One-step robust deep learning phase unwrapping

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One-step robust deep learning phase unwrapping

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Abstract: Phase unwrapping is an important but challenging issue in phase measurement. Even with the research efforts of a few decades, unfortunately, the problem remains not well solved, especially when heavy noise and aliasing (undersampling) are present. We propose a database generation method for phase-type objects and a one-step deep learning phase unwrapping method. With a trained deep neural network, the unseen phase fields of living mouse osteoblasts and dynamic candle flame are successfully unwrapped, demonstrating that the complicated nonlinear phase unwrapping task can be directly fulfilled in one step by a single deep neural network. Excellent anti-noise and anti-aliasing performances outperforming classical methods are highlighted in this paper.

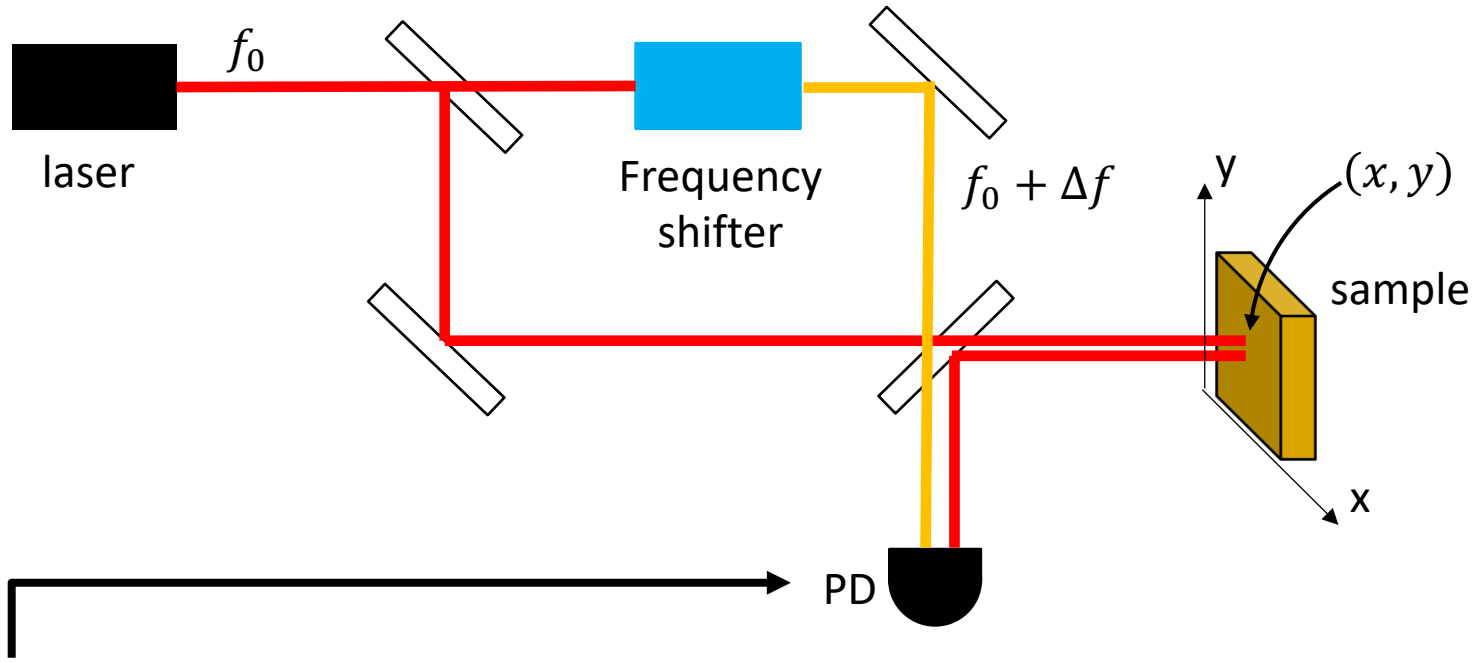
Contents

- Phase unwrapping problem
- Convolutional Neural Network(CNN)
- Materials and methods
- Testing the trained CNN
  - Accuracy test
  - Anti-noise performance test
  - Anti-aliasing performance test
  - Generalization capability test

Phase unwrapping problem

Phase unwrapping problem

- Example : opt metrology with heterodyne interferometer



$$I = |E_0 \exp[i2\pi f_0 t] + E_1 \exp[i(2\pi(f_0 + \Delta f)t + \phi(x,y)]\,|^2$$
$$= E_0^2 + E_1^2 + 2E_0E_1 \cos\big(2\pi\Delta f t + \phi(x,y)\big)$$

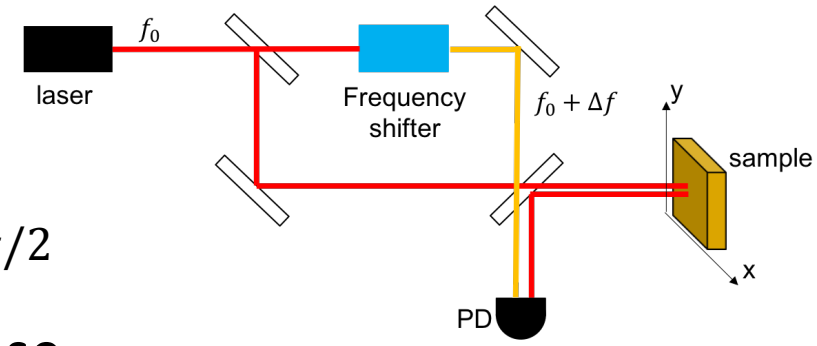
By measuring $\phi(x,y)$ from laser intensity: I,
surface roughness of the sample can be measured

Phase unwrapping problem

- **Example :** opt metrology with heterodyne interferometer

However, the phase distribution observed with interferometer is wrapped into $[-\pi, \pi]$

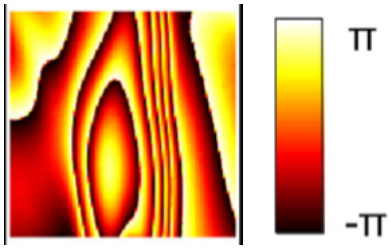
e.g. $3\pi/2 \Rightarrow -\pi/2$



$-\pi \leq \tilde{\phi}\,(x, y) \leq \pi$: wrapped phase

$\tilde{\phi}\,(x, y) \equiv \phi(x, y)\ (mod\ 2\pi)$

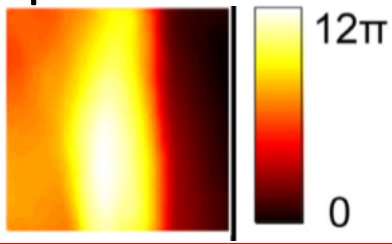
Phase unwrapping problem



$\tilde{\phi}\,(x, y)$ → unwrap → $\phi(x, y)$: real phase

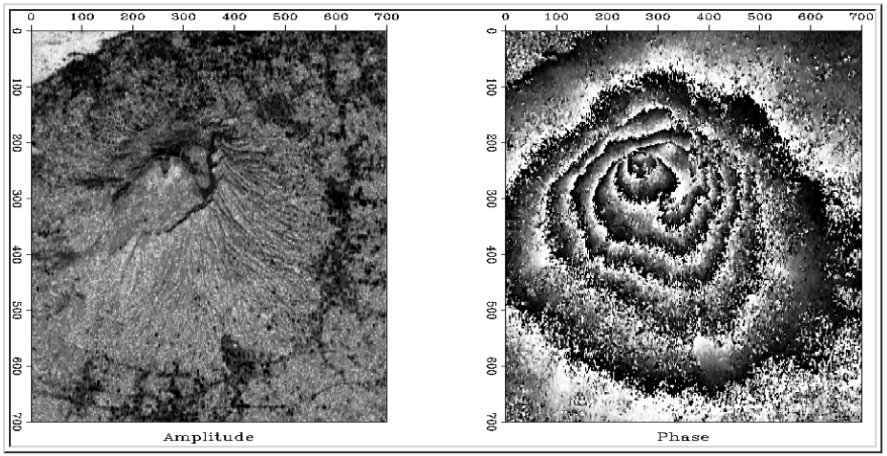
Range : $[-\pi, \pi]$
discontinuous

Range : $\mathbb{R}$
continuous

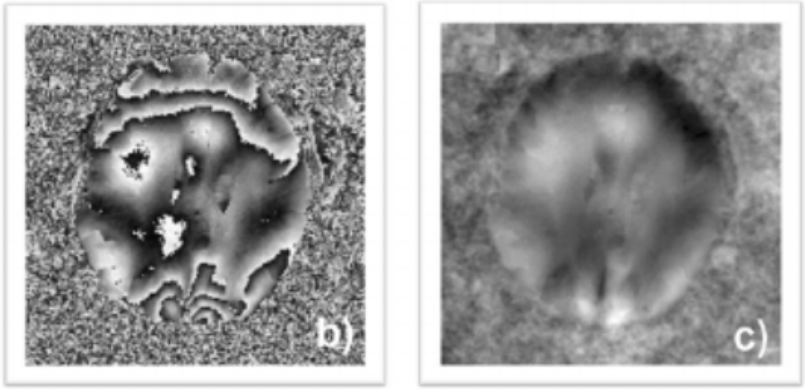


Phase unwrapping problem

- Other examples
  - ◆Radar Interferometry
  - ◆MRE(Magnetic Resonance Elastography)
  - ◆Phase-contrast X-ray Imaging



(http://sepwww.stanford.edu/sep/prof/gee/lsq/paper_html/node24.html)



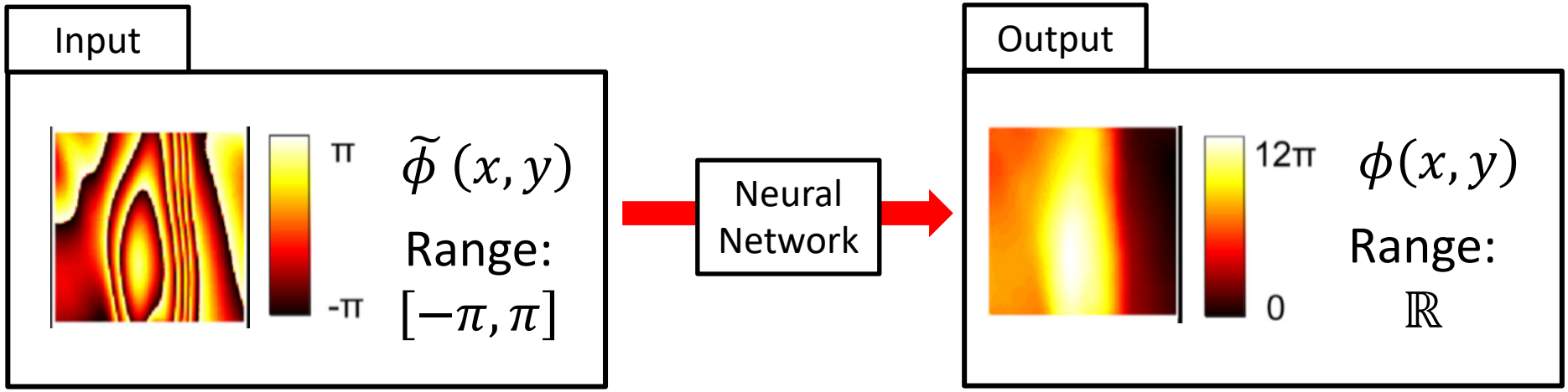
(Physics in Medicine and Biology 61(24):R401-R437)

Phase unwrapping problem

There are two classical methods to unwrap

LS (least square) method
QG (quality-guided) method
} have weak robustness to noise or aliasing

Let's solve unwrapping problem with Machine Learning



Convolutional Neural Network

What is machine learning?

- Supervised learning

Motivation

Many data: $\{(input: x_i, output: y_i)\}_{i=1\sim N}$

Machine learning model
$h_\theta(x)$

Predict y for unknown input x

What is machine learning?

- How to train a model $h_\theta(x)$

Many data: $\{(input: x_i, output: y_i)\}_{i=1\sim N}$

Cost Function: $J(\theta) = \frac{1}{N}\sum_{i=1}^{N}(h_\theta(x_i) - y_i)^2$

Minimize this ($J(\theta_{min})$: smallest)

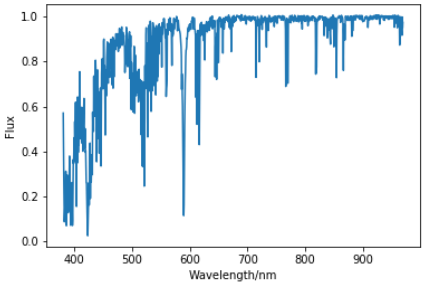
Trained model : $h_{\theta_{min}}(x)$

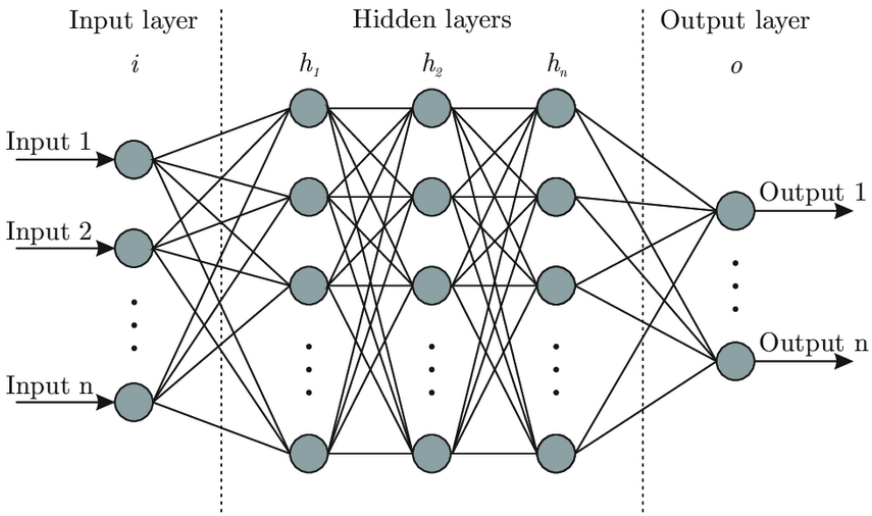
What is Neural Network?

- Neural Network

  Combination of neuron models

  Input and output can be vectors





T_{eff} : effective temperature

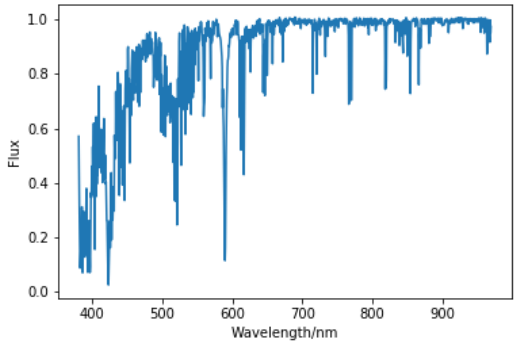
$\log g$: surface gravity

$[M/H]$: stellar metallicity

$[\alpha/Fe]$: alpha-element

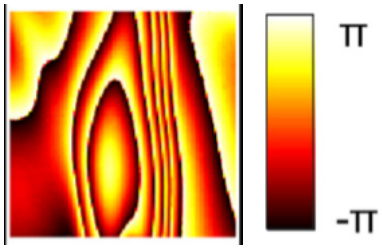
(https://www.researchgate.net/publication/321259051_Prediction_of_wind_pressure_coefficients_on_building_surfaces_using_Artificial_Neural_Networks)

Problem of 2-D input



1-dimensional data

No. of input ≅ 1000



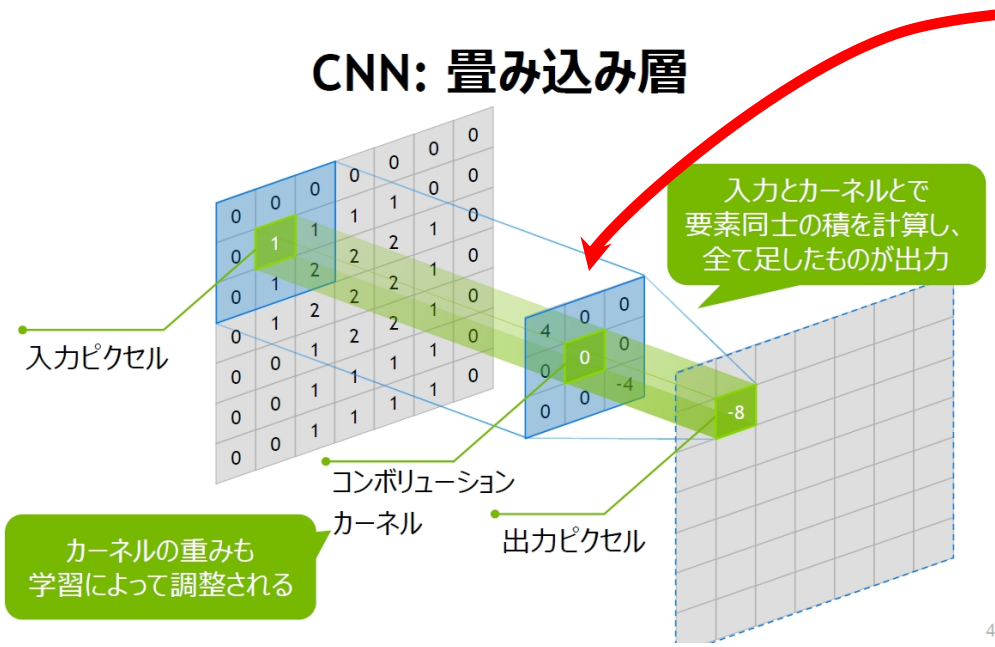
2-dimensional data

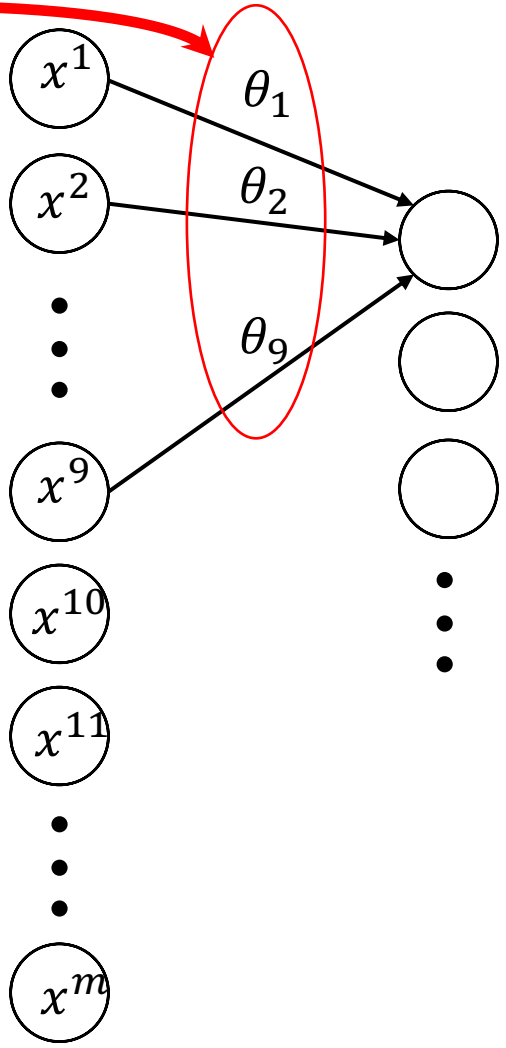
No. of input ≅ 66000

(when 256 × 256 pixels)

Neural Network needs to be more complex, and the No. of fitting parameters becomes too large…

Convolutional Neural Network





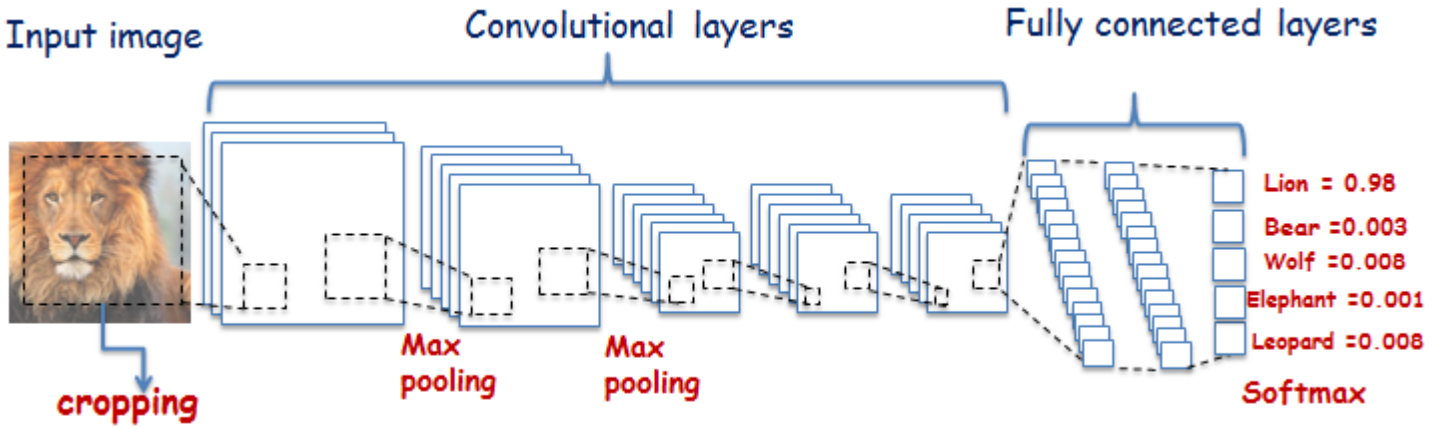
(https://image.itmedia.co.jp/l/im/ee/articles/1805/09/l_mat20180507nvidia_image00.jpg#_ga=2.44377892.1420110071.1588700292-1013448406.1588700292)

Convolutional Neural Network

- Convolutional Neural Network(CNN)

  consists of many kernels and convolutional layers.

  is the basis of image recognition.



(https://www.rug.nl/research/bernoulli/groups/autonomus-perceptive-systems/research_and_projects/phd-project_-comparative-study-between-deep-learning-and-bag-of-visual-words-for-animal-recognit)

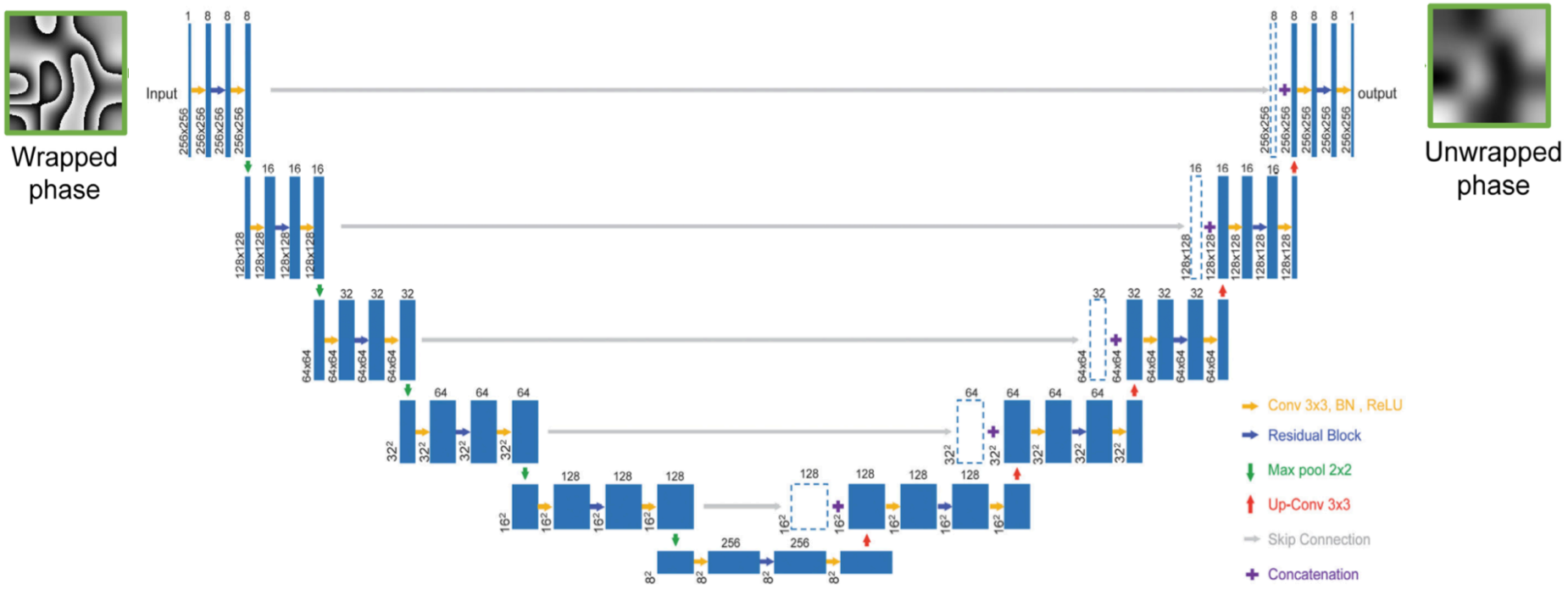
Materials and methods

Materials and methods

- Machine learning model

  Advanced CNN is used in this experiment

  This is based on residual network and U-Net



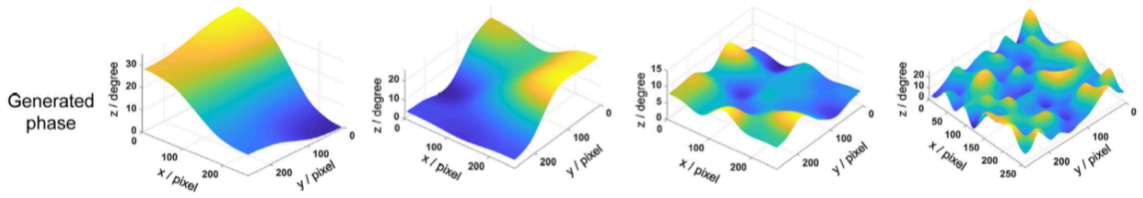
(Opt. Express 27, 15100-15115 (2019))

Materials and methods

- Generating training data and test data

37500 real phase images

(256 × 256 pixels, phase range [0,2]～[0,70])



(Opt. Express 27, 15100-15115 (2019))

output data

wrap and
add noise

37500 wrapped phase images

input data

80% of this data are used for training CNN

10% and 10% are used as test data and validation data

Testing the trained CNN

Testing the trained CNN

- In order to measure the performance of trained CNN, 4 tests were carried out

  - Accuracy test
  - Anti-noise performance test
  - Anti-aliasing performance test
  - Generalization capability test
    - Phase images of mouse osteoblasts(骨芽細胞)
    - Phase images of candle flame

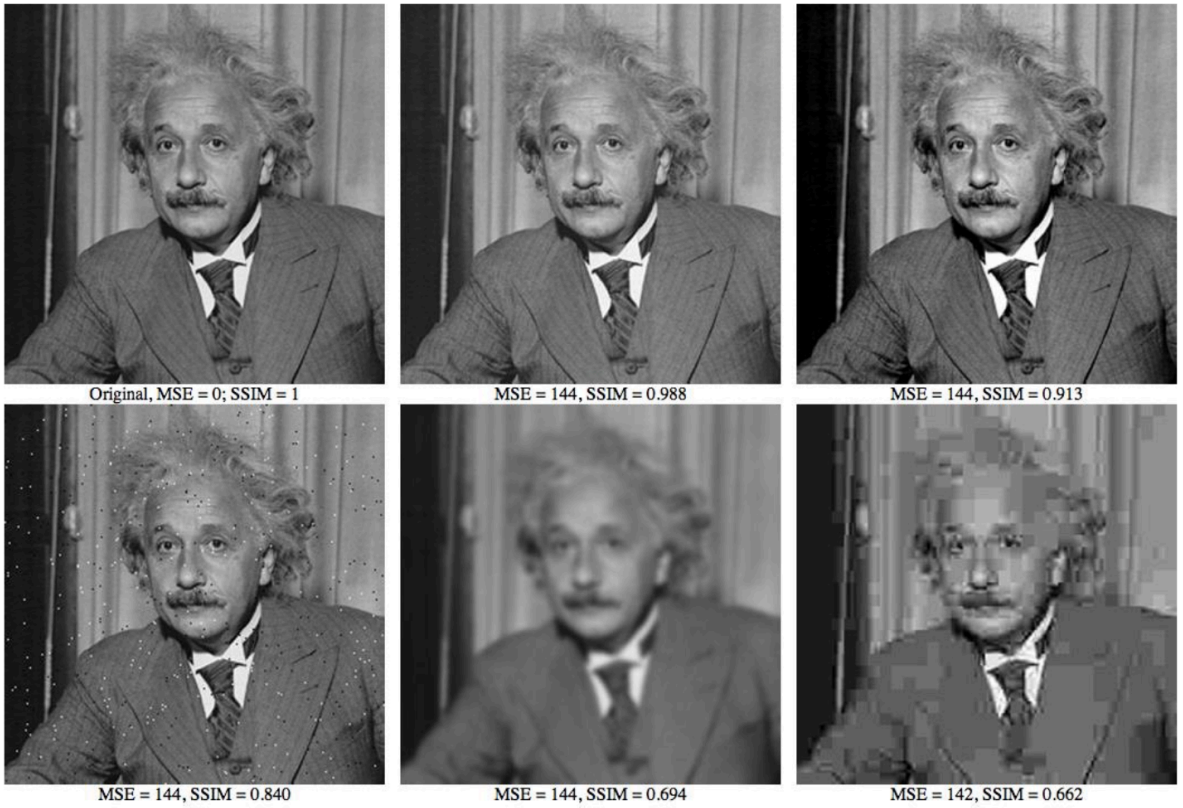
How to compare prediction and true output

- SSIM(Structural Similarity) index

$$\mathrm{SSIM}(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}$$

$$-1 \leq SSIM \leq 1$$

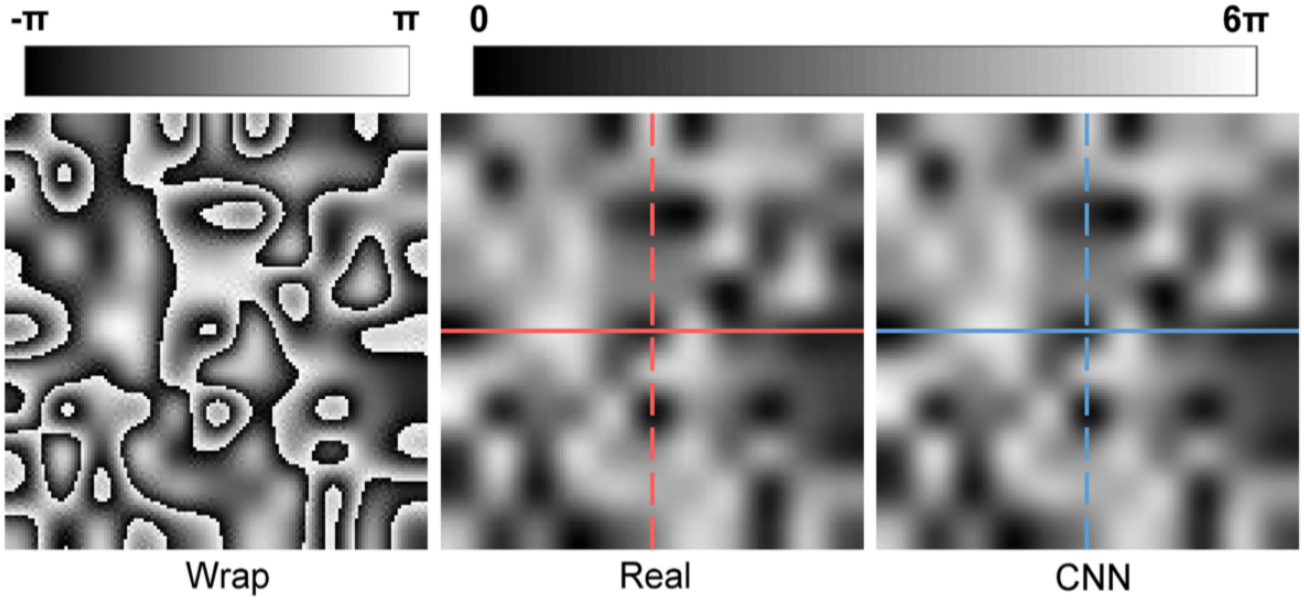
not similar ⟷ similar



(https://bluesky314.github.io/ssim/)

Accuracy test

- Test with 1 test data



SSIM = 0.991

(Opt. Express 27, 15100-15115 (2019))

Anti-noise performance test

- Adding more noise to test data

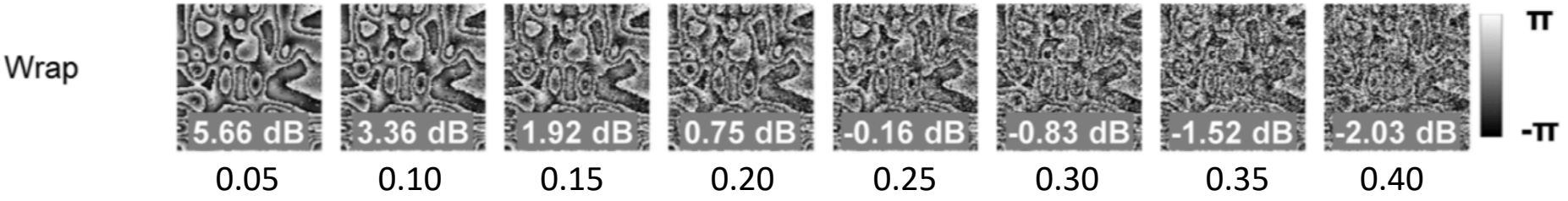
① Take 1 wrapped phase image from test data

② Normalize its phase range into [0,1]

③ Add Gaussian, salt & pepper and multiplicative noises

standard deviation of gaussian and multiplicative noise
density of salt & pepper noise
} 0.01 ～ 0.40

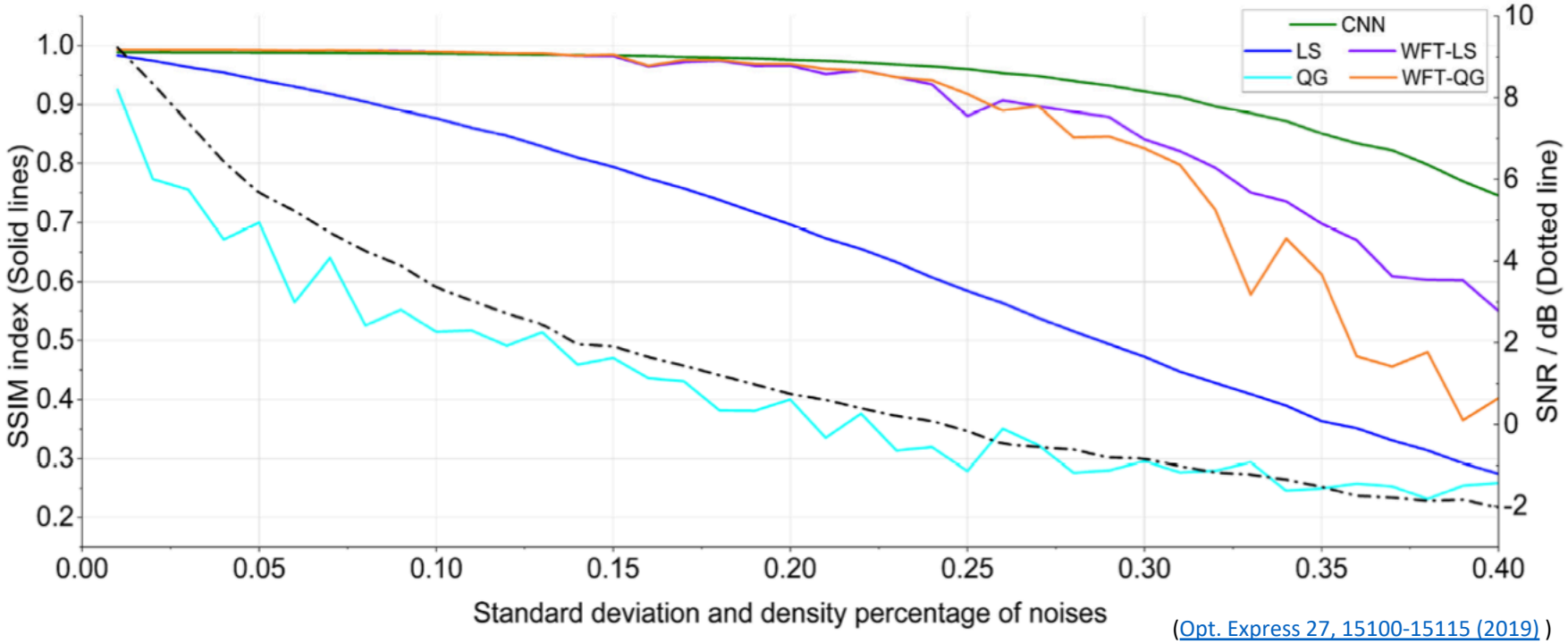
④ Change its phase range into its original ← Unwrap with CNN, LS and QG



(Opt. Express 27, 15100-15115 (2019))

Anti-noise performance test

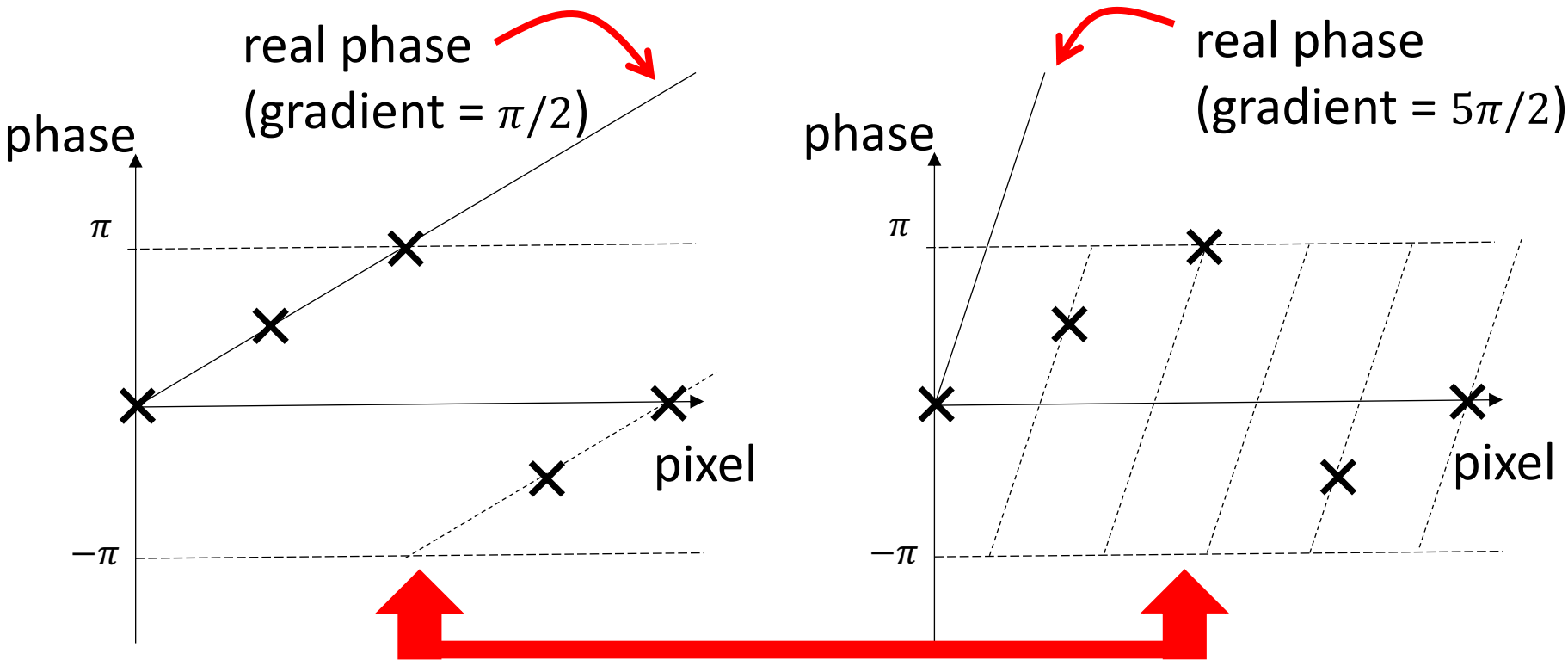
- Results



(Opt. Express 27, 15100-15115 (2019))

Anti-aliasing performance test

- Aliasing in wrapped phase



Same wrapped phase in digital image

Large gradient of real phase leads to aliasing

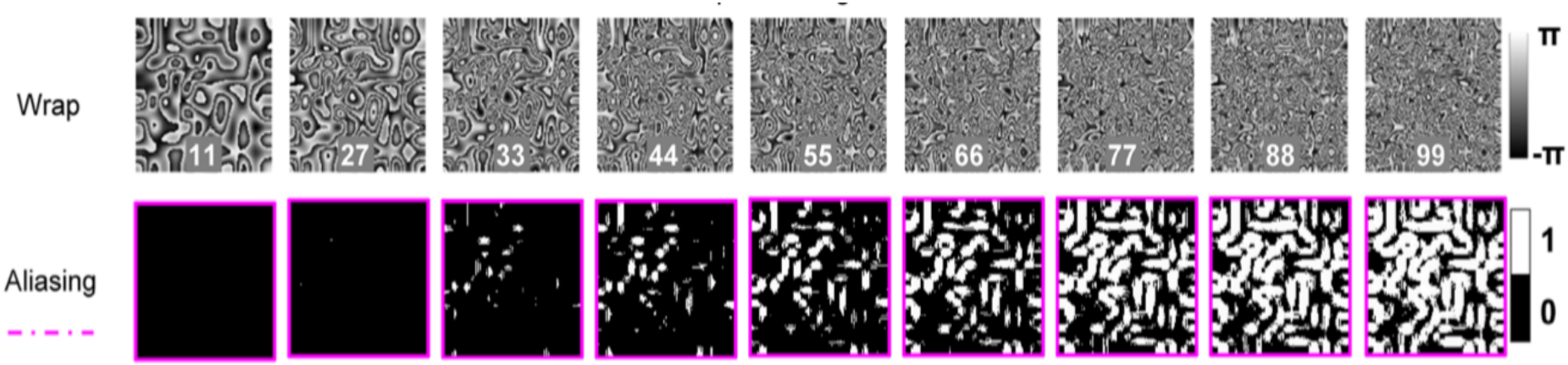
Anti-aliasing performance test

- Add aliasing noise to test data

① Take 1 real phase image from test data

② Change its phase range into [0,H] (H = 5～100)

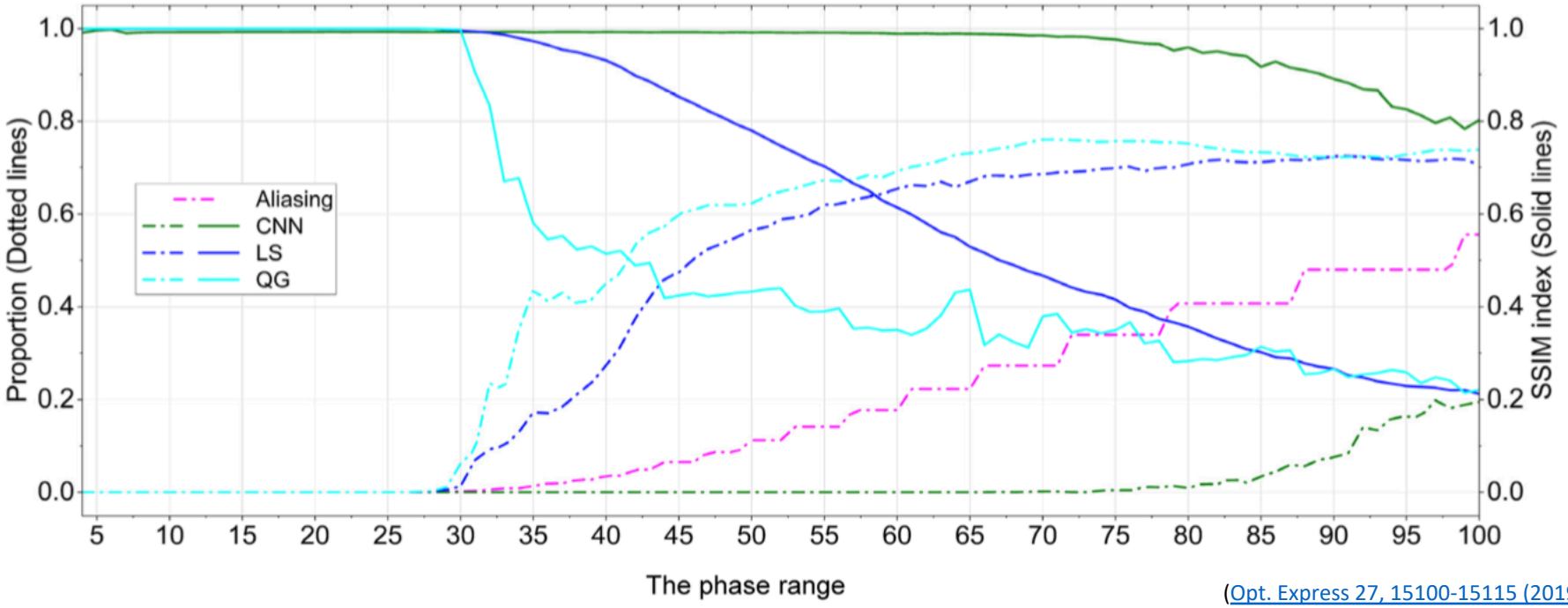
③ Wrap them into $[-\pi, \pi]$ ← Unwrap with CNN, LS and QG



(Opt. Express 27, 15100-15115 (2019))

Anti-aliasing performance test

- Results and Discussion



(Opt. Express 27, 15100-15115 (2019))

Phase range of training data : [0,2～70]

Phase range of this test data : [0,100]

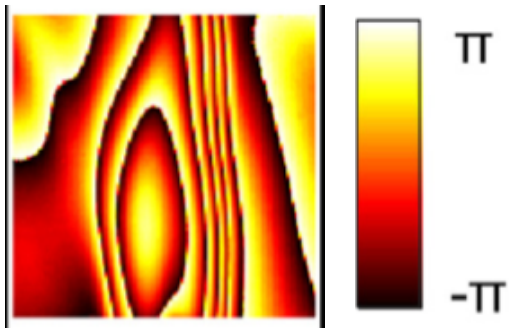
Generalization capability test

So far, CNN has been tested by artificial data

Test CNN with the measured phase data :

① the phase data of mouse osteoblast(骨芽細胞)

② the phase data of candle flame



Generalization capability test - mouse osteoblast -

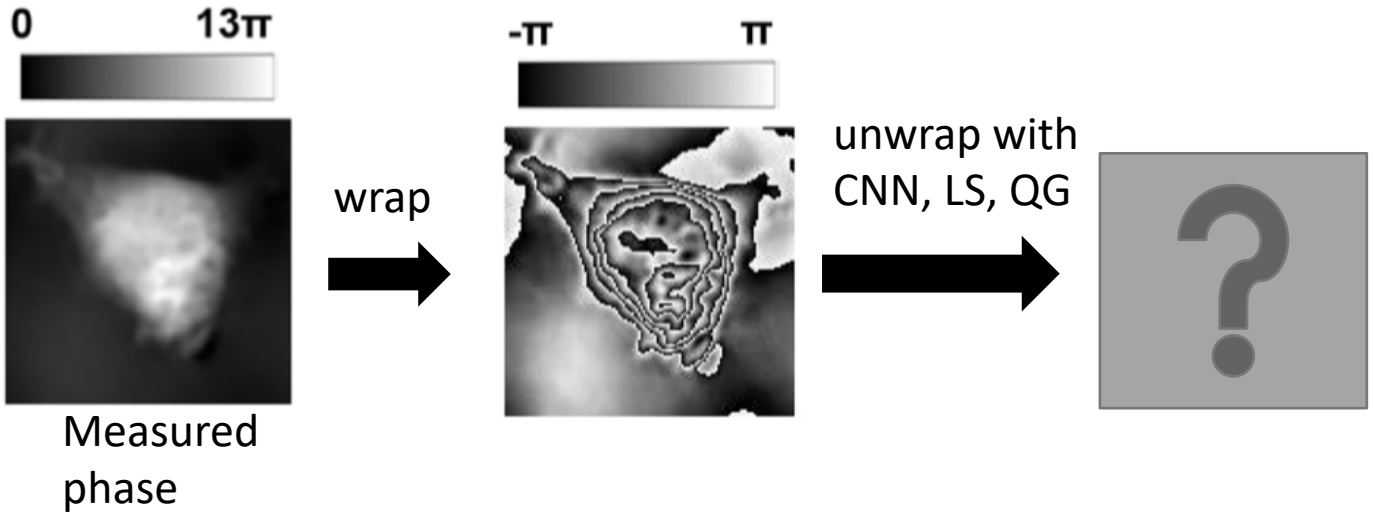
- Making test data with osteoblast

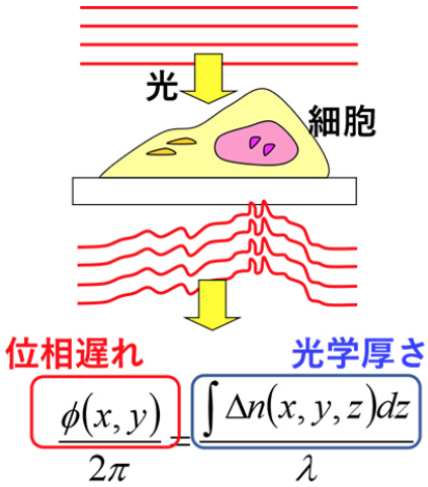
① Measure the real phase of osteoblasts directly with TIE(transport of intensity equation) methods

② Wrap them into $[-\pi, \pi]$

Output data

Input data

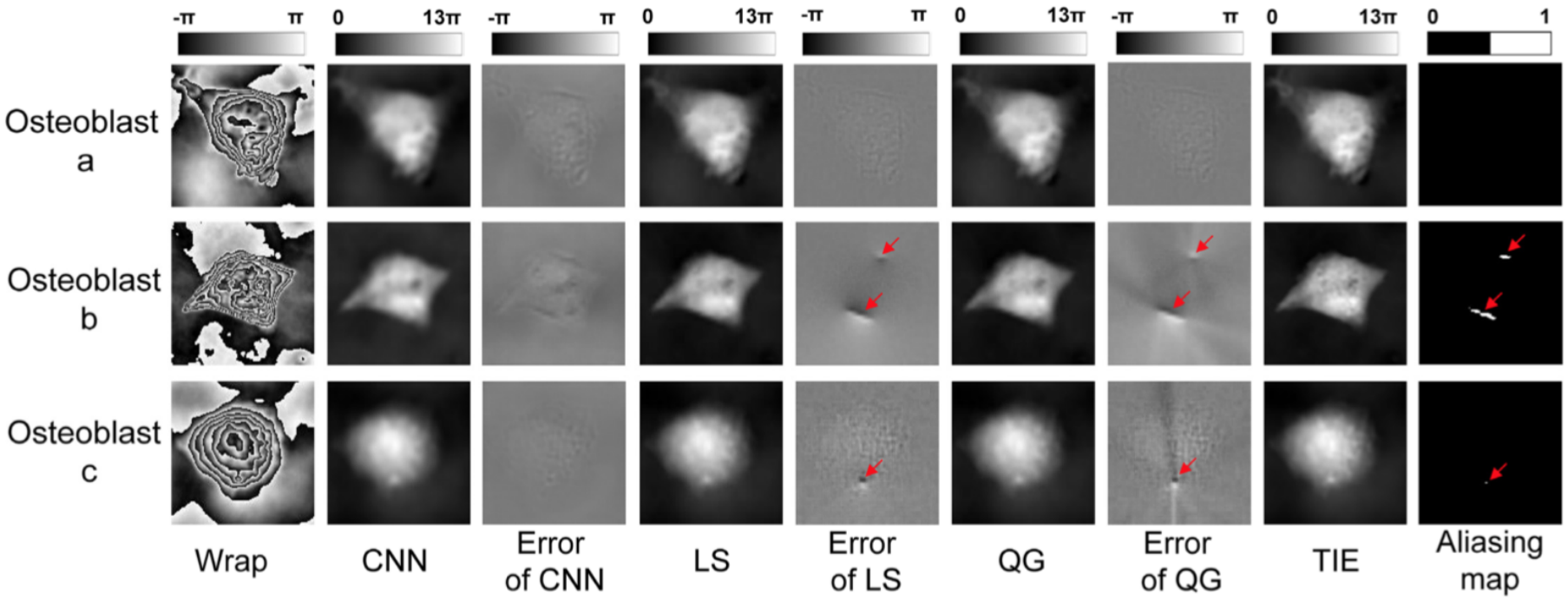




(https://www.hamamatsu.com/jp/ja/our-company/about-crl/health-and-medical-care/qpm.html)

Generalization capability test - mouse osteoblast -

- Results and Discussion



(Opt. Express 27, 15100-15115 (2019))

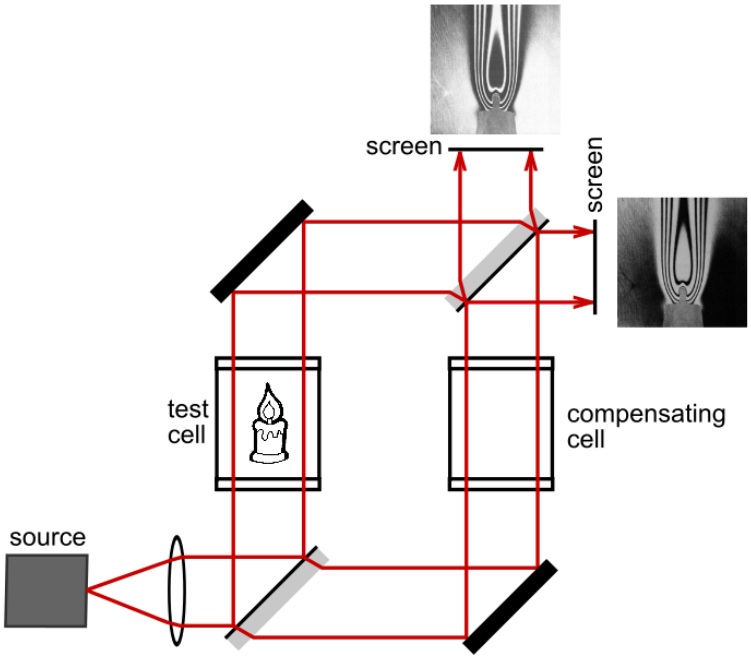
CNN performed well even if there is aliasing

Generalization capability test - candle flame -

- Measuring the phase of candle flame

The phase of candle flame was measured by Mach-Zehnder interferometer

Mach-Zehnder interferometer observes wrapped phase

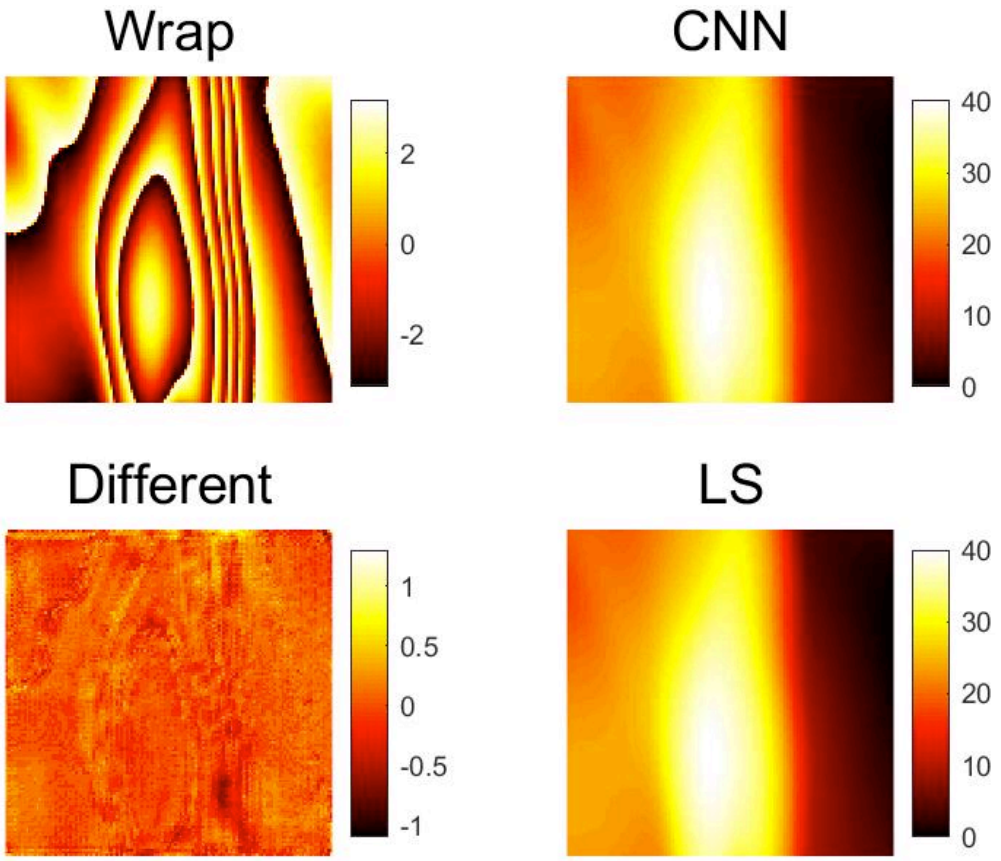


(https://ja.wikipedia.org/wiki/マッハ・ツェンダー干渉計)

There is no ground truth in this test

Generalization capability test - candle flame -

- Results



(Opt. Express 27, 15100-15115 (2019))

Summary

- CNN had greater robustness to noise and aliasing than classical methods(LS, QG)
- CNN unwrapped not only artificial phase images but also unwrapped measured phase images well
- CNN can be widely applied to measurements which need phase unwrapping

Thank you for listening