

Chapter 7 Two-wavelength single-shot interferometry

7.1 Background and objectives of the study

As described in Section 6.2, the LMF method can be used to obtain the correct height when the difference in height between adjacent pixels is less than or equal to $\pm\lambda/4$ and cannot be applied to objects with more discontinuous steps. This problem is common to the phase-shift method described in Section 1.1.3, and in that field, two-wavelength phase-shift interferometry has been proposed as a solution [Cheng et al. 1984]. By applying this concept to the single-shot method, we studied the possibility of relaxing the step limitation between neighboring pixels and consequently expanding the measurement range.

The method of estimating the interference order by using the phases at multiple wavelengths is one of the methods of phase unwrapping, but the principle is different from the method of connecting the neighboring pixels at a single wavelength. The former is sometimes distinguished by calling the optical phase unwrapping and the latter spatial phase unwrapping [Warnasooriya et al. 2006]. In this paper, we call the former unwrapping and the latter phase connection.

7.2 Two-wavelength phase unwrapping

According to the "Equivalent wavelength method", which has been proposed in the two-wavelength phase-shift interferometry [Cheng et al. 1984], from phases ϕ_1 and ϕ_2 measured at two wavelengths λ_1 and λ_2 ($\lambda_2 > \lambda_1$), the equivalent wavelength λ_{eq} and the equivalent phase Φ are defined by

$$\lambda_{\text{eq}} = \lambda_1 \lambda_2 / (\lambda_2 - \lambda_1) \quad (7-1)$$

$$\Phi = \phi_1 - \phi_2 \quad (7-2)$$

Then the height can be calculated by

$$H_{\text{eq}} = (\Phi / 2\pi + N)(\lambda_{\text{eq}} / 2) \quad (7-3)$$

where N is an unknown integer.

Selecting two wavelengths in the normal visible light range yields $\lambda_{\text{eq}} > \lambda_2$, since $2\lambda_1 > \lambda_2$. Thus, this method expands the maximum allowable step height from $\lambda_2/4$ to $\lambda_{\text{eq}}/4$.

The equivalent-wavelength method is simple, but at the same time, the range and the phase error are expanded by a factor of $\lambda_{\text{eq}}/\lambda_2$. To avoid this problem, the "Fringe order method" [Cheng et al. 1984], which uses the height obtained by the equivalent-wavelength method only to determine the order N_1 of the first wavelength λ_1 , has been proposed. The order is

$$N_1 = \text{Round}[(\lambda_1 \phi_1 - \lambda_2 \phi_2) / 2\pi(\lambda_2 - \lambda_1)] \quad (7-4)$$

Here, 'Round' refers to the rounding operation. From the obtained N_1 , the height H_{order} is calculated by the following equation

$$H_{\text{order}} = (\phi_1 / 2\pi + N_1)(\lambda_1 / 2) \quad (7-5)$$

In addition to the equivalent-wavelength approach described here, there is an unwrapping method based on the coincidence method. This is described in Section 8.6, "Three-Wavelength Unwrapping".

7.3 Two-wavelength imaging system

Schmidt [1999] applied the two-wavelength method to single-shot measurements, but the imaging system is not a single-shot measurement in the strict sense of the word, because the interference filter inserted into the illumination system is sequentially switched twice, as is the case with many two-wavelength phase shift methods. In order to perform accurate single-shot measurements, it is necessary to capture interference fringe images of different wavelengths simultaneously. There are two possible ways to realize this imaging system.

- (a) Two-wavelength mixed lighting method: Narrow-band two-wavelength light is mixed and injected into the interference system. The imaging system need only have coarse wavelength selectivity. Pfortner and Schwider [2003] realized a three-wavelength phase-shift method using three lasers as the light source and a three-plate color camera, but the details of the optical system have not been reported.
- (b) Wavelength-separated imaging system: Interference images from a white light source are wavelength-separated by an interference filter or spectrophotometer. Although there is flexibility in the selection of wavelengths, the optical system is complex and is expected to be difficult to achieve at low cost.

We have developed a compact and inexpensive two-wavelength imaging system for single-shot imaging using a commercially available three-color LED lighting system (CCS, HLV-3M-RGB-3W) (Fig. 7-1) and a color camera [Kitagawa et al. 2007e, Kitagawa et al. 2009e]. The specifications of the light sources used are shown in Table 7-1. Since the coherence length of the light is approximately equal to $(\text{central wavelength})^2/\text{bandwidth}$, the coherence length of the red (R) and blue (B) LEDs used in this study is about 9 - 20 μm . Therefore, the interference fringes can be obtained over the entire surface of the image as long as the relative tilting angle between the reference and sample planes is not excessive.

The spectral response characteristics of the color camera used (Basler, SCA640-70gc) and the central wavelengths of the R and B LEDs are shown in Fig. 7-2. When these two LEDs are turned on and an image is captured by a color camera, an image of 470 nm is obtained from the B frame and an image of 627 nm is obtained from the R frame. The crosstalk¹⁾ is negligible at less than 1%. In this case, the equivalent wavelength is 1877 nm according to Equation (7-1), and the step difference between adjacent pixels is allowed to be 469 nm.

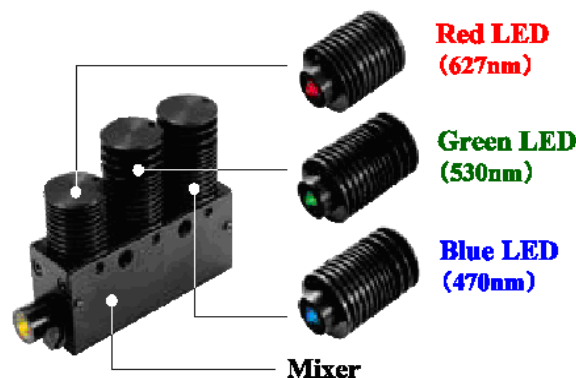


Fig. 7-1 RGB LED illuminator.

¹⁾ The definition of crosstalk and the correction method are described in Section 8.3.

Table 7-1 Specifications of the illuminator (typ.)

Color	Peak Wavelength ^{*)} (nm)	Bandwidth (FWHM) ^{**)} (nm)
R	627	20
G	530	35
B	470	25

*) The dominant wavelength is indicated in the catalog, and the peak wavelength is unknown. However, since the difference between the two is estimated to be a few nm, we refer to it as the peak wavelength in this paper.

**) FWHM : Full Width at Half Maximum.

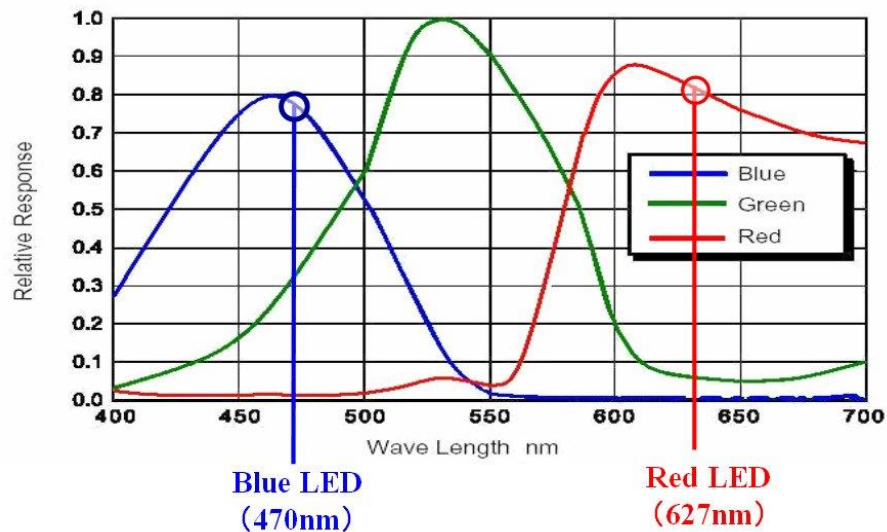


Fig. 7-2 Spectral curves of LEDs and color camera.

7.4 Measurement of 350-nm step

7.4.1 Experimental method

The illumination and imaging system of the surface profiler (Toray Engineering SP-500) [Kitagawa 2001a] (Fig. 2-10) was replaced with a two-wavelength imaging system, and two-wavelength measurement software using the LMF method was installed in order to test the proposed method. To confirm the ability of the range extension, we measured a quartz sample with a nominal step of 350 nm.

7.4.2 Experimental results

Fig. 7-3 is a color image obtained by the proposed imaging system, and Fig. 7-4 shows the B and R component images obtained by color separation. The rectangular area in the lower left quadrant is a pattern recess.

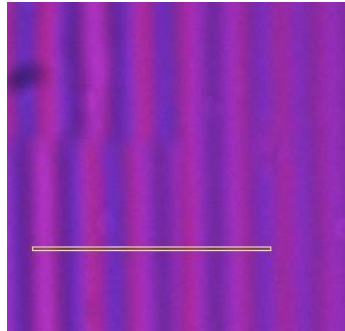


Fig. 7-3 Captured color image of 350nm step surface. The white solid line indicates the profile-analyzed line.

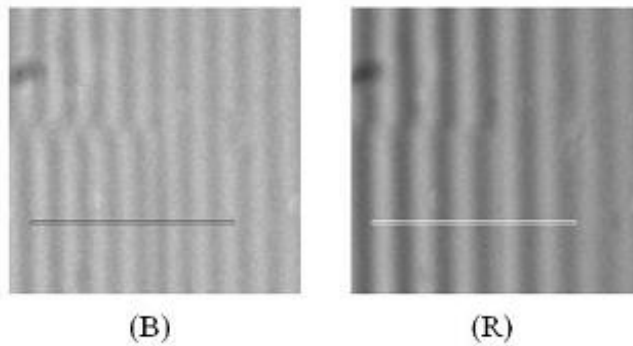


Fig. 7-4 Extracted images of B and R component.

Figure 7-5 shows the intensity profiles of the B and R components. By applying the LMF method to the data, we obtain two phase profiles shown in Fig. 7-6. The number of data points used to fit the model was 25 in the horizontal direction, and the frequency f_x was estimated by visually counting the number of stripes in the image.

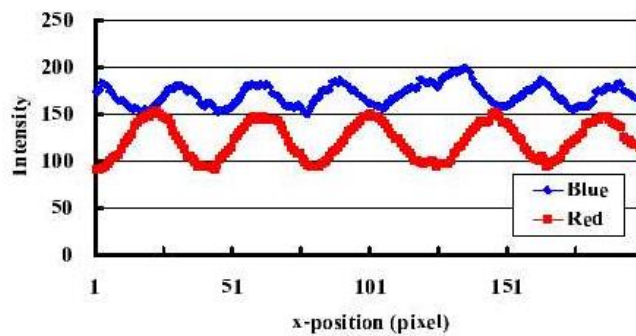


Fig. 7-5 Intensity profiles of the B and R fringes along the horizontal line indicated in Fig. 7-3.

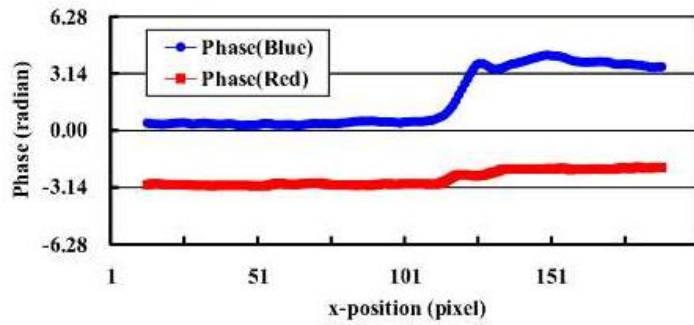


Fig. 7-6 Phase profiles of the B and R fringes.

First, the results of the single-wavelength height measurement using only phase ϕ_2 of the R signal are shown in Fig. 7-7. The step value was 44 nm. This is close to the "fractional height" of 36 nm, which is obtained by subtracting $\lambda_2/2$ ($=314\text{nm}$) from the nominal value of 350 nm.

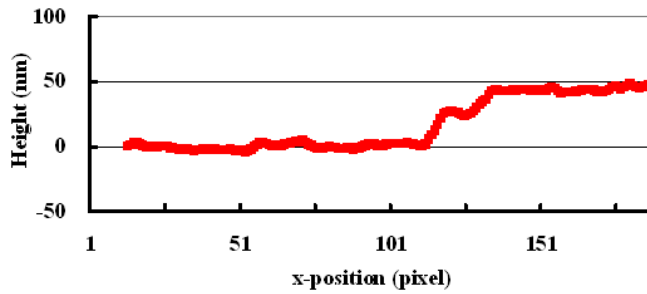


Fig. 7-7 Surface profile by one-wavelength single-shot method

Next, two-wavelength height measurements were made. The height H was determined by Eqs. (7-3) and (7-5) from the two unwrapped phase data ϕ_1 and ϕ_2 . The height H_{eq} by the equivalent wavelength method and the height H_{order} by the order method are shown in Fig. 7-8. Both measurements are correct for the 350 nm step, but as expected, the latter has less noise.

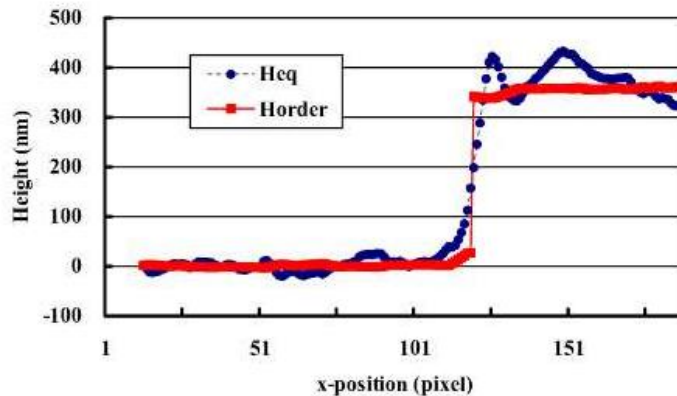


Fig. 7-8 Surface profiles by two-wavelength single-shot methods.

Table 7-2 compares the step measurements by the one-wavelength single-shot method, two-wavelength single-shot methods, and the conventional white-light interference method. The proposed two-wavelength single-shot method expands the measurement range.

Finally, experiments were conducted to measure the three-dimensional shape of the whole area of the image shown in Fig. 7-3. The number of data used for model fitting is totally 125 points (25 horizontal pixels \times 5 vertical pixels), and the order determination method of Eq. (7-5) is used. The results are shown in Fig. 7-9. This result is in good agreement with the results of white-light interferometry (Fig. 7-10). The time required to calculate the height of 512×480 points was 1.31s using a commercial PC (CPU: Intel Pentium 1.6GHz).

Table 7-2 Comparison of measured step heights

Method	Measured step (nm)
One-wavelength single-shot method	44
Two-wavelength single-shot method	357
White-light interferometry (vertical scan method)	371

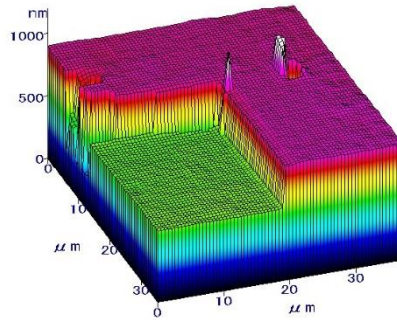


Fig. 7-9 3D surface profile by two-wavelength single-shot method.

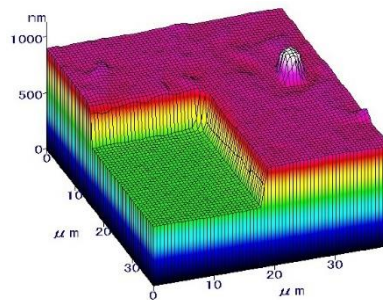


Fig. 7-10 Surface profile by white-light interferometry.

7.5 Summary

In this chapter, a two-wavelength single-shot method is proposed as a new interference measurement method. This method combines an inexpensive and compact dual-wavelength simultaneous imaging system consisting of a commercial LED light and a color camera with a fringe image analysis algorithm named Local Model Fitting (LMF) method. It was confirmed that an actual surface profile with a steep step of 350 nm can be measured correctly.

This is an English translation of the article:

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in " Study on industrial surface profile measurement method based on optical
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