

Chapter 9 Range extension by optimum wavelength selection

9.1 Research background and goal

The optimal combination of multiple wavelengths is important for further extension of the measurement range of the multi-wavelength single-shot method. Resolving the phase ambiguity problem using multiple wavelengths is common to the multi-wavelength phase shifting method and the multi-wavelength interferometry used for calibration of gauge blocks. Therefore, including those technical fields, we decided to study the wavelength optimization method and its closely related unwrapping method.

In the two-wavelength phase shifting method, the concept of equivalent wavelength described in Section 7.2 is well known. The allowable step difference between adjacent pixels is expanded to 1/4 of the equivalent wavelength. The equivalent wavelength λ_{eq} is defined by the equation (7-1), and the magnification factor of the wavelength is approximately expressed by $\lambda_2/(\lambda_2 - \lambda_1)$. Therefore, the smaller the difference between the two wavelengths, the wider the range. However, if the difference between the two wavelengths is made smaller, there are problems such as (1) wavelength stability is required, (2) crosstalk separation becomes difficult, and (3) phase error is magnified.

Table 9-1 summarizes the wavelengths used in the two-wavelength phase shifting method reported so far. The symbols below each wavelength represent the light sources, and many use laser light sources. Therefore, the wavelength is limited, and there is no report of wavelength optimization.

Table 9-1 List of wavelengths used in two-wavelength interferometry

λ_1 (nm)	λ_2 (nm)	λ_{eq} (μm)	Reference
488/515 Ar	633 HeNe	2.13/2.75	Creath 1985
477/515 Ar	633 HeNe	1.93/6.45	Chen 1985
539 WL	593 WL	(3)	Nishikawa 1991
785 LD	828 LD	15	Groot 1991
532 YAG	633 HeNe	3.3	Onodera 1998
650 WL	670 WL	20	Nishiyama 2004
612 HeNe	633 HeNe	18.5	Kiire 2006
766.7 LD	770.1 LD	173	Meiners-Hagen 2009

Note) Ar, HeNe and YAG are lasers. LD means laser diode. WL means white light source with a bandpass filter.

In the case of three wavelengths, it is expected that the optimal solution exists. Table 9-2 shows a summary of the reported wavelengths used by the phase shifting method and interferometers with more than three wavelengths. Again, there are few reports of wavelength optimization because many studies use laser sources.

Pförtner et al. [2003] used three lasers and preferred that their wavelengths are coprime and have no common divisor. Towers et al. [2004b] proposed a method of determining the three wavelengths so that the equivalent wavelength is a geometric progression, but does not describe the specific wavelength. Falaggis et al. [2008] have proposed an optimal wavelength search method based on the coincidence method for multi-wavelength interferometers using the near infrared wavelength band. It describes only the conditions that wavelength should avoid, and it cannot be said to be a general optimization method.

As mentioned above, there is no clear solution to this problem. Therefore, the research started by considering the true nature of the equivalent wavelength method and the coincidence method.

Table 9-2 List of wavelengths used in three- or four-wavelength interferometry

λ_1 (nm)	λ_2 (nm)	λ_3 (nm)	λ_4 (nm)	UMR(μm)	Reference
543 HeNe	612 HeNe	633 HeNe	-	18	Lewis 1994
473 NdYAG:	532 NdYAG:	633 HeNe:	-	(20)	Pförtner 2003
543 HeNe	612 HeNe	633 HeNe	1152 HeNe	140	Decker 2003
789 LD	822 LD	825 LD	-	14~289	Meiners-Hagen 2004
1528 FBG	1530 FBG	1531 FBG	1594 FBG	3040	Towers 2004b, Falaggis 2008
655 LD	671 LD	827 LD	-	27.78	Höink 2009

Note) FBG: Fiber Bragg Grating; UMR: Unambiguous Measurement Range

9.2 Equivalent wavelength method and coincidence method

9.2.1 Study of equivalent wavelength method in case of (2 nm, 28 nm)

The equivalent wavelength method is the best-known algorithm as the two-wavelength phase unwrapping method. However, since the difference between the two wavelengths is used as the equivalent phase and the information on the absolute value of each phase is not used effectively, it is pointed out that the range can be further expanded and a specific algorithm is proposed [de Groot 1994]. Therefore, we clarify what the equivalent wavelength method has in comparison with the coincidence method.

As an example, consider the case where the first wavelength is 2 nm and the second wavelength is 2.8 nm. A small numerical wavelength is used for simplification of calculation and discussion, but the generality of the following consideration is not impaired. In the case of this combination of wavelengths, the relationship between the surface height h and the phase ϕ of each wavelength is as shown in Fig. 9-1. Here, the origin of surface height h is the height at which the interference optical path difference becomes zero.

The phase ϕ_1 (red line) of the first wavelength and the phase ϕ_2 (blue line) of the second wavelength are folded (wrapped) in the interval $[0, 2\pi)$. From this figure, it can be seen that both phases have perfect periodicity with a period of 7 nm, and become equal with a period of 3.5 nm.

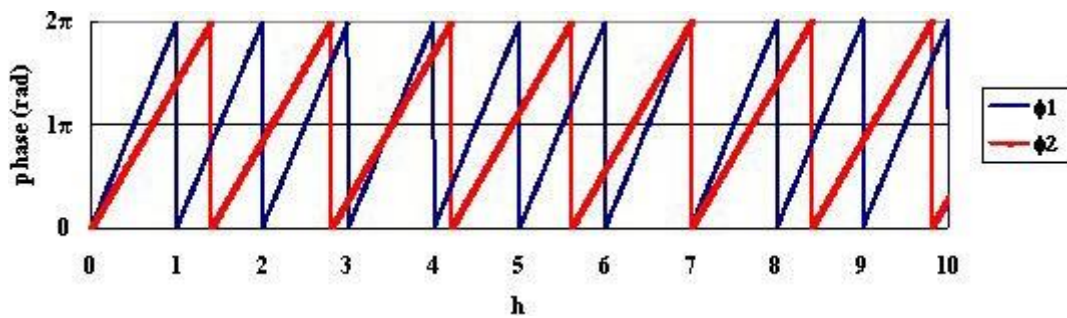


Fig. 9-1 Two-wavelength wrapped phases

In the equivalent wavelength method, the phase difference between the two wavelengths is the equivalent phase Φ . This is shown in Fig. 9-2. Φ^* is the value obtained by adding 2π to the negative equivalent phase and shifting to the interval of $[0, 2\pi)$. This figure shows that the range (UMR: Unambiguous Measurement Range) in which the height can be uniquely determined from the equivalent phase is 3.5 nm. Twice this range, 7 nm, is the “equivalent wavelength” (or synthetic wavelength).

However, although the phase difference is 0 at the height of 3.5 nm, the absolute value of each phase is π , which is different from the absolute value 0 of each phase at the height of 0 nm. That is, considering the absolute phase value, the height 3.5 nm is not the same as the height 0 nm, and is not the limit of the UMR.

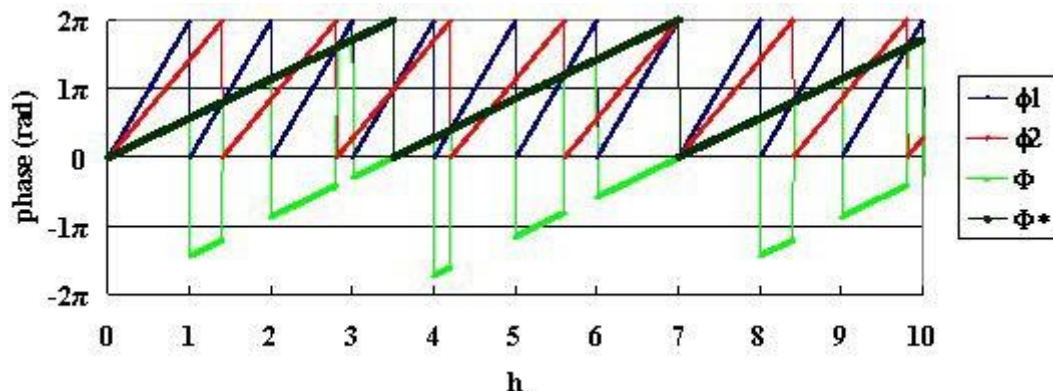


Fig. 9-2 Equivalent phase vs height

Therefore, if the relationship between the height and the phase of two wavelengths is illustrated in a two-dimensional manner, Fig. 9-3(a)(b)(c) is obtained (hereinafter referred to as the "phase diagram"). These figures are for determining the height from the phase of two wavelengths, (a) the height range from 0 nm to 3.5 nm, (b) the height range from 3.5 nm to 7 nm. (c) is the sum of both. From these figures, it can be seen that when the two phases are given, the range in which the height can be uniquely determined is 7 nm instead of 3.5 nm. This is twice the range in the idea of the equivalent wavelength method. Also, in order to correctly estimate the height, it is found that the error of each phase must be 1/2 or less of the plot line spacing, that is, $2\pi/10$ and $2\pi/14$ or less, respectively.

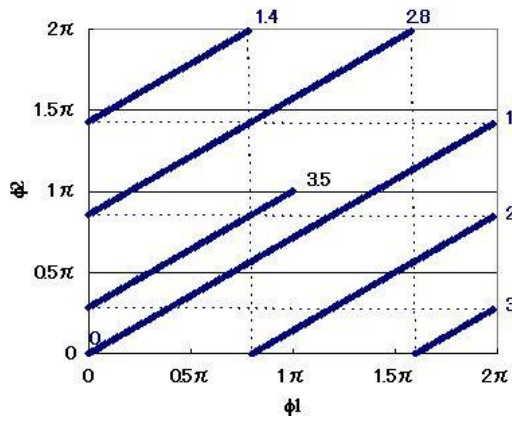


Fig. 9-3(a) Phase diagram ($h = 0\sim 3.5\text{nm}$)

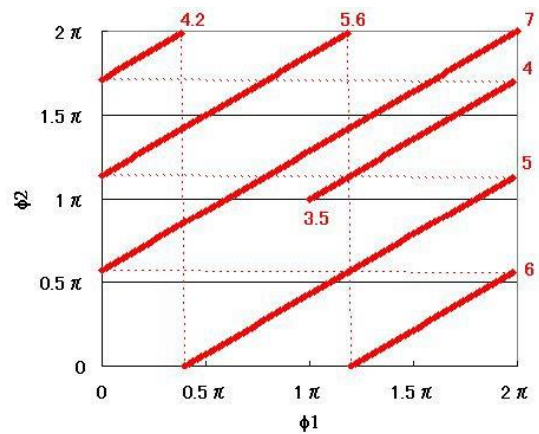


Fig. 9-3(b) Phase diagram ($h = 3.5\sim 7\text{nm}$)

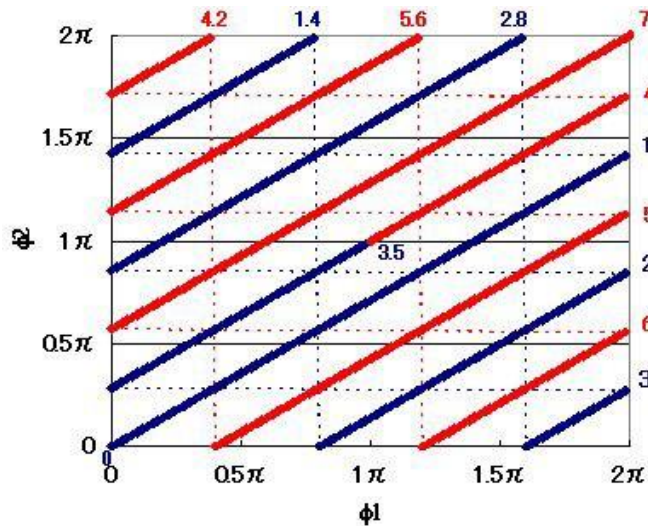


Fig. 9-3(c) Combined phase diagram ($h = 0\sim 7\text{nm}$)

As described above, it was confirmed that the measurement range can be expanded more than the equivalent wavelength method by effectively using the information of the two phases.

9.2.2 Study of coincidence method in case of (2 nm, 2.8 nm)

Next, the height is estimated using the coincidence method. Considering the case where the true height is 0, the two phases are both 0. With the order n of the first wavelength as the horizontal axis, the height candidates h_1 and h_2 for each wavelength, the nearest neighbors of the first wavelength height candidate h_1 and the second height candidates h_2' , and the candidate heights of the first and second wavelengths. If the coincidence error E is plotted on the vertical axis, Fig. 9-4 is obtained. In addition to the height $h = 0$ (order $n = 0$), the height $h = 7$ nm (order $n = 7$) period, the coincidence error E becomes 0. This means that the measurement range is 7 nm.

Moreover, in order to correctly estimate the height with the measurement range of 7 nm, the error E must not exceed 0.1, which is $1/2$ of the intermediate minimum value 0.2. When this limit is converted to a phase error using $\phi = 2\pi h/(\lambda/2)$, the phase of the first wavelength is $2\pi/10$ and the phase of the second wavelength is $2\pi/14$. This corresponds to $1/2$ of the line spacing in the phase diagram of Fig. 9-3(c).

Converting the horizontal axis of Fig. 9-4 to the height of the first wavelength and the coincidence error on the vertical axis, Fig. 9-5 is obtained. Here, the case where the true height is 0 is shown, but

the graph of the same shape can be obtained at any height by simply shifting the horizontal axis. This graph is named “Error diagram” in the coincidence method and will be used in wavelength optimization in Section 9.3. Furthermore, the period of the minimum peak of the coincidence error is called the “coincidence period” P_c . The concept of this coincidence cycle is shown in Fig. 9-6. This period depends on the phase estimation error of each wavelength. In the measurement range below this period, the correct height is obtained by the coincidence method.

By the way, in the creation of the above error diagram, the coincidence error at the height candidate point of the first wavelength was plotted, but if a candidate point of another wavelength is used, a slightly different diagram is obtained. However, in the vicinity of the coincidence point, the height candidates of each wavelength are close to each other. Therefore, even if the plot data is limited to the height candidate of any one wavelength (the longest wavelength if the calculation cost is taken into consideration), it does not affect the discussion of the coincidence period. Therefore, the data of the longest wavelength is used in the following error diagram.

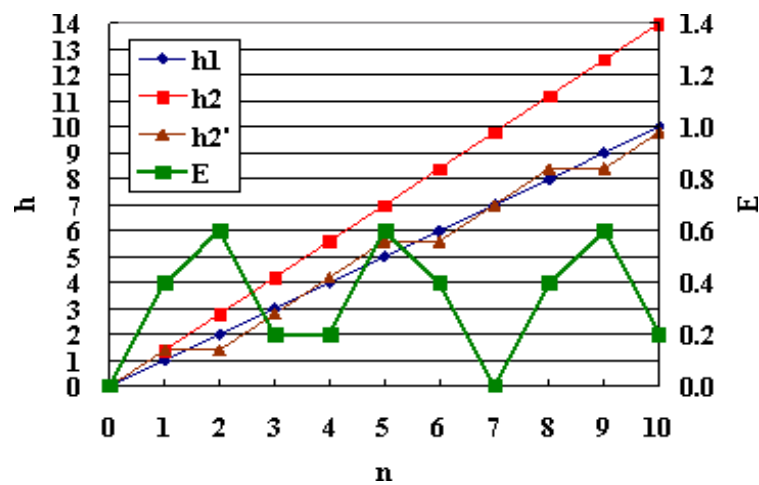


Fig. 9-4 Height and coincidence error vs fringe order

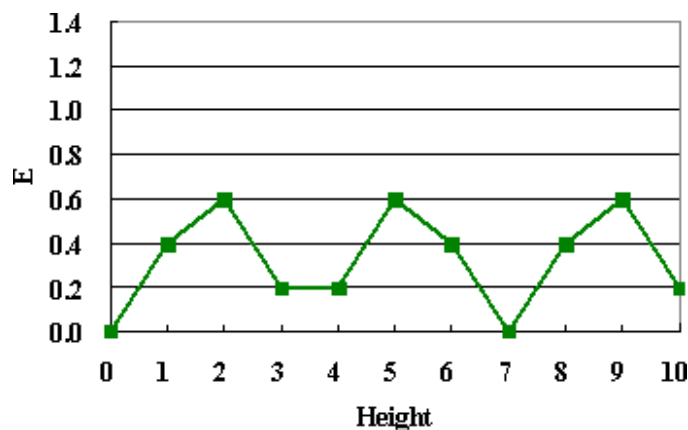


Fig. 9-5 Coincidence error diagram

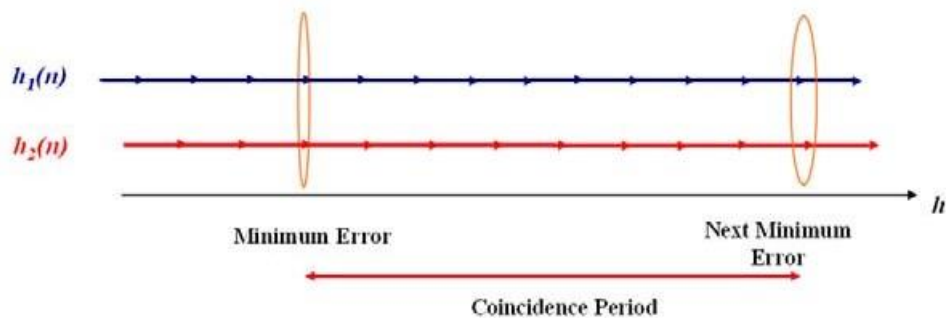


Fig. 9-6 Coincidence period

Finally, Fig. 9-7 shows the result of height estimation by the coincidence method from the phase data shown in Fig. 9-1. When the order search range is set to $[0,10]$, correct results are obtained in the range of height $[0,7)$ nm, and it is confirmed that the measurement range is 7 nm.

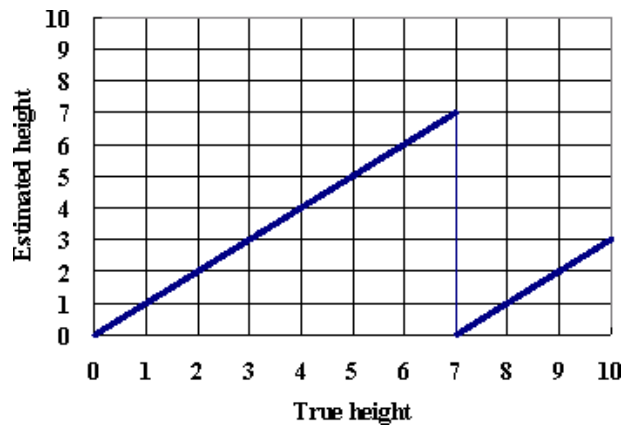


Fig. 9-7 Estimated height vs true height

9.2.3 In case of (2 nm, 2.9 nm)

Next, let us consider the case where the first wavelength is 2 nm and the second wavelength is 2.9 nm by changing only the second wavelength. In this case, the equivalent wavelength is 6.444 nm, and the measurement range by the equivalent wavelength method is 3.222 nm. However, the phase diagram is as shown in Fig. 9-8 in the range of $h = [0, 7]$ nm and does not overlap. Figure 9-9 shows an enlarged view of the display range to $[0, 29]$ nm. Although the allowable phase error is small, it can be seen that the height can be uniquely determined from the phase within the 29 nm range. This can also be confirmed from the coincidence error diagram shown in Fig. 9-10.

In other words, the coincidence period P_c in the coincidence method is 29 nm, which is $1/2$ of 58 nm, which is the "least common multiple" of both wavelengths. The "least common multiple" here is an extension of the least common multiple defined by natural numbers, and is the smallest real number that can be represented by $A = k_1\lambda_1 = k_2\lambda_2$ (k_1, k_2 : natural numbers). Then, if the ratio of the two wavelengths (λ_1, λ_2) is rational, the least common multiple A_{LCM} exists.

Table 9-3 shows a comparison between the equivalent wavelength λ_{eq} and the least common multiple A_{LCM} at wavelengths near this. The equivalent wavelength changes continuously, but the least common multiple changes greatly.

Table 9-3 λ_{eq} and A_{LCM} for various λ_2

λ_1 (nm)	λ_2 (nm)	λ_{eq} (nm)	A_{LCM} (nm)
2	2.8	7	14
2	2.9	6.444	58
2	2.95	6.211	118
2	3	6	6
2	3.05	5.762	122
2	3.1	5.636	62
2	3.2	5.333	16

Thus, the coincidence period P_c of the two-wavelength method changes greatly depending on the combination of wavelengths, and if there is no phase error, it becomes 1/2 of the “least common multiple” of the two wavelengths, but it is actually limited by the phase error.

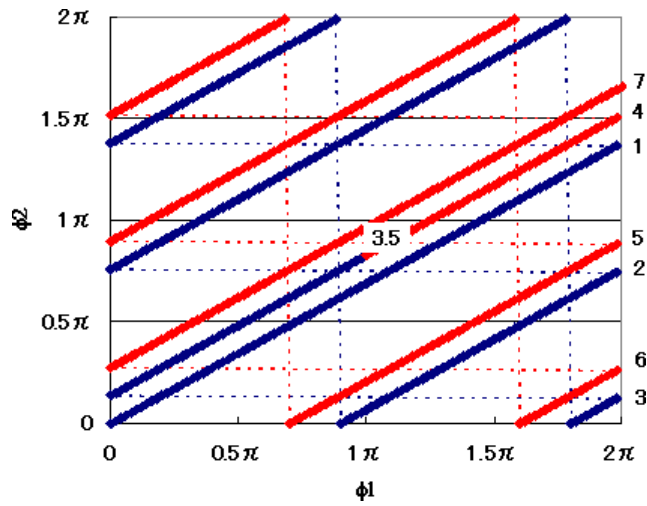


Fig. 9-8 Phase diagram ($h = 0 \sim 7\text{nm}$)

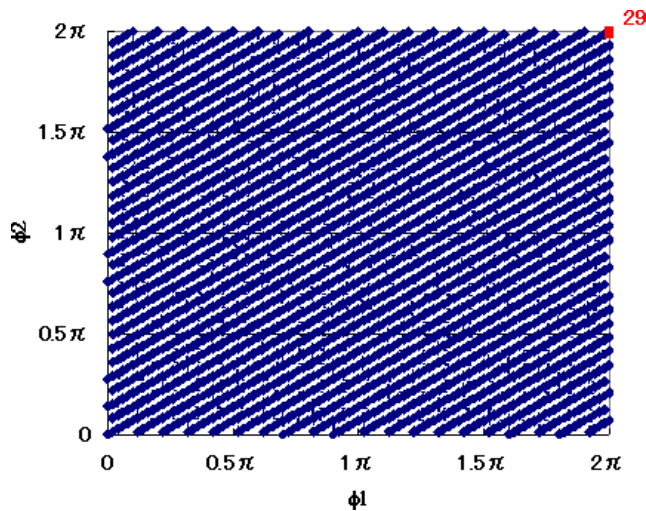


Fig. 9-9 Phase diagram ($h = 0 \sim 29\text{nm}$)

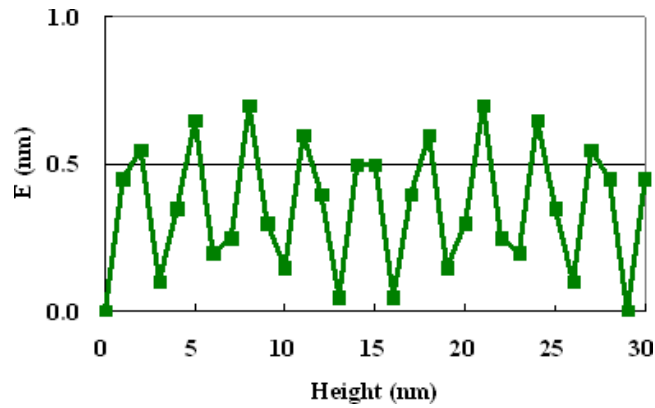


Fig. 9-10 Coincidence error diagram

9.2.4 In case of two wavelengths (470 nm, 627 nm)

Next, let us consider the case of the wavelength (B: 470 nm, R: 627 nm) used in Chapter 7, “Two-wavelength single-shot method” of this paper. In this case, the equivalent wavelength is 1877 nm, and the range is 1/2, which is 938.5 nm.

On the other hand, the error diagram of the coincidence method is as shown in Fig. 9-11. 470 and 627 are coprime and the least common multiple is 294690. Therefore, if there is no error, the range will be 147345 nm, but this wavelength combination (unfortunately) has a height candidate of 940 nm (4 times 235 nm) and 940.5 nm (3 times 313.5 nm), which are close to each other. Considering the phase measurement error, the coincidence period P_c is 940 nm. Therefore, in this case, the equivalent wavelength method and the coincidence method have the same range.

In Chapter 7, the usual idea of the equivalent wavelength method was adopted, and we assumed that the step between adjacent pixels could be up to 1/4 of the equivalent wavelength (469.25 nm), and measured the step of 350 nm. If the coincidence method described in Chapter 8 is adopted and an appropriate height range is set, it will be possible to measure up to a step of 940 nm.

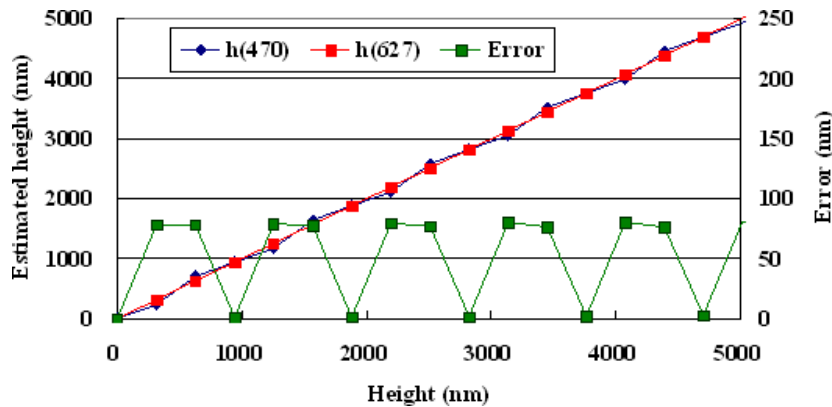


Fig. 9-11 Coincidence error diagram (470~627nm)

9.2.5 In case of (470 nm, 530 nm, 627 nm)

Consider the case of three wavelengths (B: 470 nm, G: 530 nm, R: 627 nm) used in Chapter 8 “Three-wavelength single-shot method” in this paper. The three equivalent wavelengths (λ_{BG} , λ_{GR} , λ_{BR}) are 4151.7 nm, 3425.9 nm and 1877.0 nm, respectively. Therefore, the measurement range is expected to be about 2076 nm, which is half the longest equivalent wavelength.

However, the error diagram of the coincidence method (height range: 0 to 5000 nm) is as shown in Fig. 9-12, and the first minimum error point (error is 50 nm or less) is the height where each wavelength

candidate values are 1855 nm, 1880 nm, 1881 nm (average 1872 nm). Therefore, assuming that the phase error is several tens of nm, the coincidence period P_c is 1872 nm.

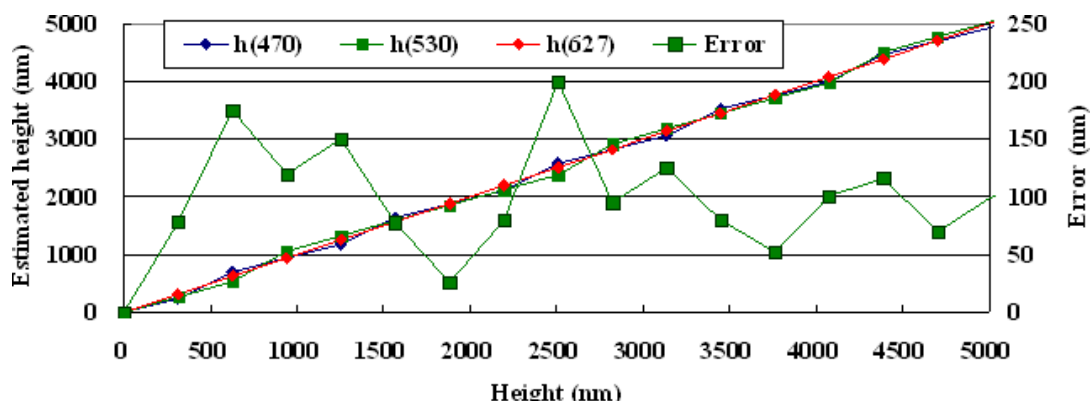


Fig. 9-12 Coincidence error diagram (470-530-627nm)

9.2.6 Comparison of two-wavelength method and three-wavelength method

By comparing the error diagrams of the two-wavelength method and the three-wavelength method, we consider the mechanism for expanding the measurement range, that is, how the addition of one wavelength contributes. Figure 9-13 is obtained by superimposing the error diagram for two wavelengths (BR) and the error diagram for three wavelengths (BGR). The effect of adding the wavelength G can be clearly read from this diagram. In other words, at two wavelengths of BR, there was a minimal peak of coincidence error near 940 nm, but at three wavelengths of BGR, the minimal peak extended to around 1872 nm. This is because there is no height candidate near 940 nm for the G wavelength.

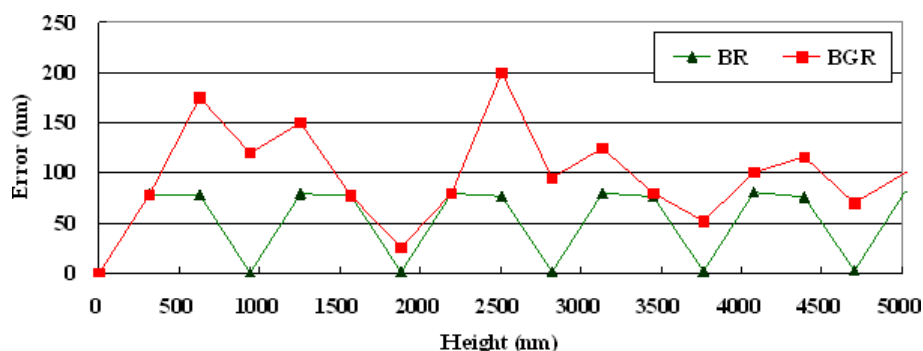


Fig. 9-13 Coincidence error diagrams of two (BR) and three (BGR) wavelengths

Figure 9-14 is obtained by superimposing the BG wavelength diagram that gives the longest equivalent wavelength of 4151.7 nm as the two-wavelength method and the BGR wavelength diagram of three wavelengths. The minimum peak around 2200 nm disappeared.

However, the peak around 1872 nm does not change, and the effect of adding the R wavelength is small. Therefore, it can be said that there is room for optimization in the R wavelength.

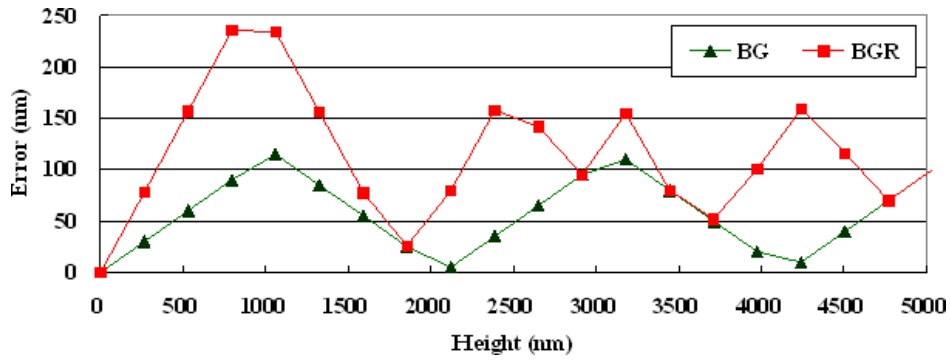


Fig. 9-14 Coincidence error diagrams of two (BG) and three (BGR) wavelengths

9.2.7 Relationship between coincidence period and phase error

The measurement range in the coincidence method is a coincidence cycle that considers the phase error. Let us consider how this coincidence cycle P_c is determined.

In addition to the phase, the wavelength error also affects the coincidence error defined by Eq. (8-36). Therefore, including the wavelength error, it is called the phase error and expressed by the value converted to the height. For the three wavelengths in the previous section, the error diagram is shown by the green line in Fig. 9-15. In this graph, the coincidence period P_c for the given phase error is determined by the three points connected by red circles, and the red line connecting these three points shows the relation between the phase error and the coincidence period. For example, if the phase error is less than 1/2 of 26 nm, the coincidence period is 5000 nm or more, and if the phase error is less than 1/2 of 77.5 nm, the coincidence period is 1872 nm.

Rewriting this figure, and letting the horizontal axis be the allowable phase error and the vertical axis the coincidence period, Fig. 9-16 is obtained. Using this figure (called the coincidence cycle diagram), the coincidence cycle P_c for the given phase error can be found. That is, if the phase error is 38.75 nm or less, the coincidence period is 1872 nm or more, and if the error is 39 nm or more, the coincidence period is 271 nm, which is the same as in the case of the original one wavelength, and there is no effect of range expansion by three wavelengths.

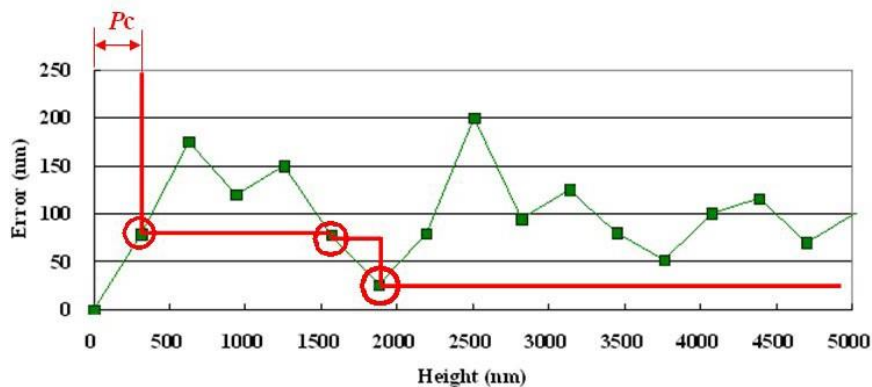


Fig. 9-15 Coincidence error diagram (green) and its critical points (red) determining the coincidence period P_c

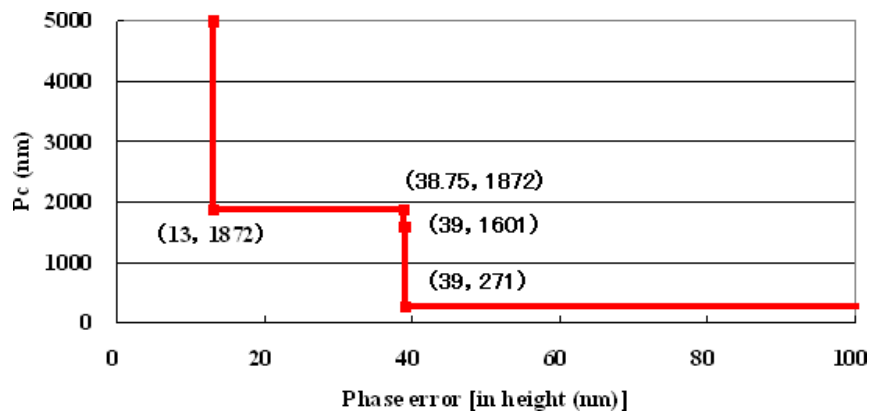


Fig. 9-16 Coincidence period diagram

9.2.8 Spatial unwrapping and spectral unwrapping

Conventionally, the equivalent wavelength method often assumes spatial unwrapping for surface shape measurement. On the other hand, the coincidence method is mainly used for measuring the length of a gauge block and a distance meter. Since it only needs to measure one point, and the height (or length) range can be set, it does not think about spatial unwrapping. For this reason, there is no report that treats both in a unified manner.

However, both the equivalent wavelength method and the coincidence method can be considered as methods for giving a range R (UMR = Unambiguous Measurement Range; described as "measurement range" in this paper) in which the height can be uniquely determined from the phase. That is, in the case of the equivalent wavelength method, $1/2$ of the equivalent wavelength is R , and in the case of the coincidence method, the coincidence period P_c is R . The calculation formula of the height candidate of order n is expressed by the following formula.

$$h(n) = h_0 + nR, \quad (9-1)$$

where, h_0 is the fraction of height, and in the case of the equivalent wavelength method, it is the equivalent phase \times (equivalent wavelength/2), and in the case of the coincidence method, it is the coincidence height within the given height range.

Thus, to unwrap the height (Fig. 9-17) convoluted into the interval R (that is, to determine the order n), the following two methods are used regardless of the equivalent wavelength method and the coincidence method.

(1) Spatial unwrapping: Generally called "phase connection," assuming that the target surface is smooth, it connects smoothly to adjacent pixels (Fig. 9-18). The allowable step is $1/2$ of the measurement range R .

(2) "height-range unwrapping": A method of estimating the order using the phases at multiple wavelengths is also called optical unwrapping. It specifies a range of heights and select candidate values within that range (Fig. 9-19). The calculation is an independent calculation for each pixel, and the maximum allowable step between adjacent pixels is the measurement range R .

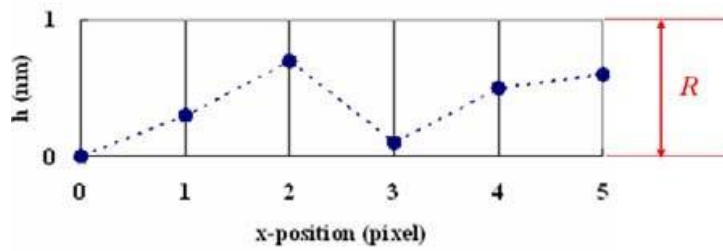


Fig. 9-17 Wrapped height

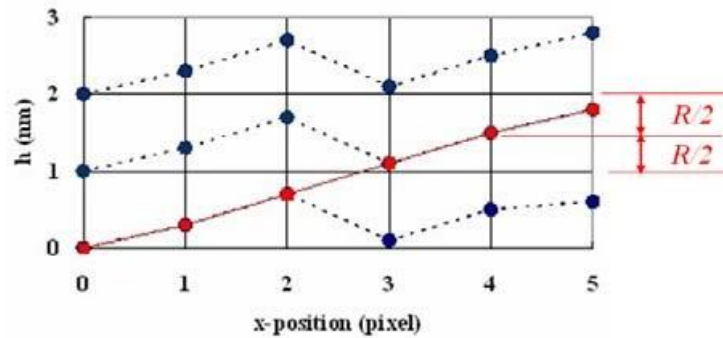


Fig. 9-18 Unwrapped height by spatial unwrapping

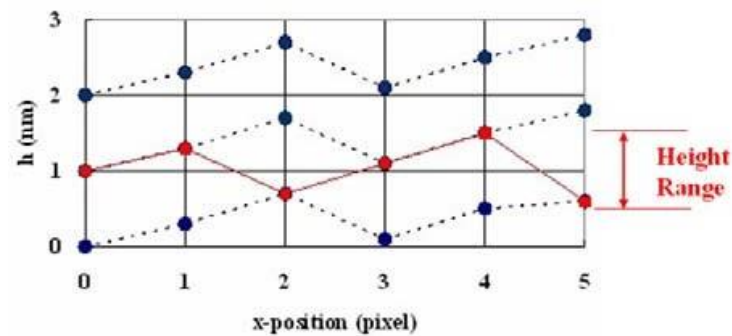


Fig. 9-19 Unwrapped height by height-range unwrapping

9.2.9 Summary

Summarizing the above considerations, we obtain the following conclusions.

- (1) Even in the two-wavelength method, there are optimum wavelength combinations.
- (2) The coincidence method gives a correct and wider measurement range than the equivalent wavelength method.
- (3) The measurement range depends on the phase error.
- (4) “Phase diagram” is useful for understanding these.
- (5) The measurement range estimation considering the error is possible by the graph of the coincidence error and height (Error diagram) or the graph of the coincidence period and the phase error (Coincidence period diagram).
- (6) Both the equivalent wavelength method and the coincidence method can be considered as methods that give a measurement range in which the height can be uniquely determined from the phase.
- (7) In both cases, spatial unwrapping or height-range unwrapping (range specified unwrapping) can be selected.

9.3 Optimum wavelength selection

From the results of the examination in the previous section, it was found that estimation of the measurement range considering the error is possible by the graph of the coincidence error and height (Error diagram). In this section, we propose a wavelength optimization method, taking three wavelengths as an example.

9.3.1 Error diagram

The procedure for creating an error diagram is described below, where the maximum wavelength of the three wavelengths is λ_1 .

(1) The height candidates of the first wavelength when the phase is zero are calculated by the following equation. The range of order n_1 ($n_1 = 0, 1, \dots$) is determined from the target height range.

$$h_1(n_1) = n_1(\lambda_1/2). \quad (9-2)$$

(2) The height candidates h_j of the j -th wavelength ($j = 2, 3$) closest to each height candidate obtained above are calculated by the following equation, where Round [] means rounding off to the nearest integer.

$$h_j(n_j) = \text{Round}[h_1(n_1)/(\lambda_j/2)](\lambda_j/2). \quad (9-3)$$

(3) The coincidence error E of the obtained height candidates are calculated by Eq. (8-36).

(4) Create a diagram with h_1 on the horizontal axis and E on the vertical axis.

9.3.2 Selection of the optimal wavelength combination

From the error diagrams for various combinations of wavelengths, select the one with the highest minimum value of the coincidence error within the desired range. If this local minimum is more than twice the expected maximum phase error, the desired range is achieved.

9.4 Optimal wavelength selection result

Based on the method in the previous section, we obtained an error diagram for various wavelength combinations and searched for the optimum wavelength. The search conditions are as follows:

- (1) Each wavelength band = RGB band of color camera
- (2) Search pitch = 10 nm (depending on availability of commercial bandpass filter)¹⁾

As an example of the search, the first wavelength was fixed at 470 nm, and the third wavelength was fixed at 600 nm. Error diagrams for 530, 540, 550, and 560 nm of the second wavelength are shown in Fig. 9-20(a)(b)(c)(d).

As a result of the search, the combination of 470 nm (B), 560 nm (G) and 600 nm (R), whose diagram is shown in Fig. 9-20(d), was selected as the optimum wavelength combination. The coincidence period diagram of this combination is shown in Fig. 9-21, compared with the case of the conventional combination. From this figure, it can be seen that a measurement range of 4 μm or more can be expected if the phase error for each wavelength is less than 33 nm.

¹⁾Wavelengths that are multiples of 10 nm (e.g., 470, 480, 490 nm) were selected as candidates. A few years later, we developed a new illumination system that does not depend on a commercially available filter (Section 10.5), so optimization that is not restricted by this condition has become possible. However, as described in Section 9.2.3, since the coincidence period is not determined by the least common multiple, even if the search pitch is 1 nm, it does not change the result dramatically. For example, when a certain wavelength is changed by 1 nm, the change in coincidence error is at most 1 nm multiplied by the order, and the Error diagram changes continuously.

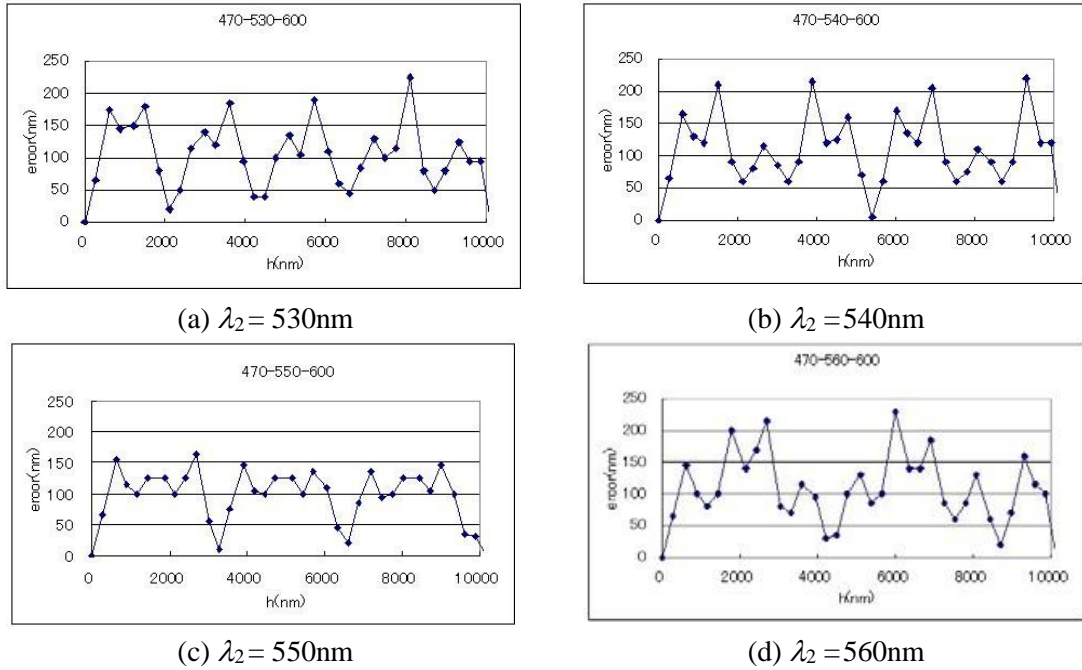


Fig. 9-20 Coincidence error diagrams to select the optimum second wavelength with the 1st and 3rd wavelengths fixed

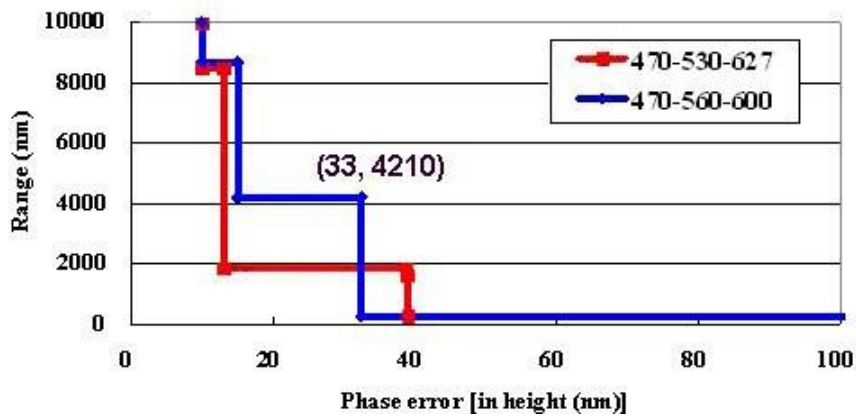


Fig. 9-21 Coincidence period diagram of the optimum wavelength combination

9.5 Actual measurement of 4 μ m step height

9.5.1 Experimental method

In order to confirm the range expansion function, a measurement experiment was conducted on a standard step sample (NTT-AT; HS-40) with a nominal step of 4 μ m.

(1) Interference optical system and imaging system

The optical system is shown in Fig. 9-22. As the three-wavelength illumination system, a commercially available three-color LED illumination device was used up to the previous chapter, but this time, a three-wavelength mixed illumination system was constructed using three halogen light sources with built-in bandpass filters and optical fibers. The purpose is to increase the degree of freedom in wavelength selection and to narrow the bandwidth of the illumination light and increase the coherence length.

A filter with a bandwidth of 10 nm is used to set the coherence length to about 20 μ m. The imaging system used a 1.4-megapixel (1360 x 1024 pixel), 3-CCD color camera (Hitachi Kokusai Electric, HV-F22CL). The high-definition camera is used to cover a wide field of view with one measurement. Figure 9-23 shows the spectral sensitivity characteristics of the color camera and the three wavelengths used.

(2) Crosstalk compensation coefficient

The crosstalk compensation coefficient was obtained by the method in Section 8.3.3. The result is as follows, and the crosstalk is very small. This is also expected from Fig. 9-23.

$$\begin{pmatrix} B' \\ G' \\ R' \end{pmatrix} = \begin{pmatrix} 1 & 0.00 & 0.00 \\ 0.00 & 1 & 0.11 \\ 0.00 & 0.00 & 1 \end{pmatrix} \begin{pmatrix} B \\ G \\ R \end{pmatrix} \quad (9-4)$$

where (B, G, R) is before compensation, and (B', G', R') is after compensation.

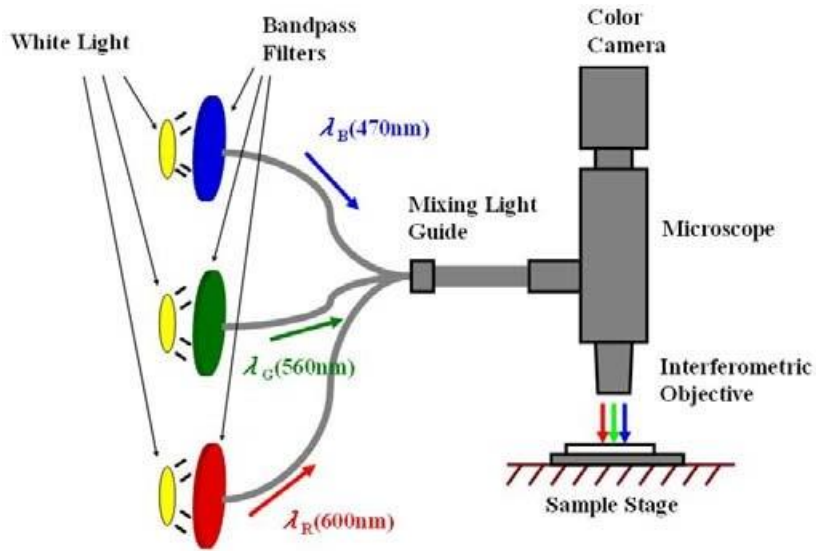


Fig. 9-22 Three-wavelength illumination system

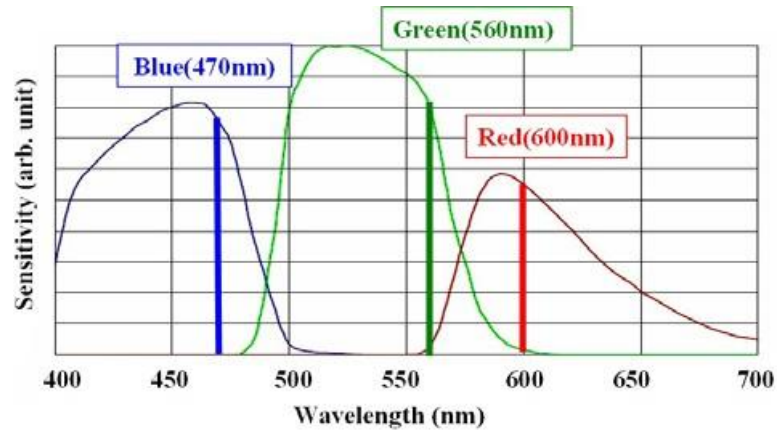


Fig. 9-23 Spectral sensitivity of camera and three wavelengths

9.5.2 Experimental results

From the conclusion of the optimal stripe direction described in the next section (Section 10.2), we set the stripe direction as horizontal stripes. The captured color image is shown in Fig. 9-24. Figures 9-25, 9-26, and 9-27 show the intensity, phase, and height profiles for each wavelength at the $x = 672$ line in the center of the image. The data size used by the LMF method is 25 pixels vertically \times 5 pixels horizontally. The measurement results for the entire field are shown in Figures 9-28 and 9-29. Figure 9-28 shows the PC screen of the SP-500 device, in which the color map of height and the profiles in the x and y directions are displayed. A step of $4 \mu\text{m}$ could be measured stably, and the measurement reproducibility of the step was about 1 nm. The calculation time for 1.4 million pixels was about 11s (CPU: Intel Pentium 1.6GHz).

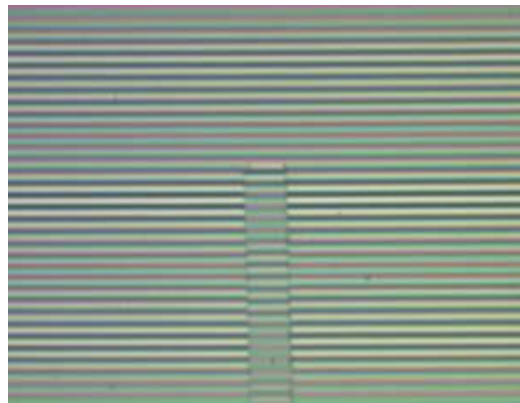


Fig. 9-24 Captured image of $4 \mu\text{m}$ step height

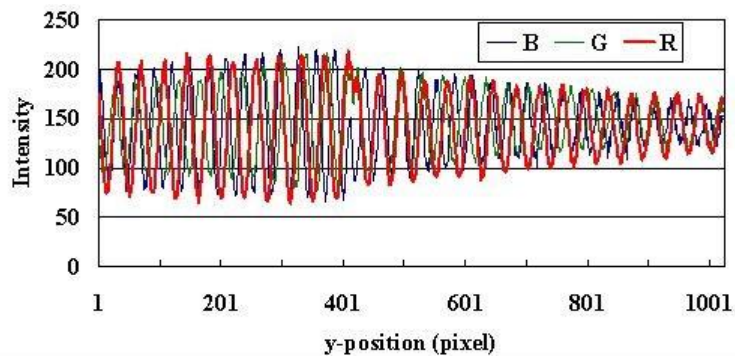


Fig. 9-25 Intensity profiles at $x = 672$

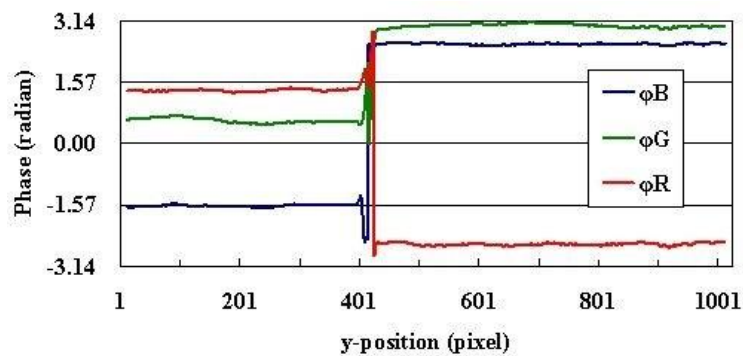


Fig. 9-26 Phase profiles at $x = 672$

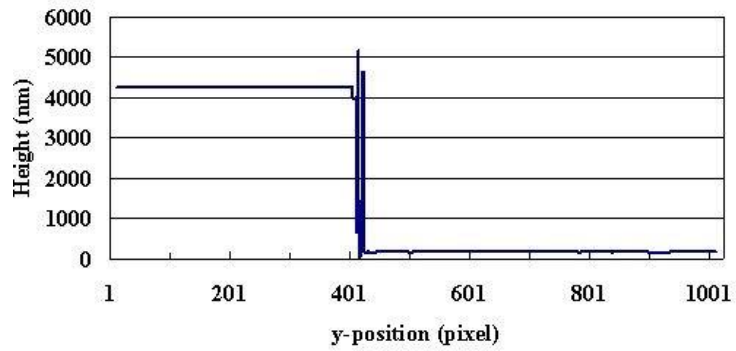


Fig. 9-27 Height profile at x = 672

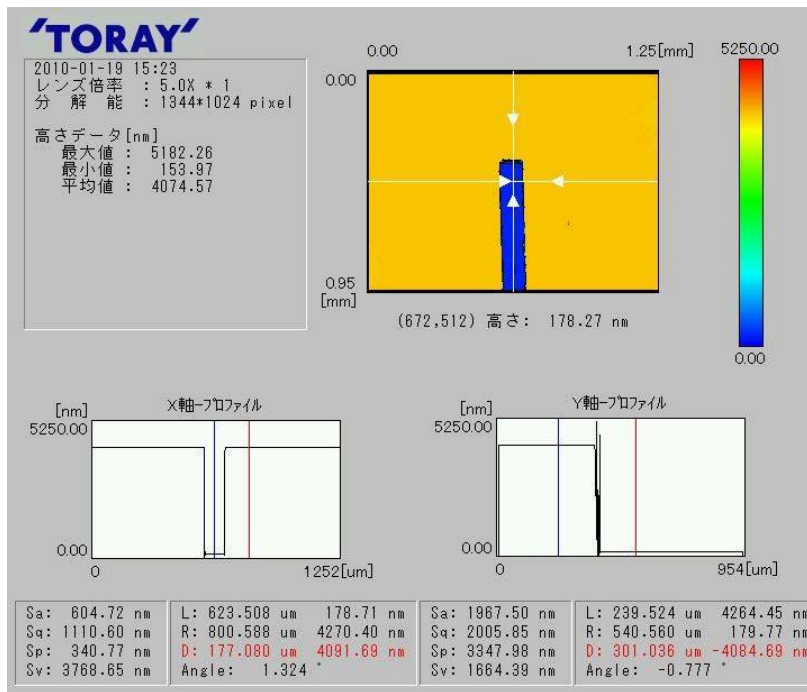


Fig. 9-28 Test result display of 4μm step height

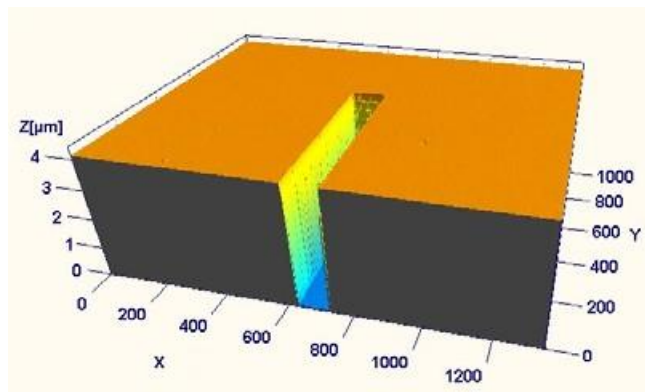


Fig. 9-29 Test result of 4μm step height (3D view)

9.6 Summary

In order to further expand the measurement range of the three-wavelength single-shot method, we established a search method for the optimum combination of wavelengths. In this process, the relationship between the equivalent wavelength method and the coincidence method was clarified. Assuming the use of a commercially available color camera, we selected 470nm(B)-560nm(G)-600nm(R) as the optimum combination of wavelengths. An illumination system of this wavelength was constructed with three halogen illuminators and a three-branch optical fiber light guide. As a result, we succeeded in measuring a standard step sample of 4 μm .

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