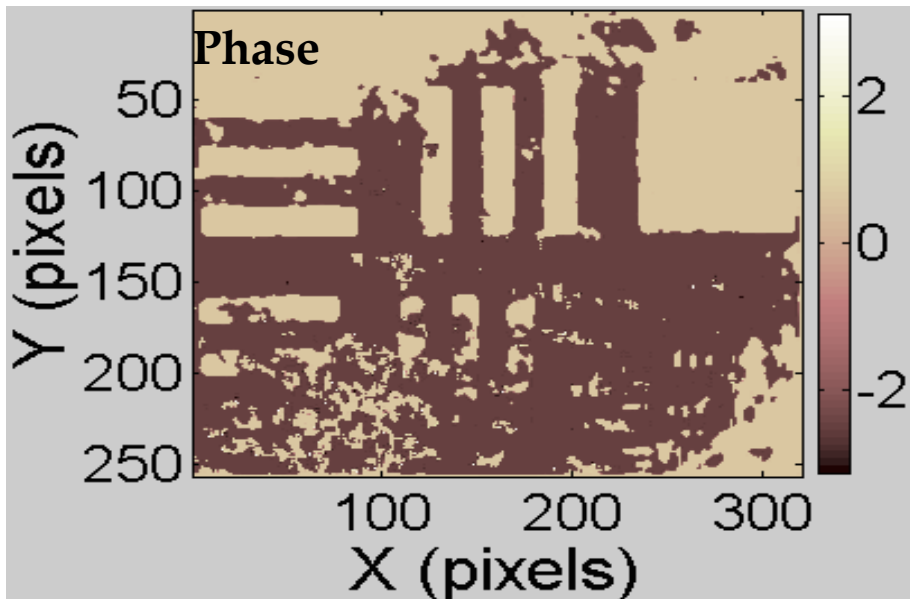
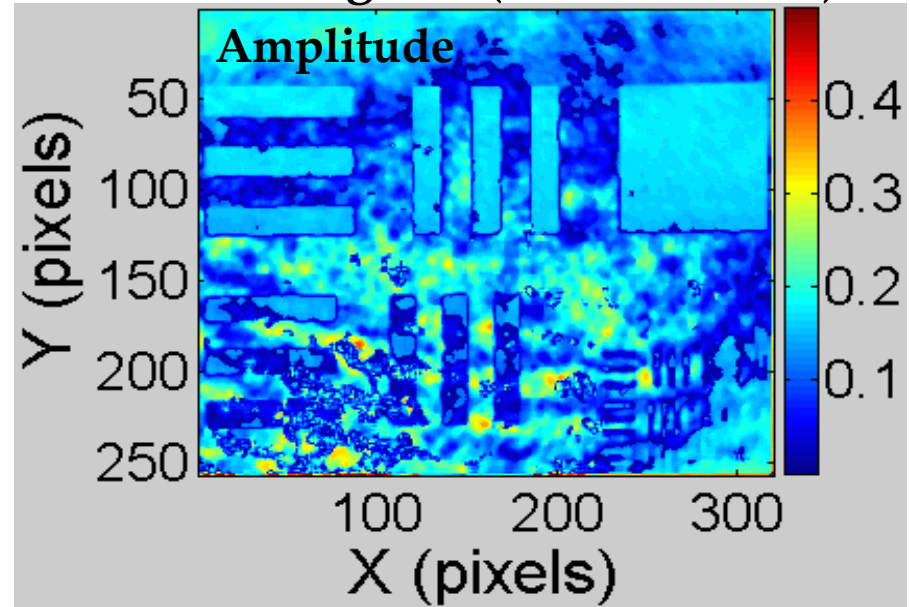


# 1-1. Reconstruction (corrected)

(Wavelength = 1538.8721 nm)



Wavelength = (1537.8711 nm)

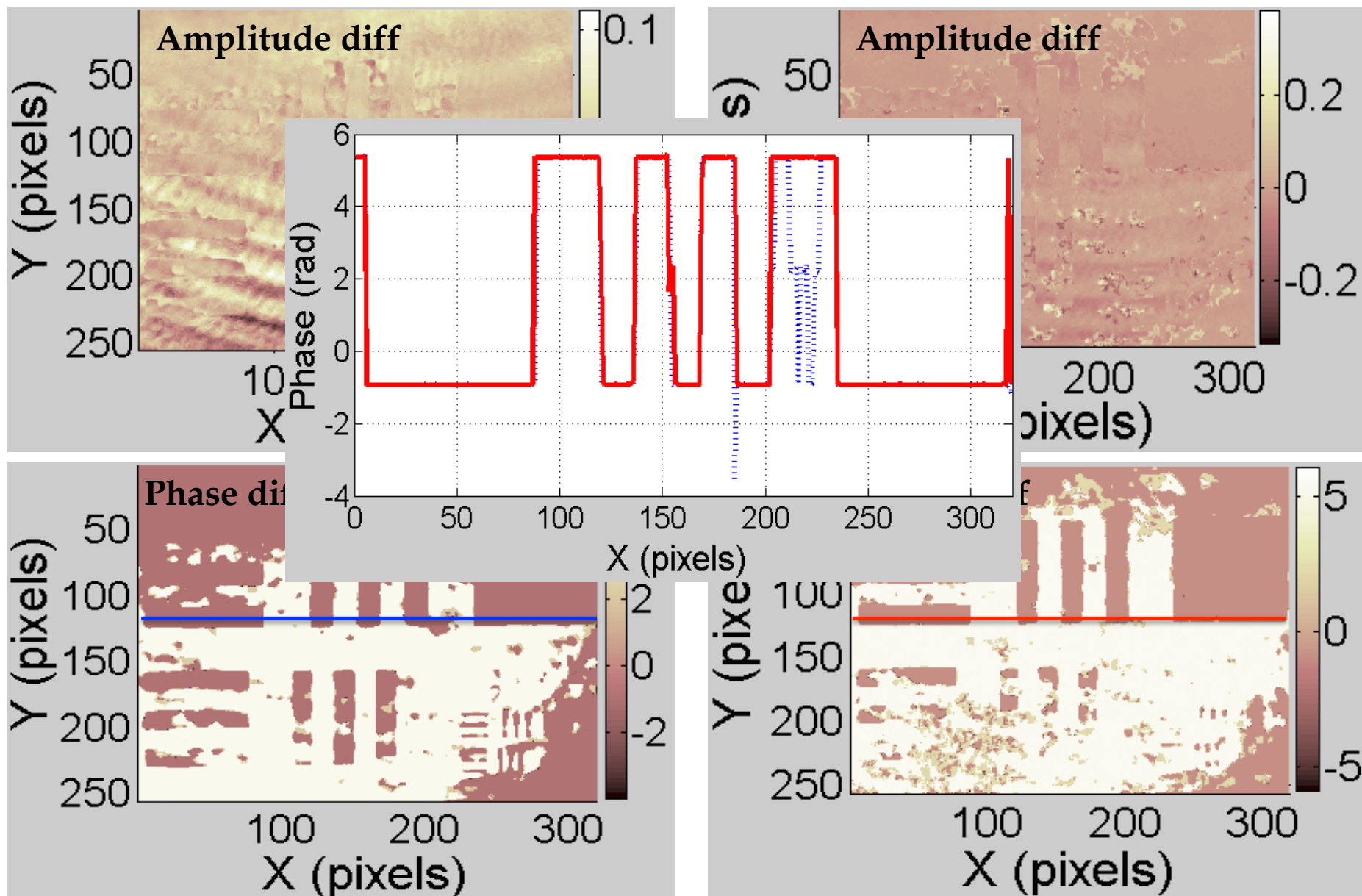




# 1-1. Differences (amplitudes & phases)

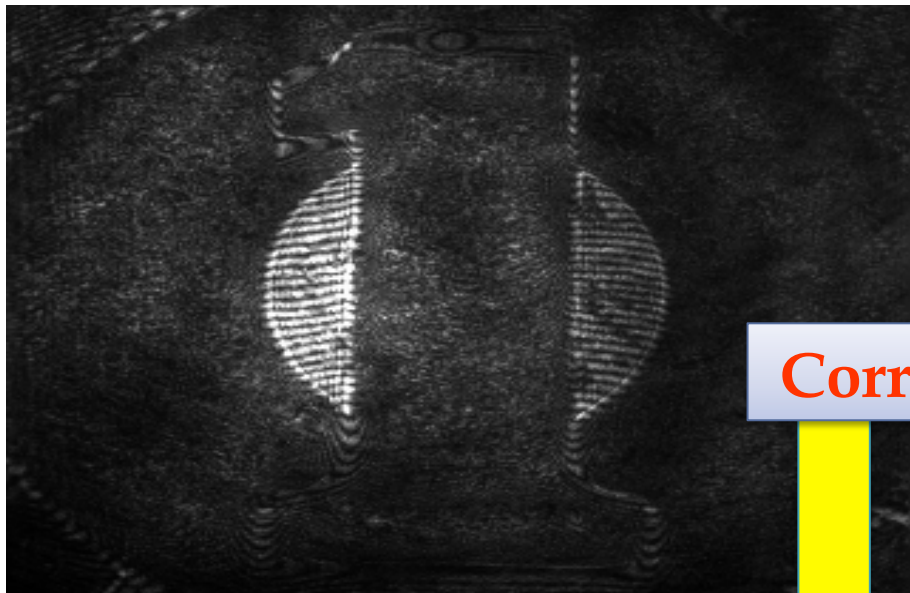
Original

Corrected

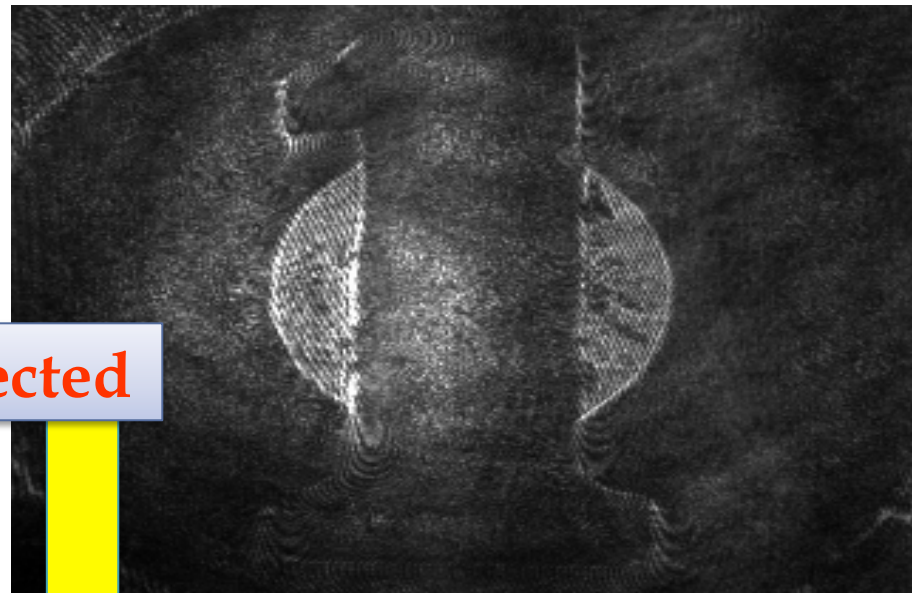


## 1-2. Rough object (Japanese 1 yen coin)

1542.7661 nm



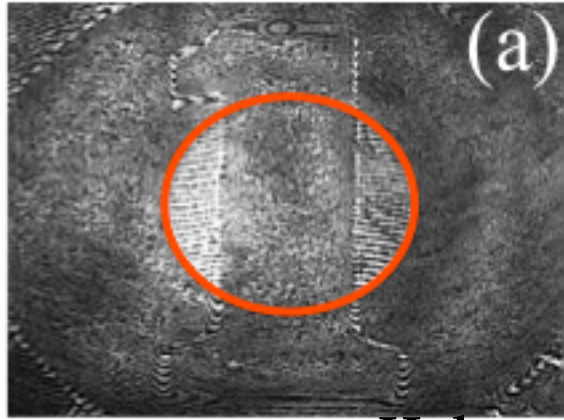
1534.8211 nm



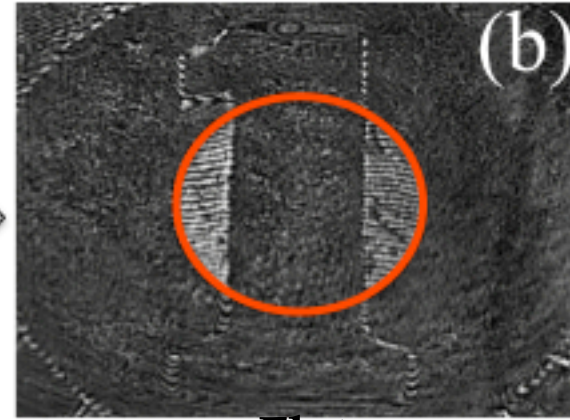
Corrected



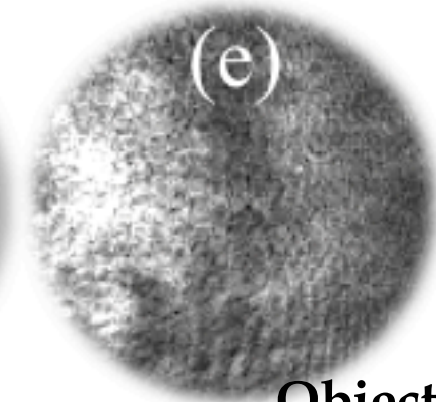
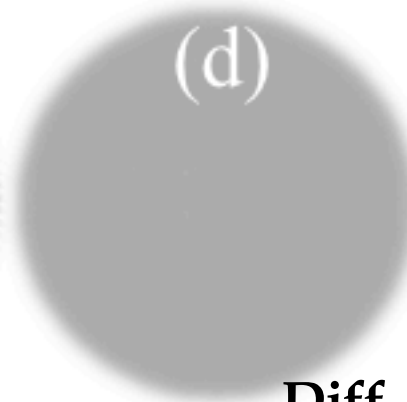
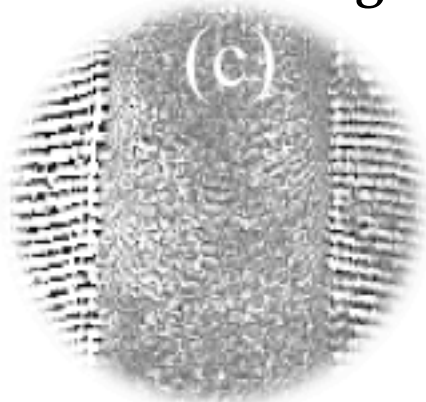
# 1-2. Hologram correction



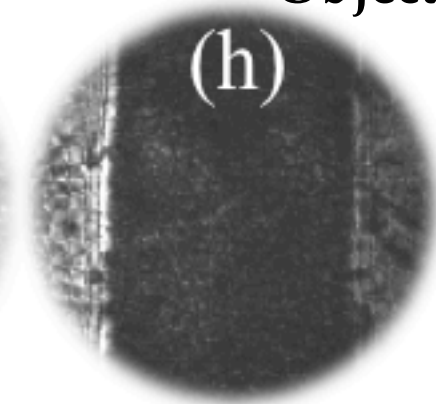
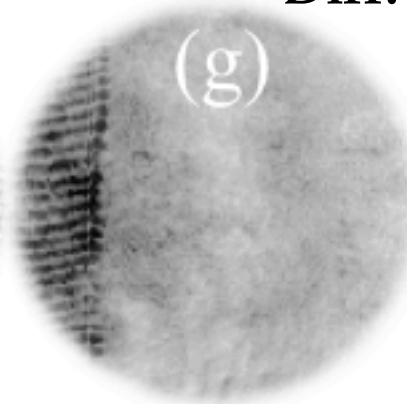
Corrected



Before  
correction



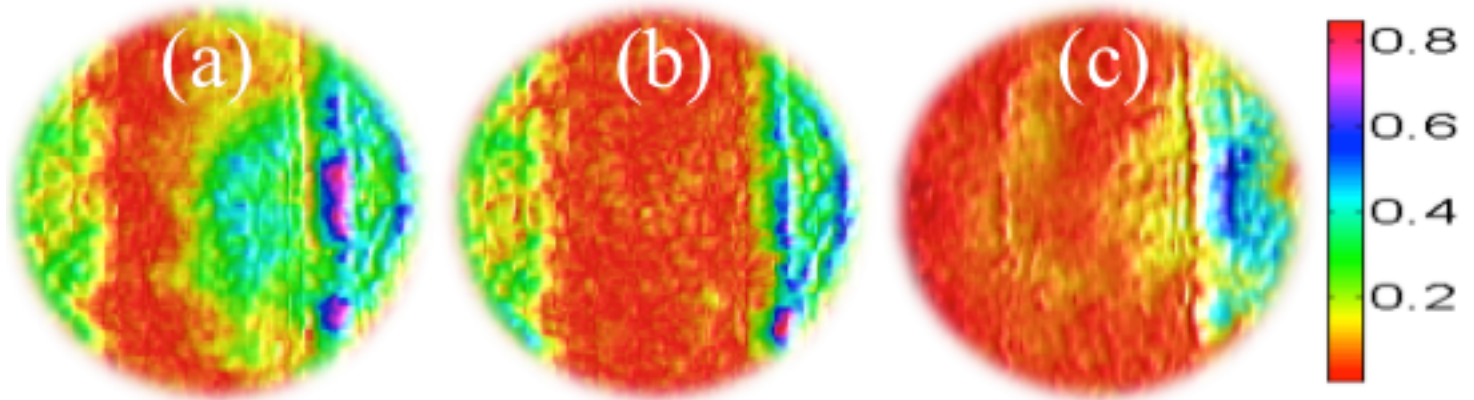
After  
correction



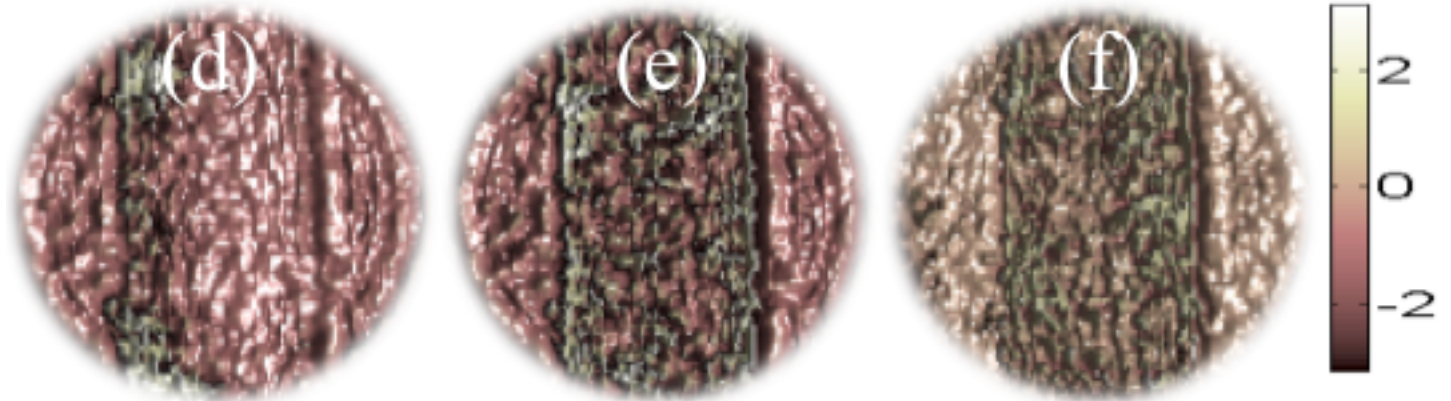


# 1-2. Impact of noise on reconstruction

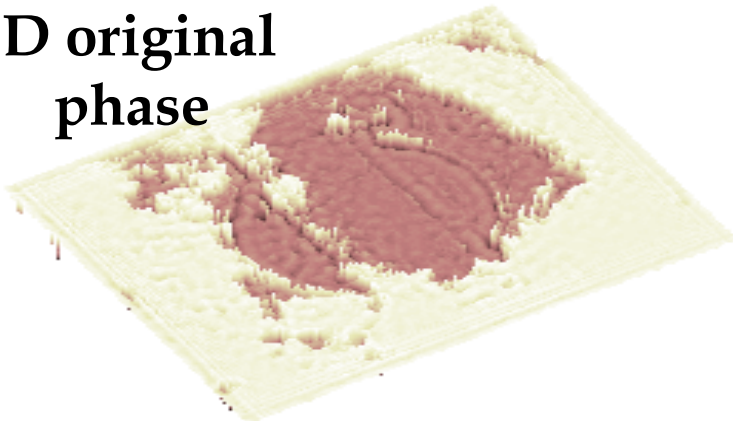
**Amplitude**



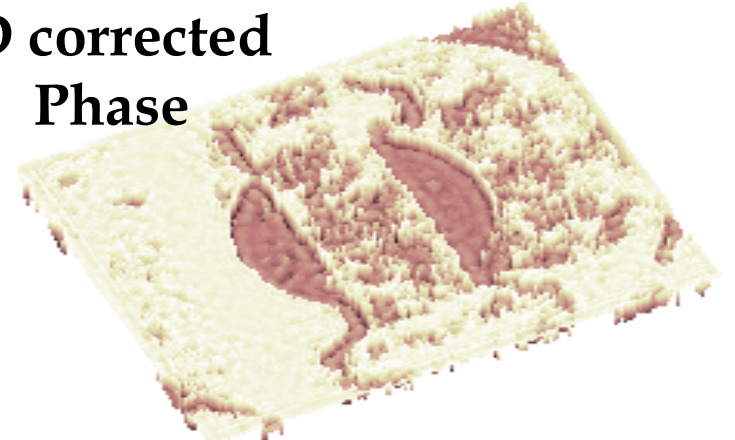
**Phase**



**3D original  
phase**



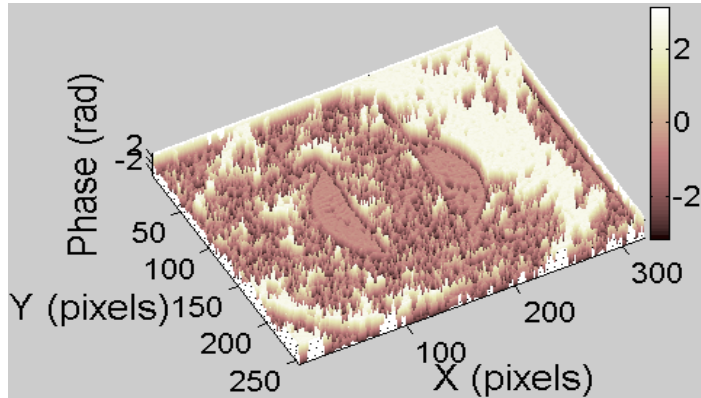
**3D corrected  
Phase**





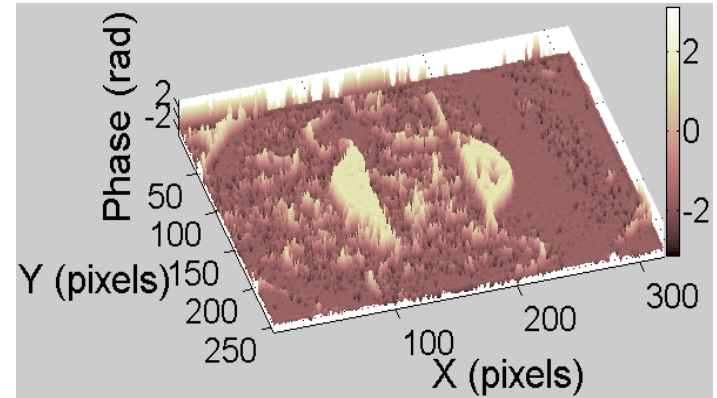
# 1-2. Reconstruction of two holograms at different wavelengths

1542.7661 nm

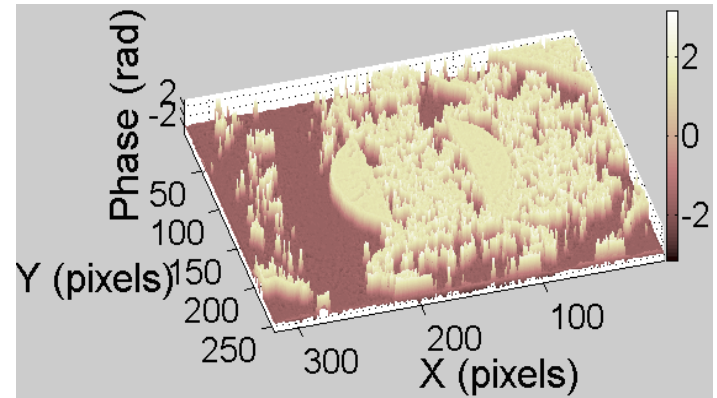
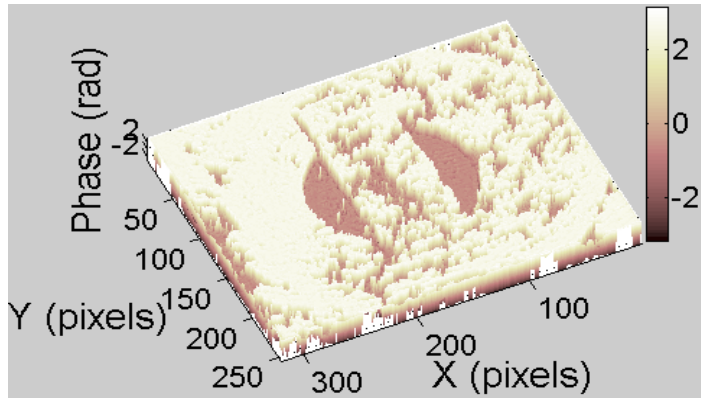


3D Phase

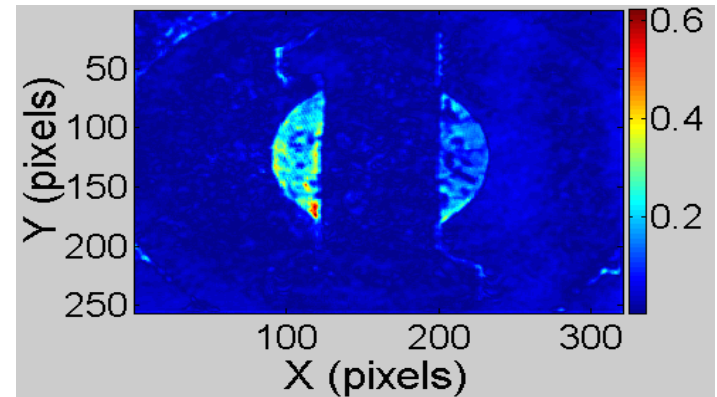
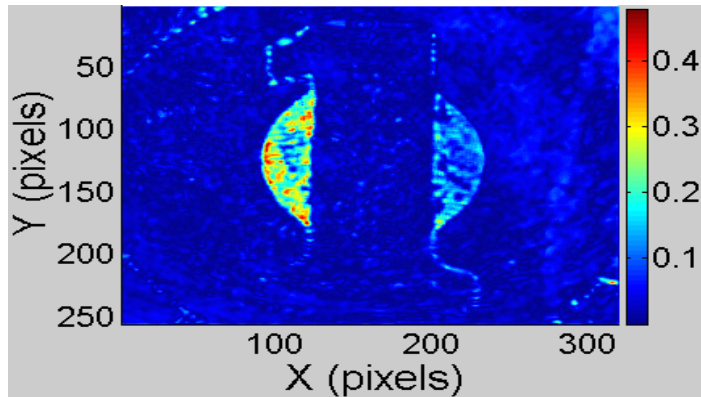
1534.8211 nm



3D reversed  
Phase

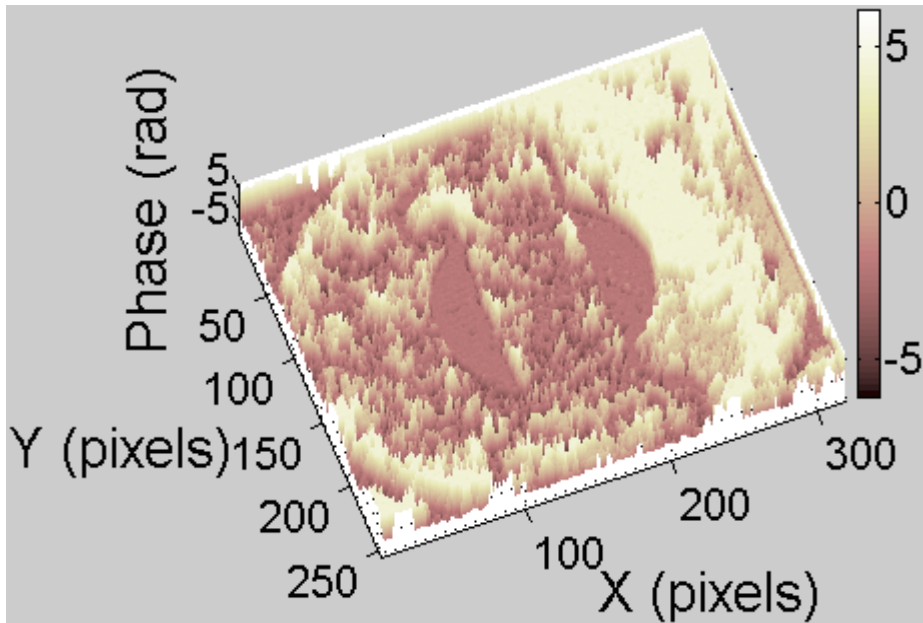


3D Amplitude

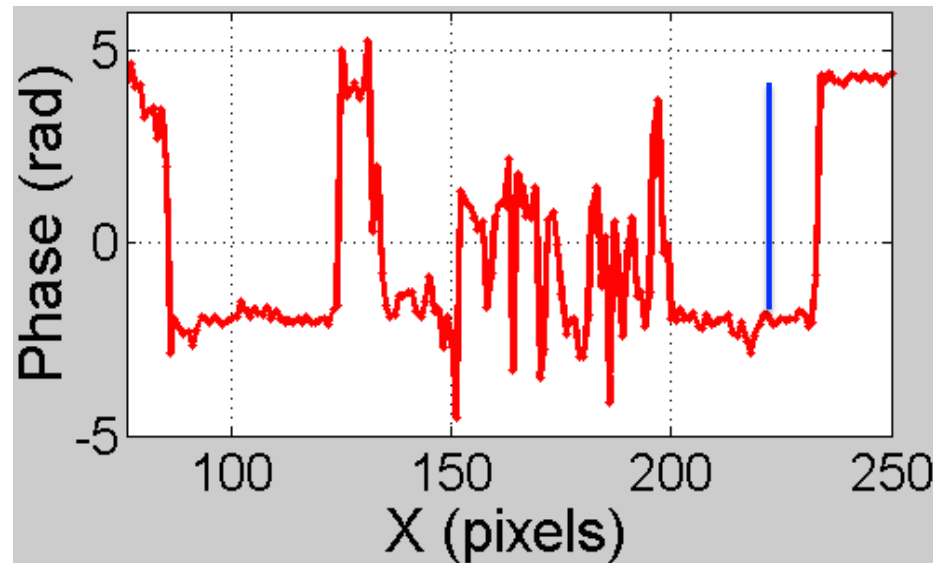
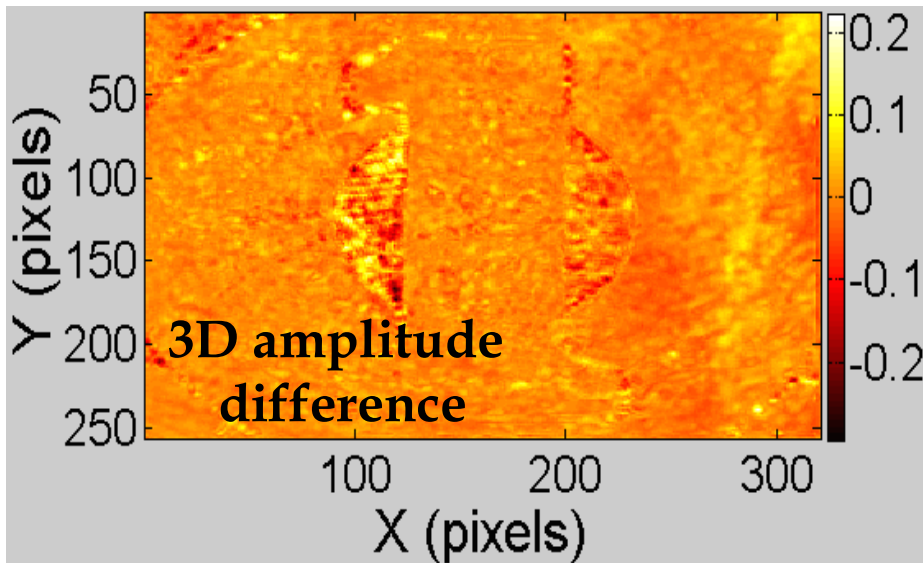
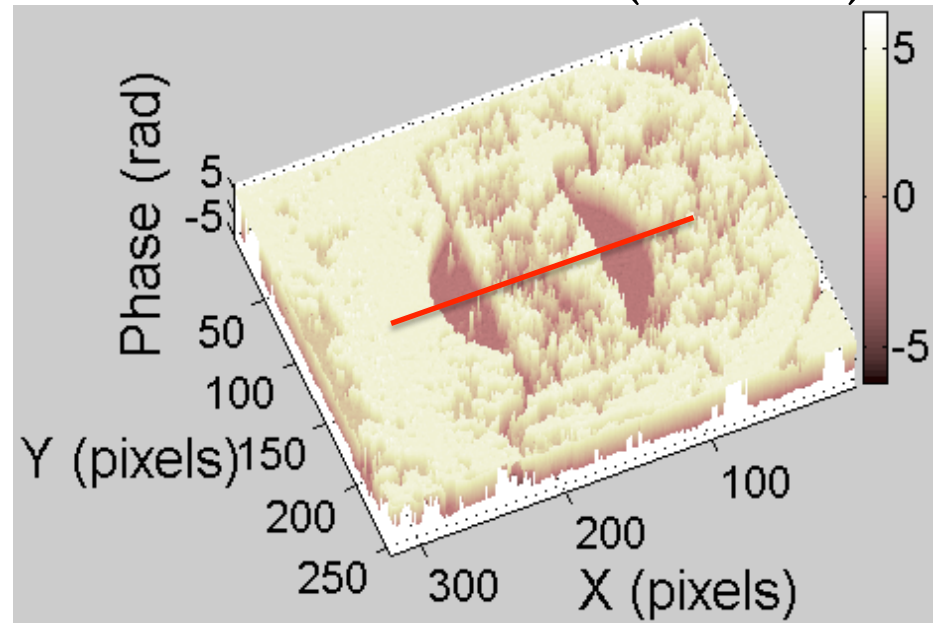


# 1-2. 3D amplitude and phase differences

## 3D Phase difference

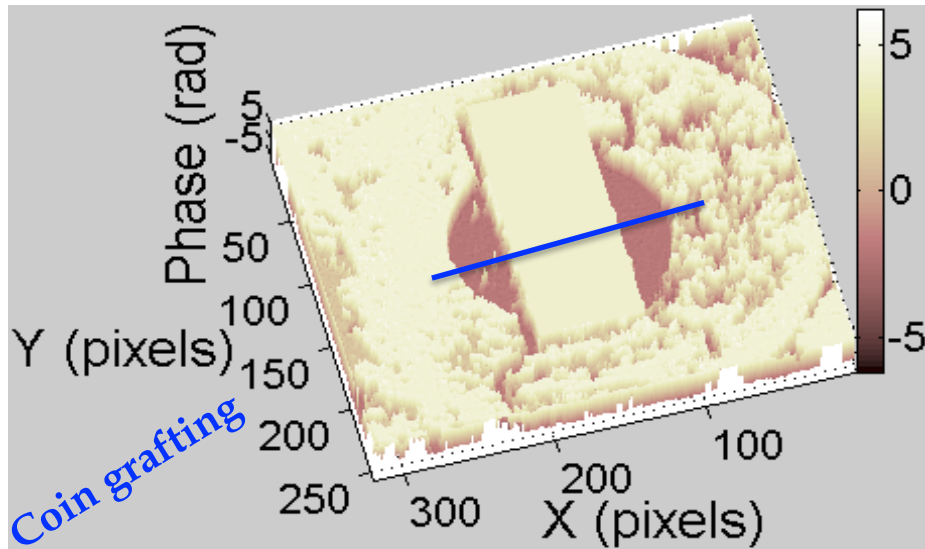


## 3D Phase difference (reversed)

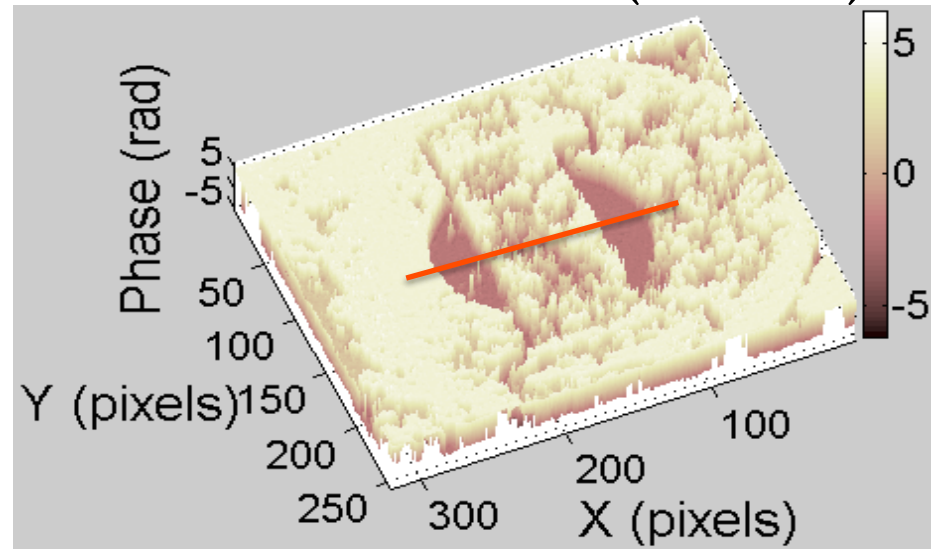


# 1-2. 3D amplitude and phase differences

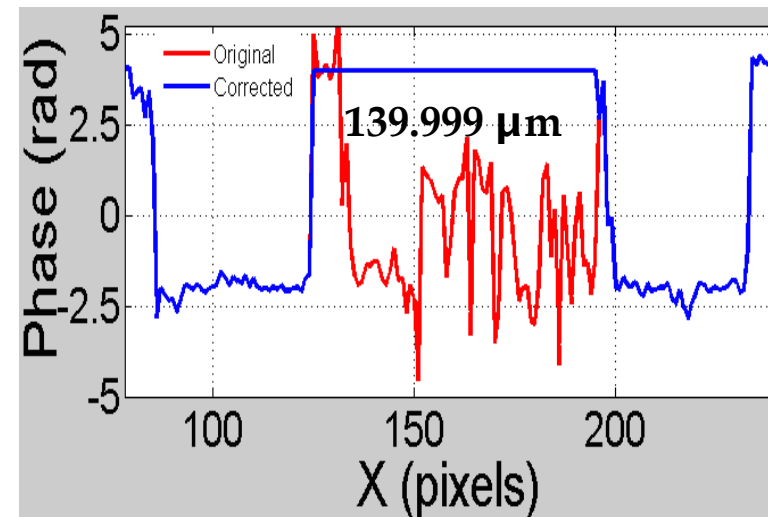
## 3D Phase difference



## 3D Phase difference (reversed)

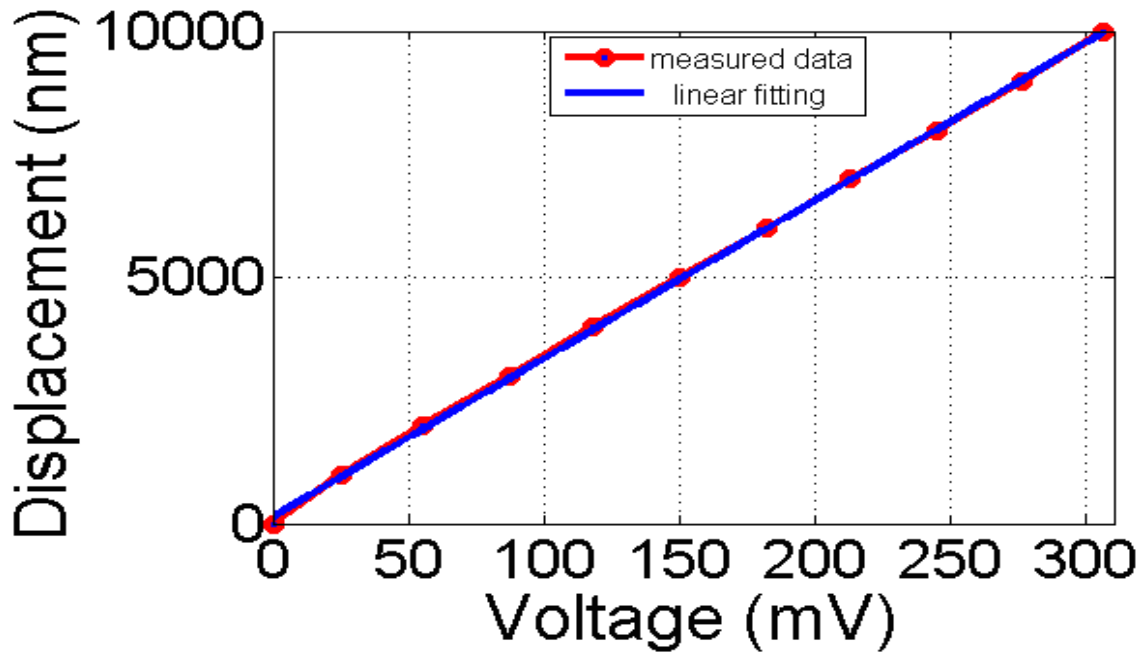


	Surface height measurement (holography)	Surface height measurement (confocal microscope)
Apparent wavelength (nm) (1542.7661 & 1534.8211)	139.999 45 $\mu\text{m}$	120.00000 $\mu\text{m}$
Actual wavelength (+nm) (1542.7657 & 1534.8207)	139.999 37 $\mu\text{m}$	
Actual wavelength (-nm) (1542.7665 & 1534.8215)	139.999 52 $\mu\text{m}$	

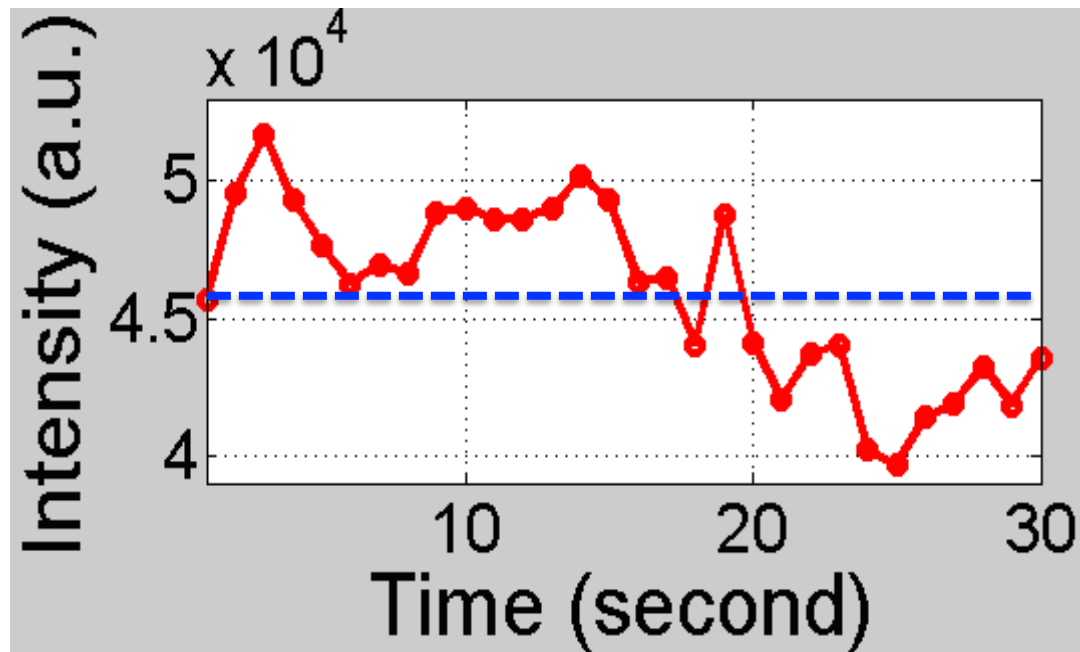




# 3-1. Calibration and impact of ambient vibrations



Voltage (mV)  
vs. Disp. (nm)



Instability of  
hologram  
intensity



## 3-2. USF object (pattern 1)

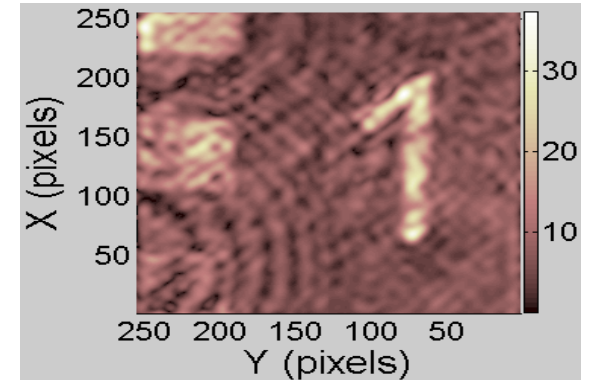
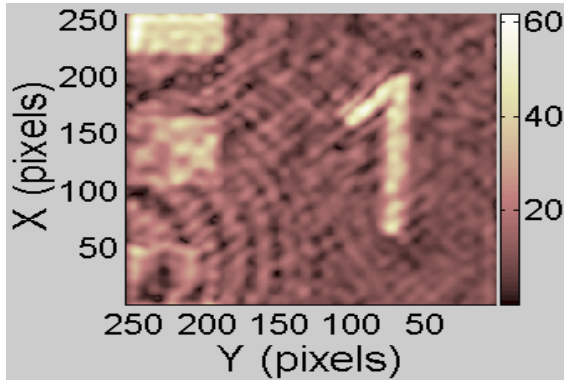
Image (1537.3840 nm)



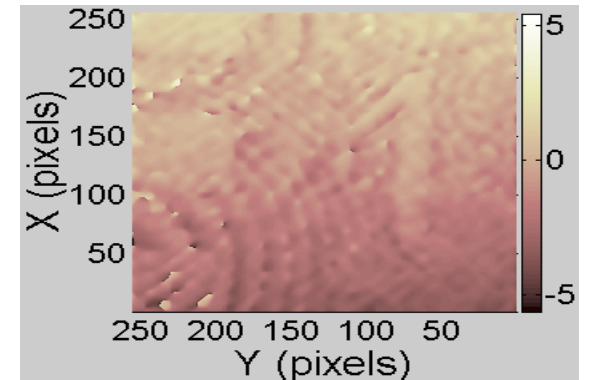
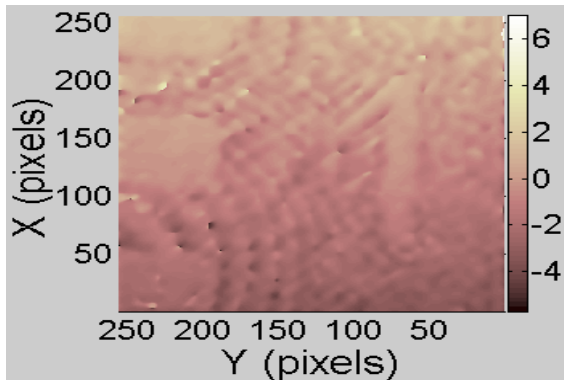
Corrected (1537.3840 nm)



Holograms



3D Amplitude



3D Phase

## 3-3. USF object (pattern 5)

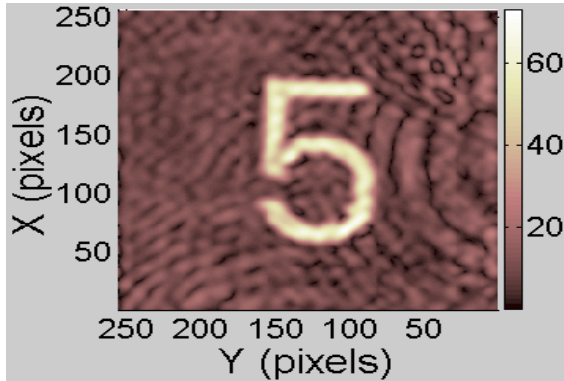
Image (1536.9372 nm)



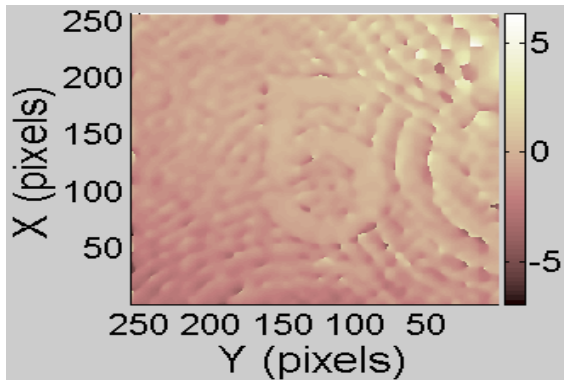
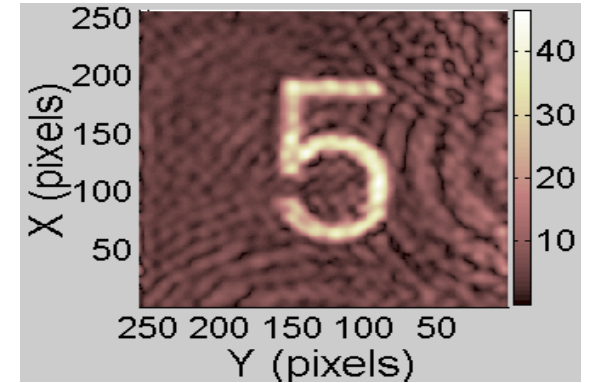
Corrected (1536.9372 nm)



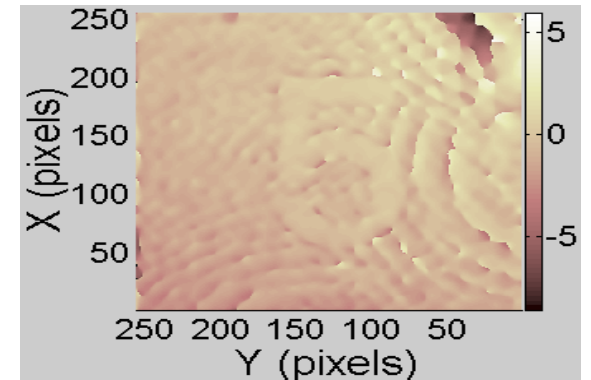
Holograms



3D Amplitude

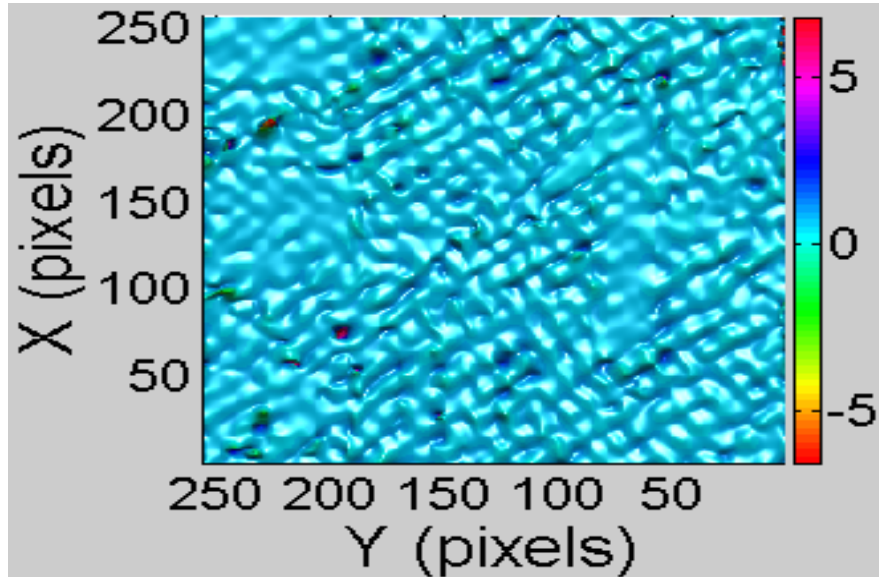


3D Phase

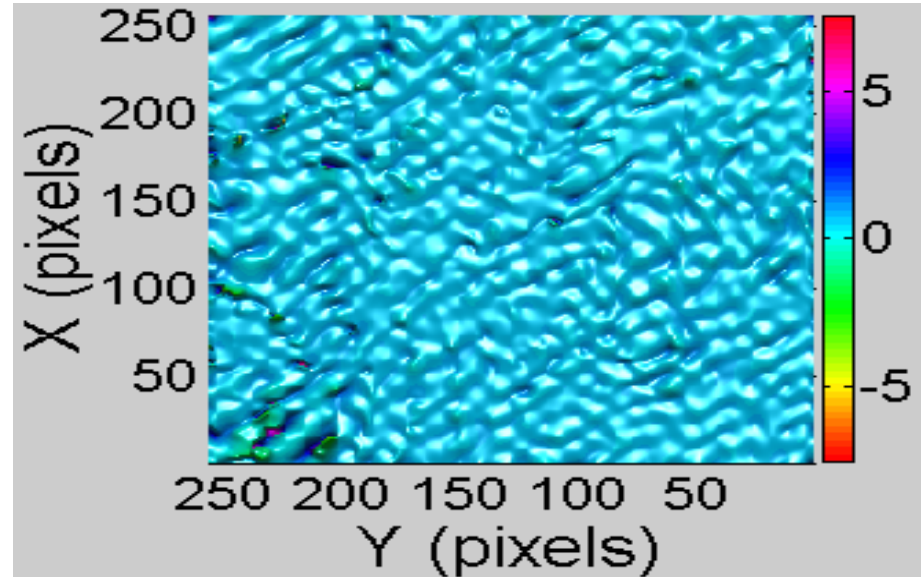


### 3-2. Phase difference (1537.3840nm - 1537.3845nm)

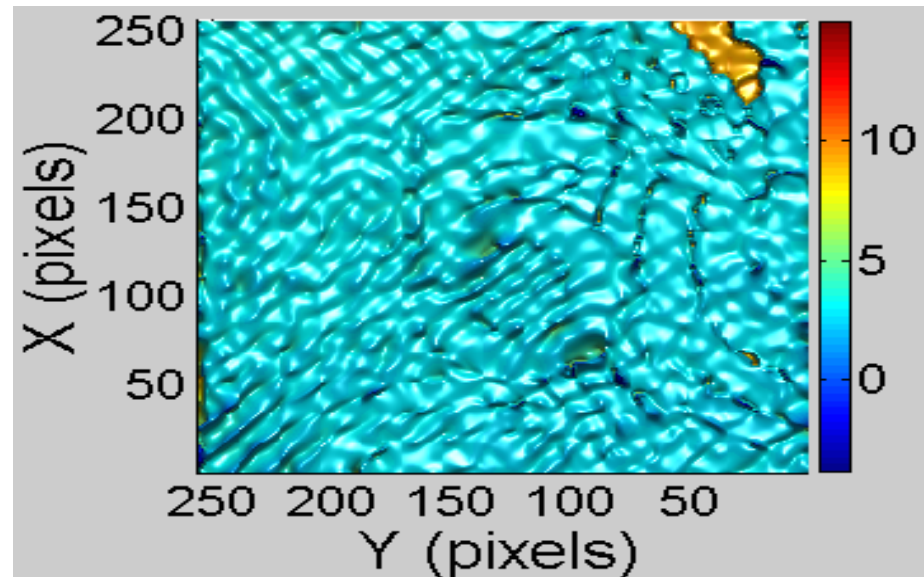
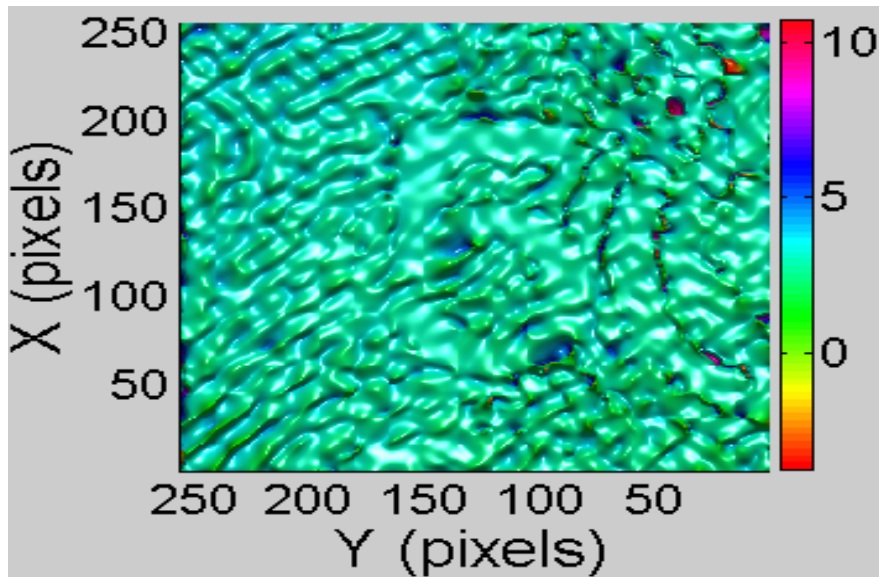
Phase diff (original phase)



Phase diff (corrected phase)

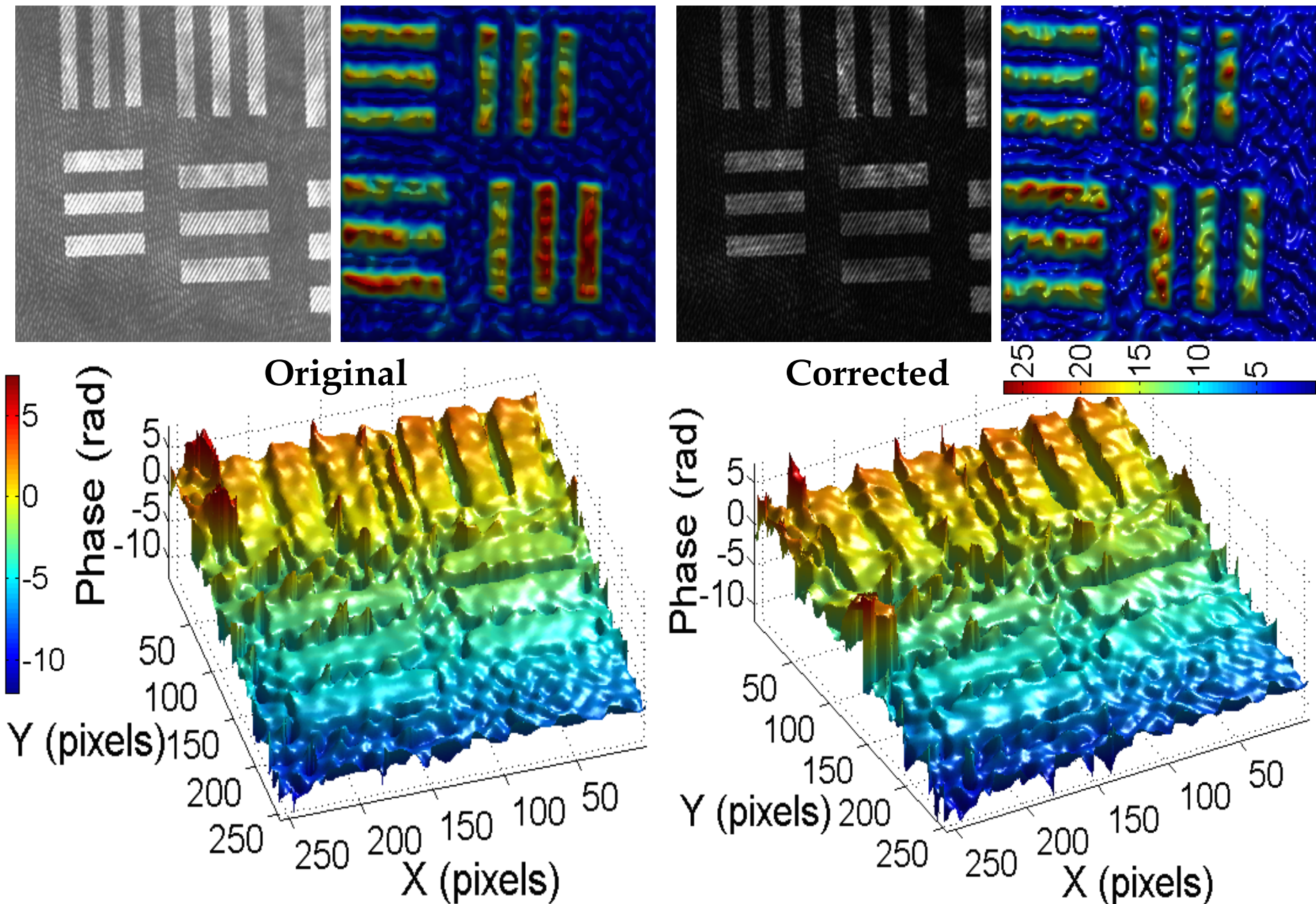


### 3-3. Phase difference (1536.9372nm - 1537.0236nm)

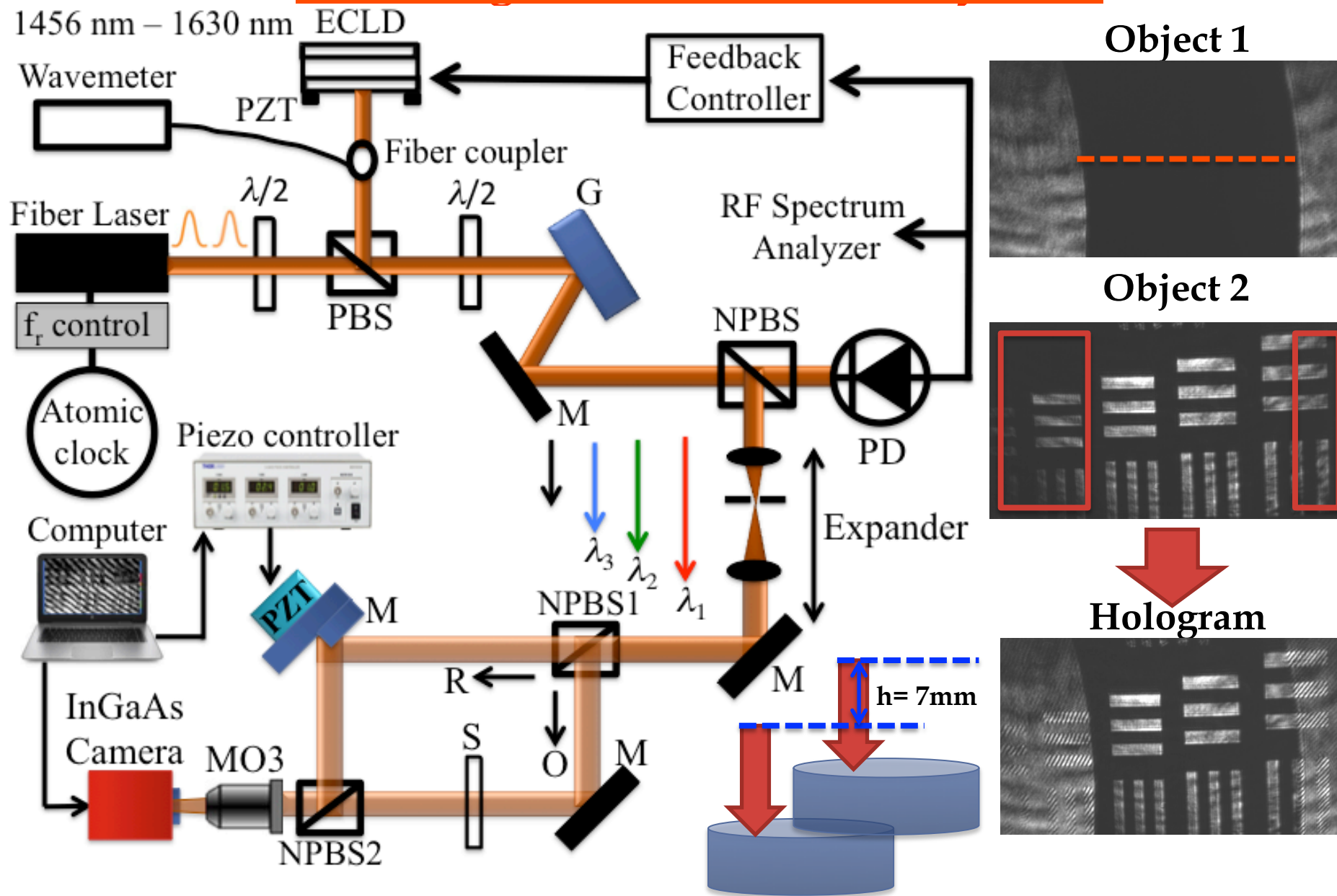




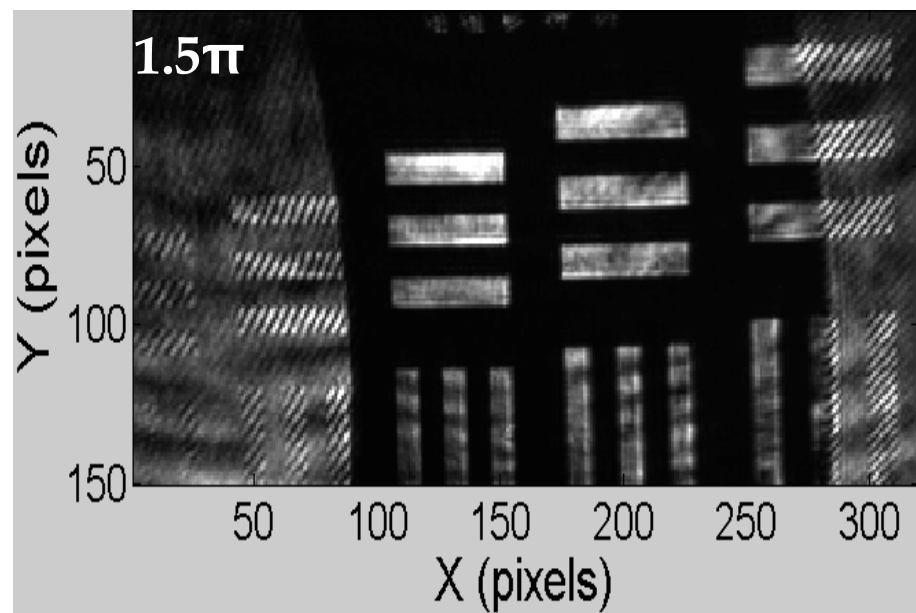
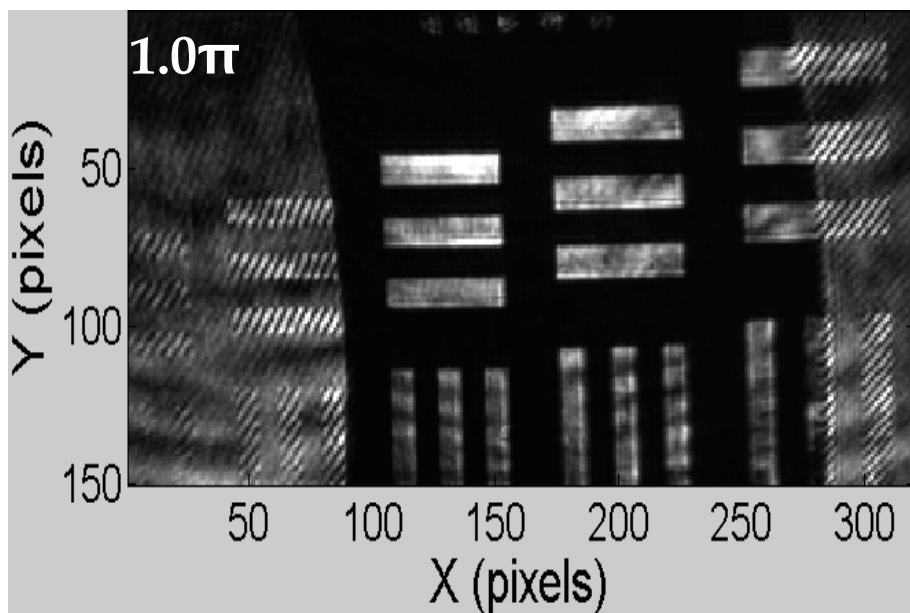
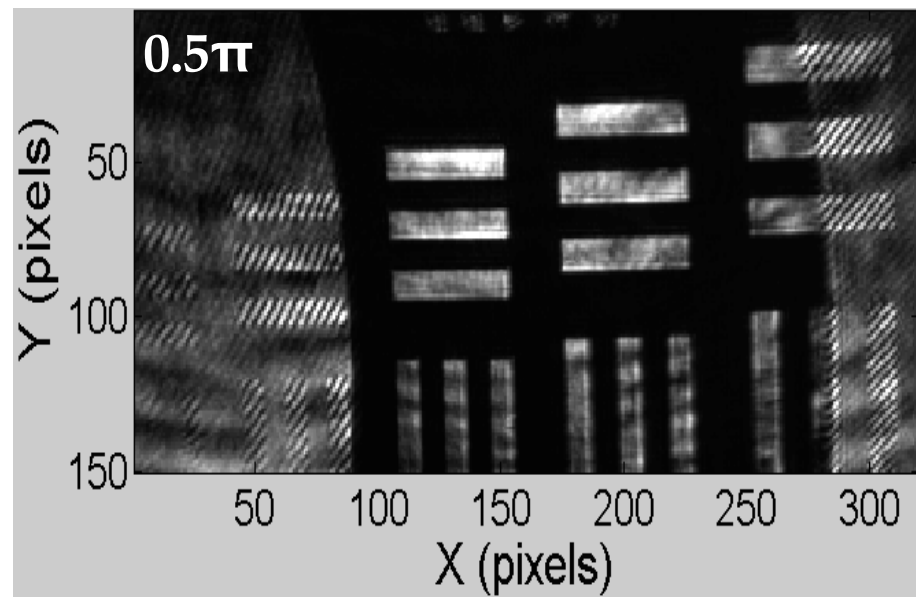
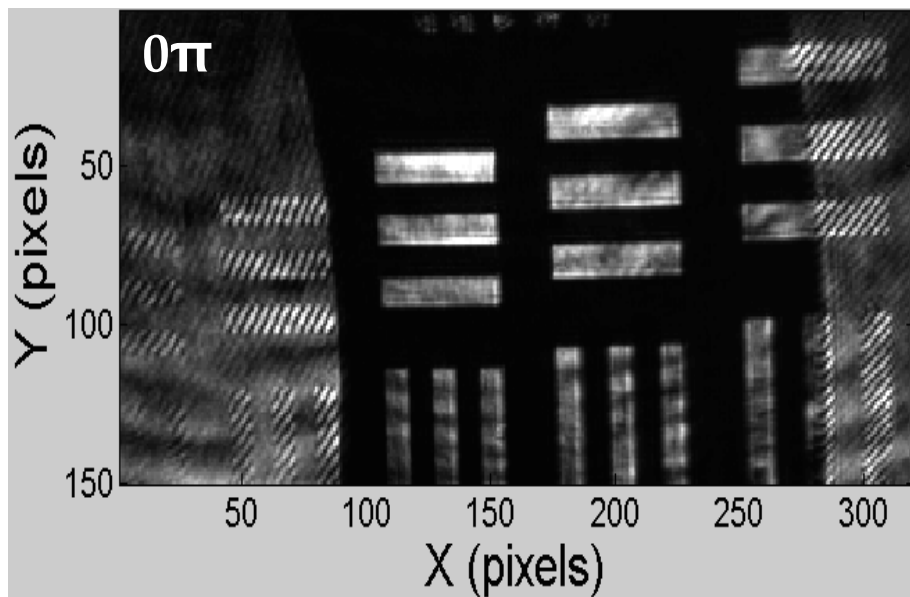
### 3-4. USF object (some patterns) at 1540.8583 nm



# 4. High-precision multi-object investigation by multi-wavelength DH referenced by OFC

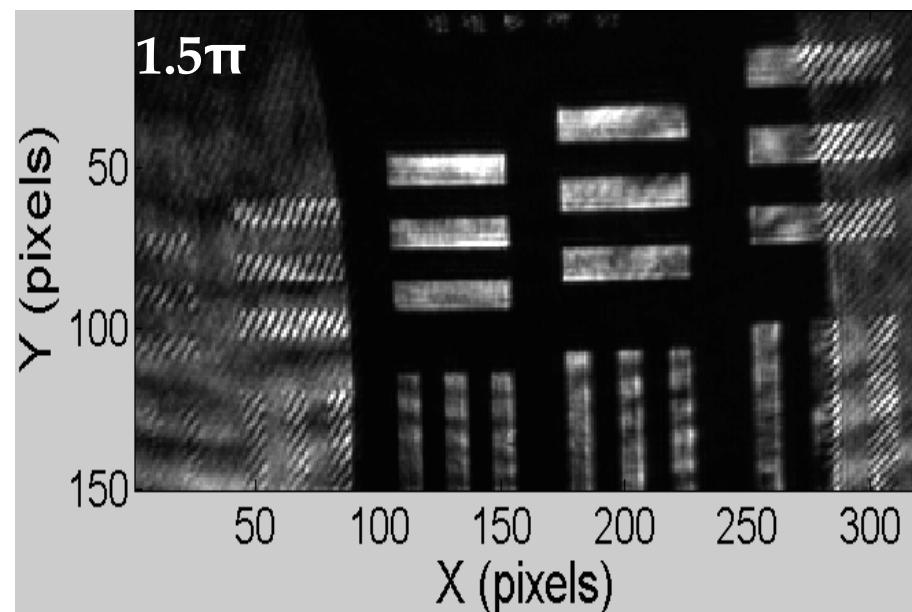
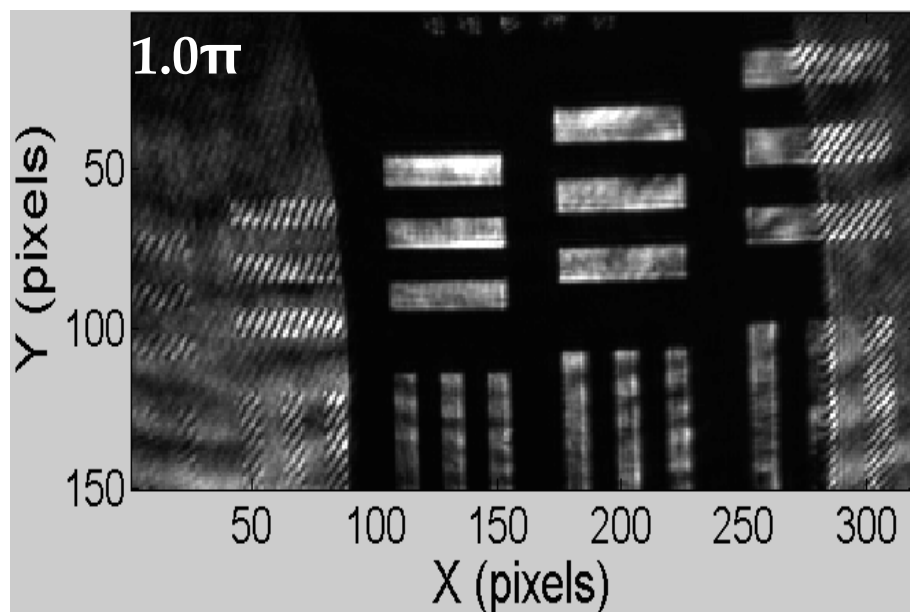
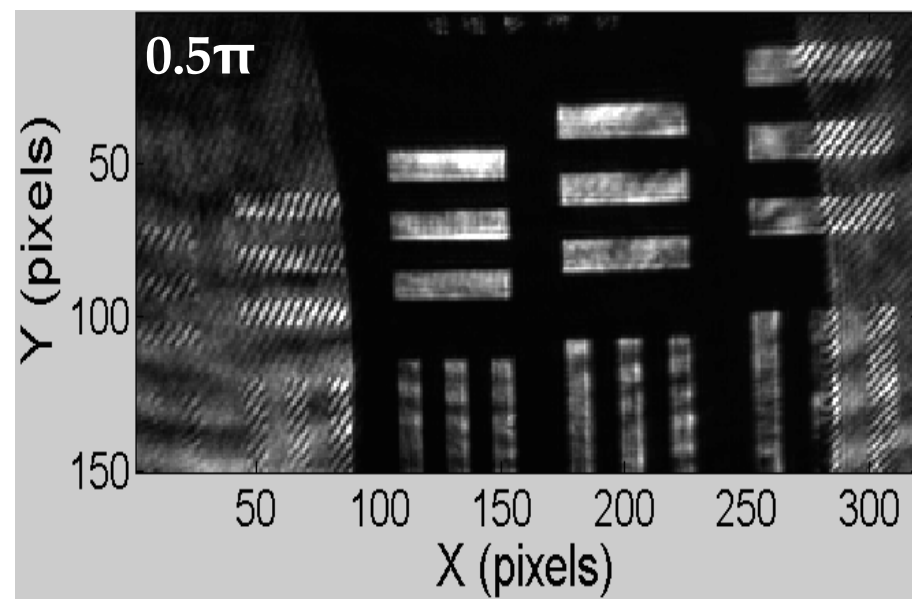
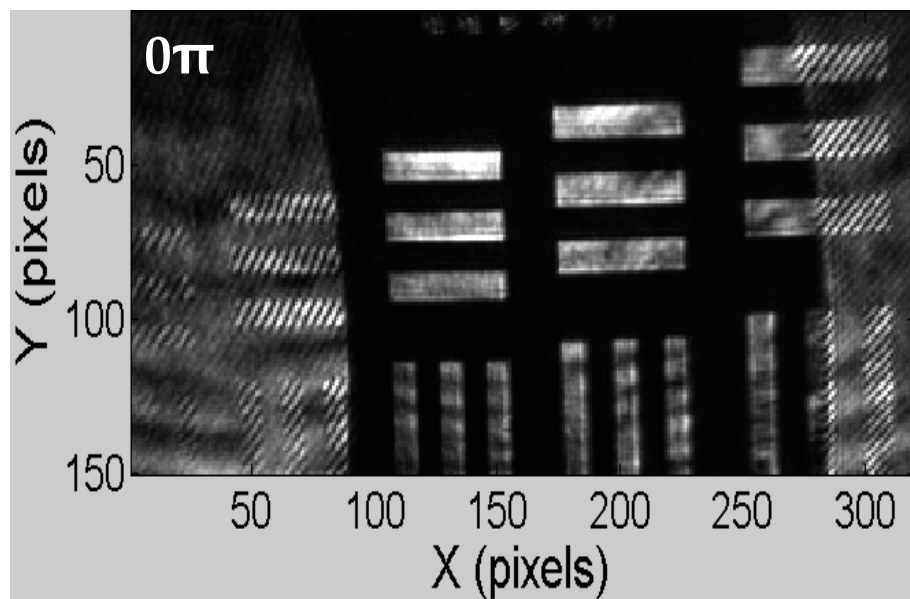


## 4-1. Phase shifting (1540.4010 nm)



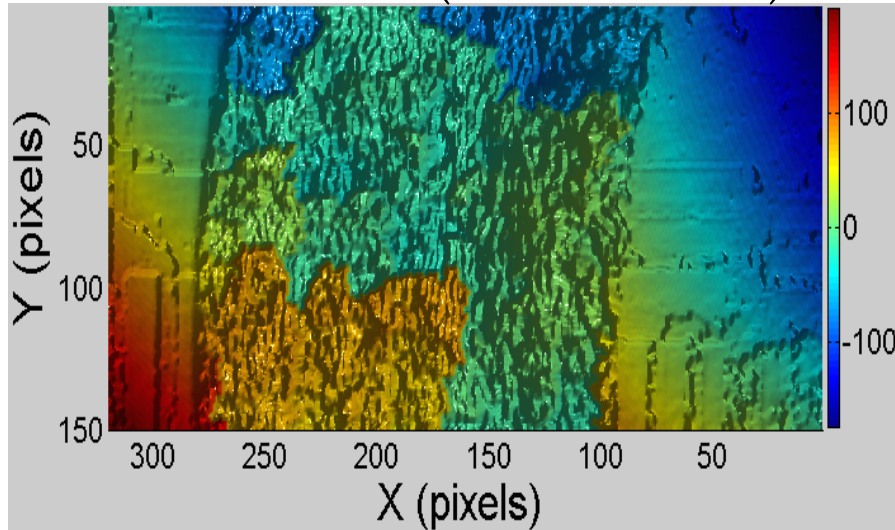


## 4-1. Phase shifting (1541.4015 nm)

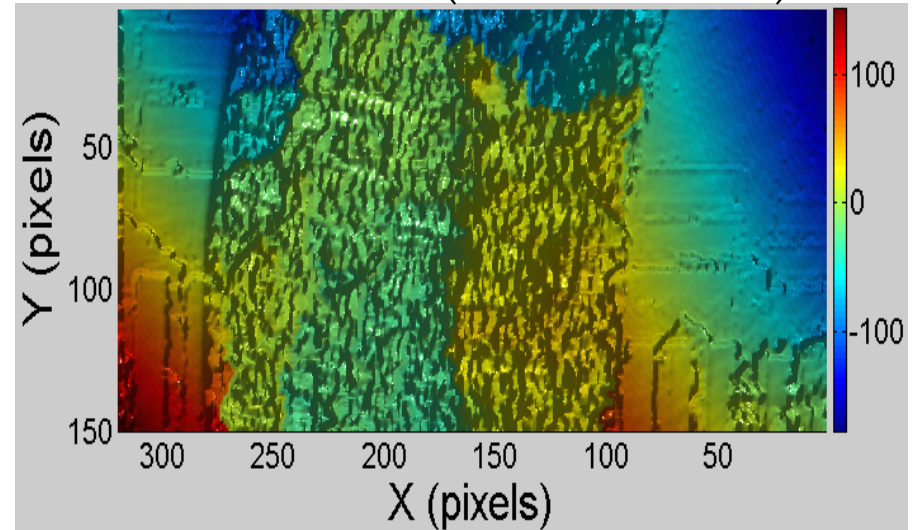


# 4-1. Reconstruction

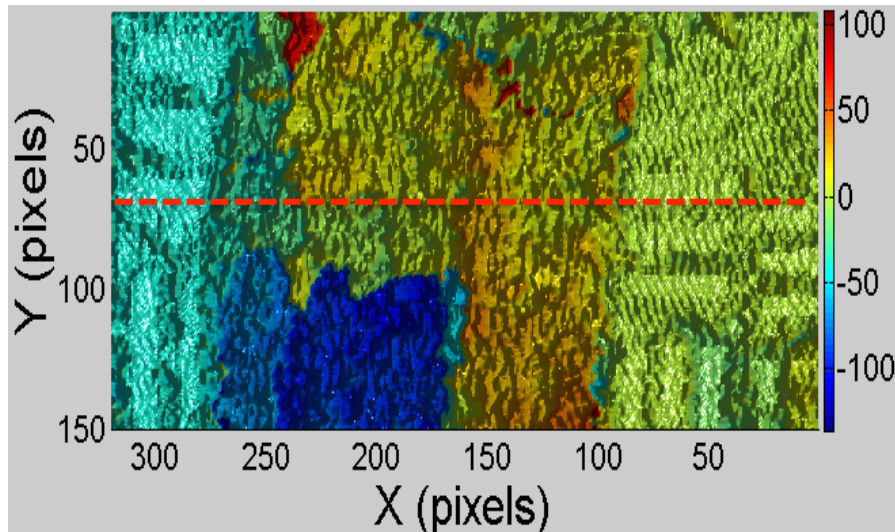
3D Phase at (1540.4010 nm)



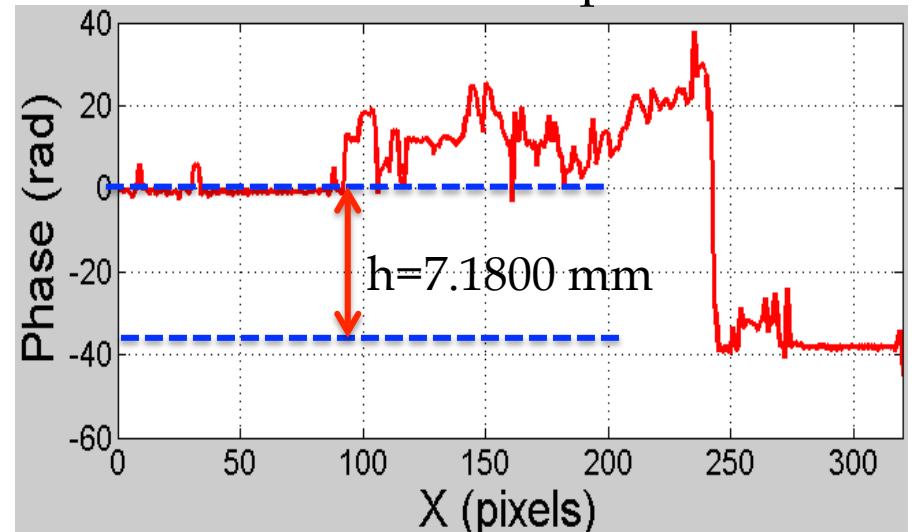
3D Phase at (1541.4015 nm)



3D Phase diff.



1D Phase diff. profile





Thank you for listening.  
Any questions or suggestions?