

# Novel 3D Resolution Measurement Method for Autostereoscopic Display

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## Abstract

The resolution of a 2D display can be easily defined by the number of physical pixels. Two-view autostereoscopic 3D display expresses images by distinguishing pixels directed to the left and right eyes, so the maximum resolution is usually defined as half the number of pixels. However, the resolution of the autostereoscopic 3D display that is actually perceived by the viewer is far less than half the resolution of the number of pixels. Therefore, the resolution of autostereoscopic 3D displays must be quantified in terms of perceived resolution. In this study, we studied a method to accurately evaluate sinusoidal patterns with different slanting angles and cycle frequencies using a two-dimensional LMD to quantify the resolution of 3D displays. We analyze each measurement image with 2D-FFT method to define the resolution that the autostereoscopic 3D display can actually express. Finally, the resolution that viewers can perceive was quantified through perceptual evaluation using the landolt ring, and the threshold value that matches the recognition characteristics with the resolution evaluation results analyzed through evaluation was confirmed.

## Author Keywords

Resolution of 3D display, measurement method of resolution, 2D-FFT analysis method, perceptual evaluation of resolution,

## 1. Introduction

Autostereoscopic 3D displays utilize optical structures to control the direction of light emitted from each pixel. The 3D display currently in mass production mainly checks the positions of the both eyes with an eye-tracking camera, divides each pixel into two-views, and displays both images in the pixels of the corresponding view. Therefore, two-view 3D displays generally define resolution as half of the total number of pixels.

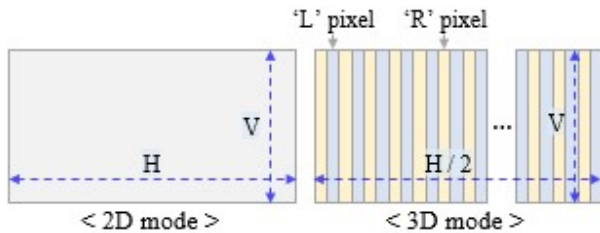


Figure 1. Resolution definition for 3D display

For example, in an autostereoscopic 3D display with 3840\*2160 pixels, the resolution is defined as 1920\*2160 when the pixels are divided into two views for the left and right eyes. Figure 2 is an image evaluated by two-dimensional LMD of 2D image in which the resolution of the original image was divided in half, and a 3D image obtained by 3D-mode running the original image. The resolution of 3D mode is defined as 1920\*2160, which is half of the resolution, but it can be seen that the actual resolution is greatly reduced compared to the 2D mode image of 1920\*2160. Therefore, in this study, we studied to quantify the resolution at which 3D displays can actually express.

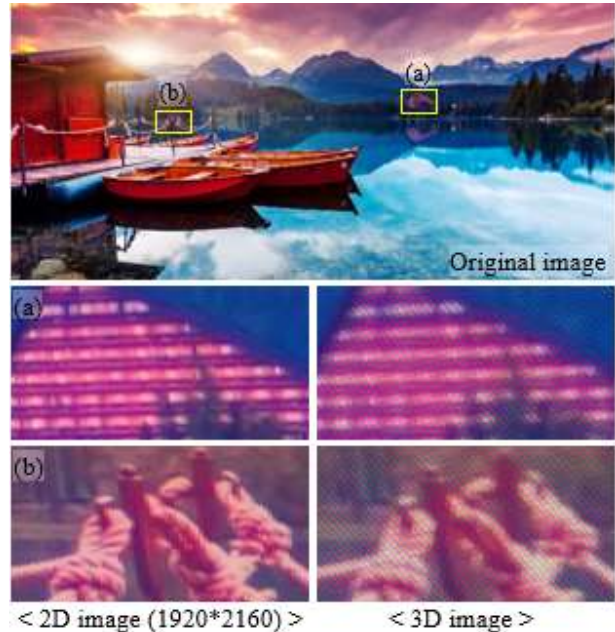


Figure 2. Decreased resolution in 3D mode

## 2. Evaluation and analysis method of resolution

As shown in Figure 3, in order to evaluate how well the periodic pattern is expressed, we evaluated each periodic pattern image with different angles and frequencies using two-dimensional LMD. And we analyzed the periodic intensity of measurement image using 2D-FFT analysis method. If the cycle is expressed well, the intensity of other cycle components is low compared to the intensity of the intended cycle. Conversely, if the cycle is not expressed well, the intensity of other cycle components increases compared to the intensity of the intended cycle. Therefore, whether resolution could be expressed was determined based on the ratio of the intensity of the intended cycle and the max intensity among unintended noise cycles. We used the sinusoidal cycle pattern for each angle and period as shown in table 1 for the evaluation pattern. The sinusoidal pattern was divided into angles at 30° intervals, and the frequency of the cycle was utilized at intervals of 0.05 from 0.05 to the maximum resolution (1.0).

### (a) Measurement method

There are two main things to pay attention to measure periodic patterns with a two-dimensional LMD: the number of data per pixel and the focal distance. Because measurement moire may occur depending on the number of data per display pixel and the intensity of other periodic components may change, it is necessary to check the minimum number of data per pixel. And since the periodic pattern can be evaluated blurry depending on the focal distance, it is necessary to check how much the intensity of the noise cycle changes depending on the focal distance and check the allowable error range using the focal distance.

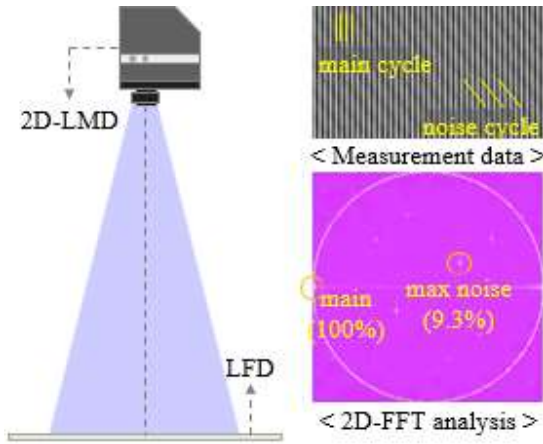


Figure 3. Measurement and analysis method

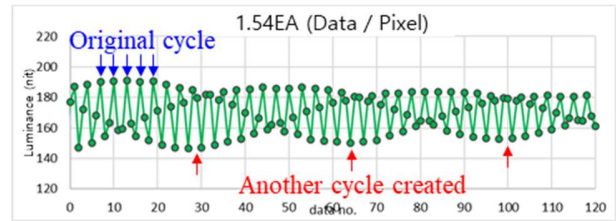
Table 1. Evaluation patterns of resolution analysis

	0°	30°	60°	90°	...
0.1					...
0.2					...
...	...	...	...	...	...
1.0					...

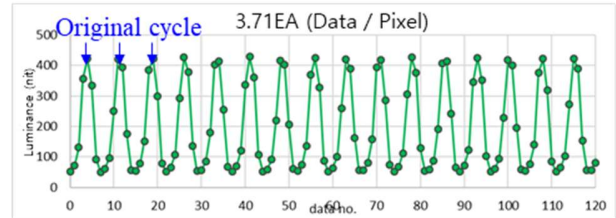
First, in order to confirm the minimum number of data per pixel for consistent evaluation as shown in Figure 4, we checked how much the intensity ratio of the noise cycle by changing the number of evaluation binnings for the same image. If the number of data is insufficient, another cycle is additionally created in addition to the original cycle, and if the number of data is sufficient, other cycles are rarely created. As shown in Figure 4(c), it can be seen that the intensity of the noise cycle varies unstable when the number of data per pixel is small, and it has been confirmed that stable data can be obtained when the number of data per pixel is 2.5 or more. Second, as shown in Figure 5, we confirmed how much the intensity of the noise cycle varies depending on the focal distance. When evaluated at the focal distance where the focus level is maximum, the intensity of the noise ratio is minimized, and when evaluated at a difference of  $\pm 0.002\text{m}$  or more from the standard focal distance, the intensity ratio of noise cycle increases significantly. In this study, the evaluation was conducted under the condition that the number of data per pixel exceeded about 4, and the focal distance was fixed at the focus level of the max.

**(b) Analysis method**

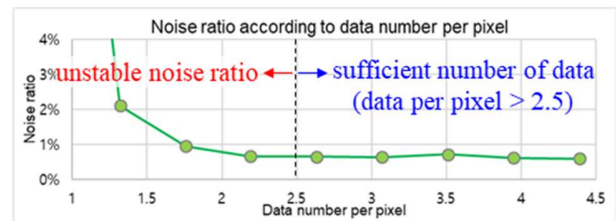
In this study, we defined the expression ability of resolution by evaluating the cycle pattern for each frequency and each angle with a two-dimensional LMD and analyzing the intensity for each cycle pattern with 2D-FFT. To confirm consistency with the perceptual evaluation, we used two autostereoscopic display products and evaluated and defined the resolution of product A (2D mode / 3D mode) and product B (2D mode). Figure 6 is an example of evaluation and analysis of the 0 degree pattern of 3D mode of product A. In 2D mode, the intensity of noise cycle does not increase significantly, but in 3D mode, as the cycle frequency increases, the intensity of the noise cycle increases significantly.



a) Insufficient number of data (1.54EA / pixel)



b) Sufficient number of data (3.71EA / pixel)



c) Noise ratio according to data number per pixel

Figure 4. Check minimum number of data per pixel

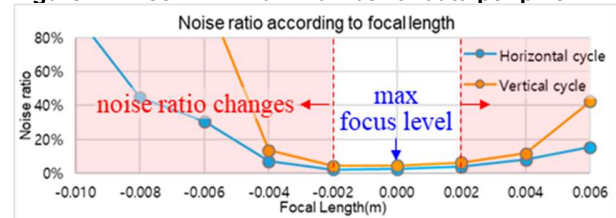
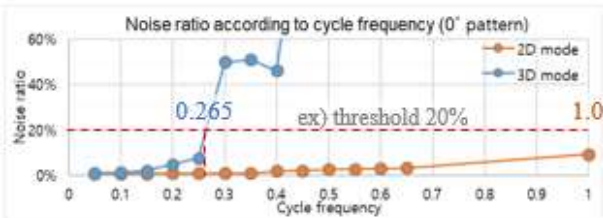


Figure 5. Noise ratio according to focal length

Figure 6 b) is a graph of noise ratio according to the frequency of the cycle of 0 degree pattern (2D & 3D mode). If resolution is not expressed well, undesired cycles of frequency and direction are realized, so whether resolution can be expressed is defined as whether the intensity ratio of noise cycle is below the threshold. In the graph, for example, if the threshold is defined as 20%, the 2D mode with a 0 degree pattern can express maximum resolution (1.0) with less than 20% at all cycle frequencies, but the 3D mode exceeds 20% as the cycle frequency increases. Therefore, the resolution can be defined at the (0.265) level. Therefore, it is very important to determine the threshold value of the intensity of the noise cycle in order to define the displayable resolution of each display. Figure 7 shows the resolution expression range when the threshold is set to 10% / 20% / 30%. It can be seen that the resolution expression range varies greatly depending on the threshold of the noise cycle intensity. Therefore, in order to know the absolute value of resolution that a display can actually express, matching through a perceptual experiment is essential. In this study, we conducted a perceptual evaluation to select an appropriate threshold value that can match the resolution that the display can actually express and the measurement & analysis resolution.



a) Measurement image & 2D-FFT raw data

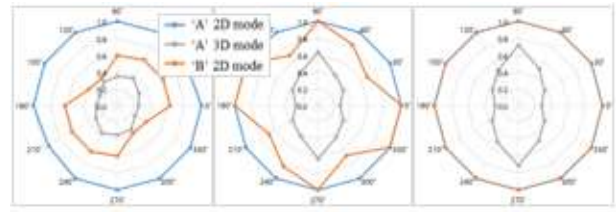


b) 2D-FFT analysis of 2D & 3D mode (0° pattern)

Figure 6. Analysis of 0 degree pattern (2D & 3D mode)

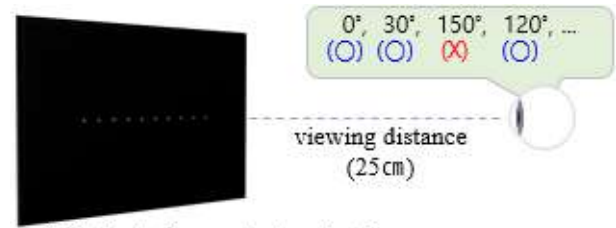
### 3. Perceptual evaluation of resolution

In order to confirm the range of resolution that can actually be expressed, we created Landolt rings by size and angle at 30-degree intervals and evaluated whether the angle at which the Landolt ring was opened could be recognized. A Landolt ring with 1 empty pixel means maximum resolution (1.0), and a Landolt ring with 2 empty pixels means half resolution (0.5). Because perceptual evaluation results can vary greatly depending on a person's visual acuity, more than 10 people with a corrected visual acuity of 1.0 or higher were selected and the correct response rate was confirmed through more than 5 repeated tests for each pattern. Figure 8 shows the method of perceptual evaluation. We produced Landolt rings with different angles on an autostereoscopic display and checked whether the test subject recognized the direction of opening of each pattern. We repeatedly evaluated the same pattern size with randomly mixed angles several times and checked the percentage of correct answers for each angle. Then, patterns of different sizes were created and evaluated repeatedly. In addition, we conducted perceptual evaluations on the 2D and 3D mode of product A and the 2D mode of product B, respectively, to confirm the resolution that can be expressed for each product or mode. Figure 8 (b) is an image of a landolt ring with an opening on the right created by size and evaluated as a two-dimensional LMD in 2D mode and 3D mode. As can be seen in the figure 8(b), in 2D mode it is possible to clearly recognize the direction of the opening even in the smallest landot ring, but in 3D mode it is not clear, making it difficult to recognize the direction of the opening in the landot ring. Table2 is the correct rate of perceptual evaluation by landolt pattern angle and size for product A (2D & 3D mode) and product B (2D mode). As can be seen in the table, the 1pix pattern is impossible to recognize in 3D mode, and the rate of correct answers is significantly lower than in 2D mode.

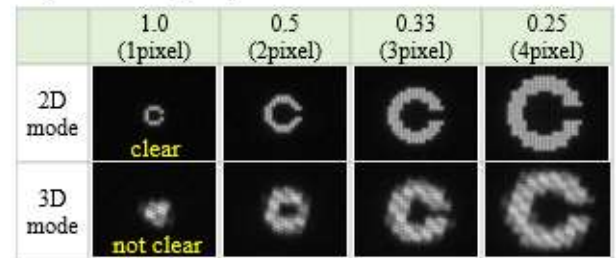


a) Threshold 10% b) Threshold 20% c) Threshold 30%

Figure 7. Resolution range according to threshold



a) Method of perceptual evaluation



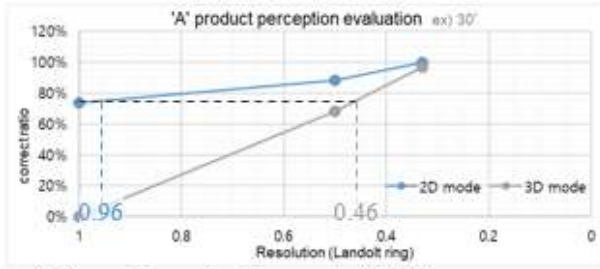
b) Landolt ring measurement image (2D & 3D mode)

Figure 8. Method of perceptual evaluation

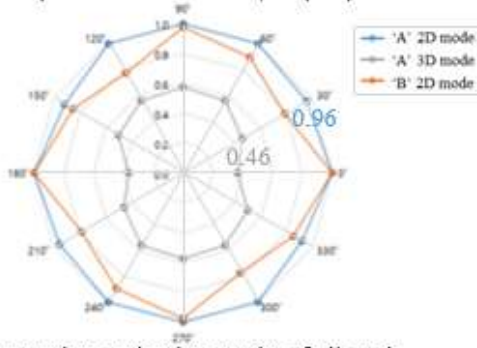
Figure 9 is a method of quantifying resolution through perceptual evaluation. Figure 9 (a) is a graph of the correct answer rate of the 30 degree landolt ring of product A (2D & 3D mode) from the correct answer rate in table2. Even if it is not clearly visible, there are cases where the direction is randomly selected and corrected, so we defined a perceptible resolution as when the correct answer rate is 75% or more. Based on a correct answer rate of 75%, the resolution of 30 degrees can be defined as 0.96 for 2D mode and 0.46 for 3D mode, respectively. In the same way, the resolution by angle of product A (2D & 3D mode) and product B (2D mode) through perceptual evaluation is expressed as figure 9 (b).

Table 2. Correct ratio of the perceptual evaluation

		0°	30°	60°	90°	120°	150°
'A' (2D)	1 Pix	90.5%	73.8%	81.0%	76.2%	78.6%	71.4%
	2 Pix	97.6%	88.1%	88.1%	92.9%	90.5%	92.9%
	3 Pix	100%	100%	100%	100%	100%	100%
'A' (3D)	1 Pix	0%	0%	0%	0%	0%	0%
	2 Pix	36.7%	68.3%	85.0%	88.3%	85.0%	75.0%
	3 Pix	83.3%	96.7%	98.3%	100%	98.3%	98.3%
'B' (2D)	1 Pix	76.2%	61.9%	69.0%	73.8%	61.9%	65.5%
	2 Pix	100.0%	92.9%	97.6%	97.6%	90.5%	97.6%
	3 Pix	100%	100%	100%	100%	100%	100%



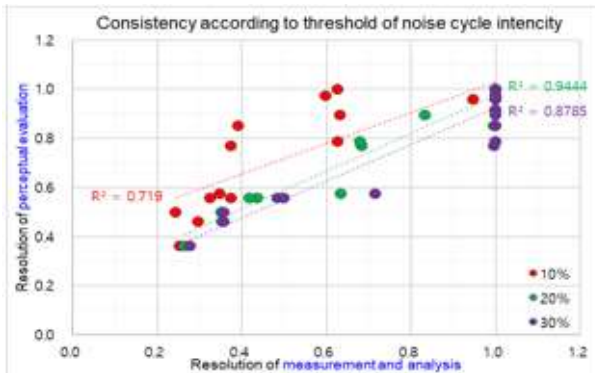
a) Perception evaluation analysis (30°)



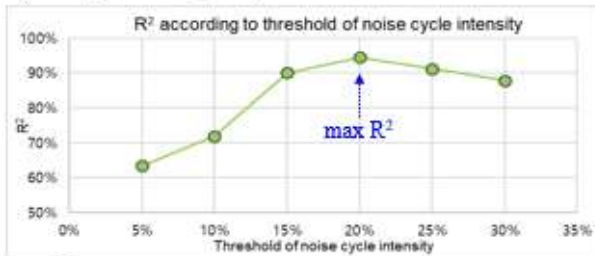
b) Perception evaluation results of all angle

Figure 9. Quantification of perceptible evaluation

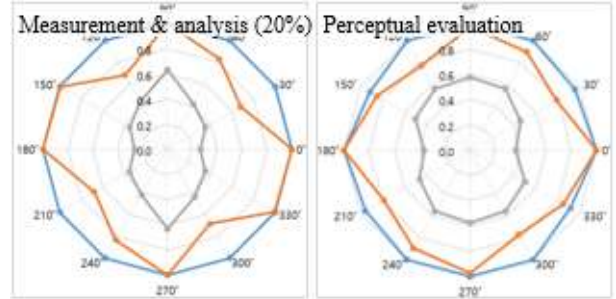
To check the consistency of the perceptual evaluation and the measurement, analysis resolution, we checked the threshold of noise cycle intensity at 5% intervals as shown in figure 10. To confirm consistency, we compared the perceptual evaluation resolution and measurement, analysis resolution for each pattern and size of each product. When the threshold of noise cycle intensity is 20%,  $R^2$  between the resolution of perceptual evaluation and the resolution of measurement, analysis show quite high consistency with 0.944.



a) Comparison of perceptual evaluation & measurement



b)  $R^2$  according to threshold of noise cycle intensity



c) Comparison of resolution range

Figure 10. Consistency according to threshold

#### 4. Conclusion

A two-view 3D display using eye-tracking operates with separate views for the left and right eyes, and the resolution is usually defined as half the number of pixels. However, the resolution expression ability of the actual 3D mode is considerably lower compared to the half resolution of the 2D display. Therefore, it is very important to evaluate the resolution is usually defined as half the number of pixels. However, the resolution expression ability of the actual 3D mode is considerably lower compared to the half resolution of the 2D display. Therefore, it is very important to evaluate the resolution that can actually be expressed in autostereoscopic 3D displays. In this study, we measured the sinusoidal cycle patterns by angle/frequency and analyzed the intensity of the noise cycle of each pattern using 2D-FFT analysis. However, in order to define resolution by the intensity of the noise cycle, selection of the threshold value is very important because the resolution can vary greatly depending on the threshold. Therefore, in this study, we conducted a perceptual evaluation using a landolt ring to check the consistency between the measured and analyzed resolution and the actual perceived resolution. Also, by checking the percentage of correct answers matching the direction of the landolt ring by angle and size, the threshold value of the noise cycle intensity with the highest consistency was selected as 20%. Through the results of this study, we believe that we will be able to quantify the resolution that viewers can actually perceive of autostereoscopic 3D displays through measurement and analysis.

#### 5. References

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