Lab Write-Up Week 3

Aberrations and Illumination

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22 February 2023

PCX Lens

The effects of using a diffuser on diffraction artifacts are shown in Figure 1 and Figure 3. Resolution is approximately the same between both images, with the image showing diffraction artifacts having marginally better contrast. However, adding the diffuser element to reduce diffraction artifacts does make it easier to view the bars in the image with the eye.

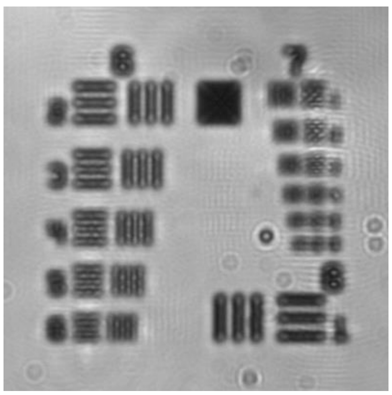


Figure 1. Resolution test target illuminated by halogen lamp (630nm). Exposure: 25ms. No gain. PCX lens orientated with planar surface facing resolution target. No diffuser was used. Diffraction pattern are apparent when compared with Figure 3.

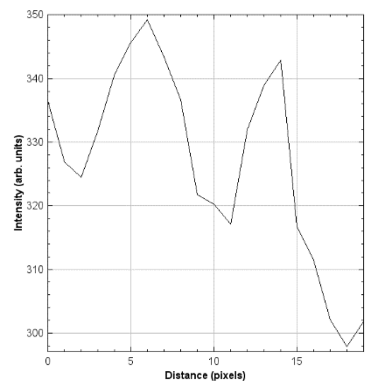
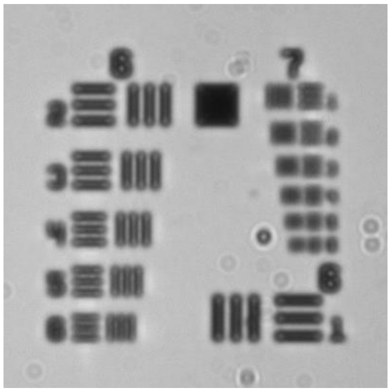


Figure 2. Line plot of Group 6, Element 6 of Figure 1. Maximum intensity is 433, minimum is 335. Contrast is 12%



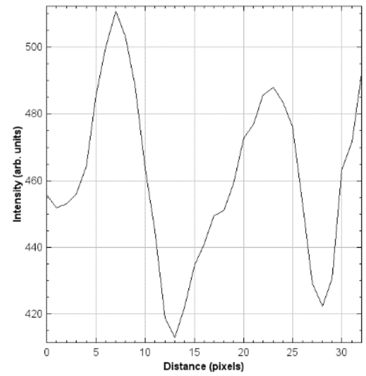
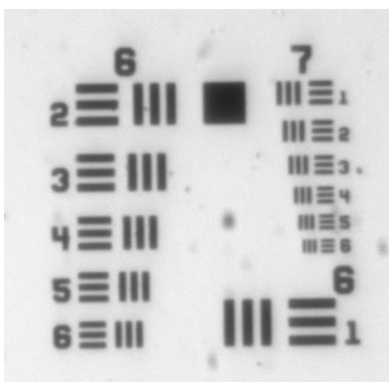


Figure 3. Resolution test target illuminated by halogen lamp (630nm). Exposure: 25ms. No gain. PCX lens orientated with planar surface facing resolution target. Diffuser was placed between lamp and resolution target. The diffraction lines are not visible as they are in Figure 1.

Figure 4. Line plot of Group 6, Element 6 of Figure 3. Maximum intensity is 510, minimum is 412. Contrast is 10.6%

PCX lens wavelength and resolution

Figure 5 through Figure 7 show the imaging with a PCX lens as the objective. A series of LEDs were used as the light source to image the resolution target. These include blue(404nm), green(526nm), red(642nm), and infrared(938nm).



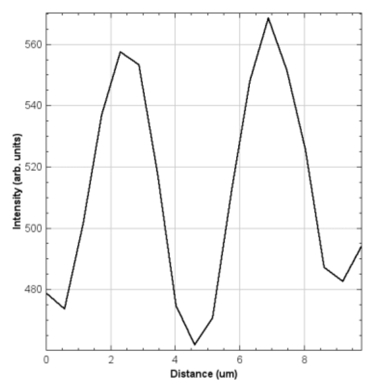


Figure 5. Resolution test target illuminated by Blue Led (404nm). Exposure: 14.5ms. No gain. PCX lens orientated with planar surface facing resolution target.

Figure 6. Line plot of Group 7, Element 6 of Figure 5. Maximum intensity is 569, minimum is 462. Contrast is 10.4%

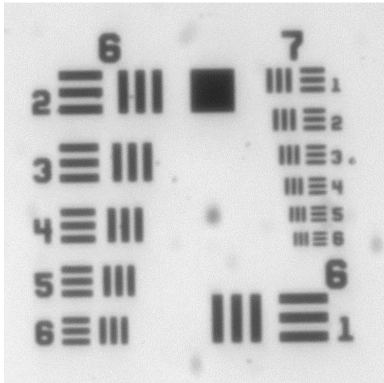


Figure 7. Resolution test target illuminated by Green Led (526nm). Exposure: 18.5ms. No gain. PCX lens orientated with planar surface facing resolution target.

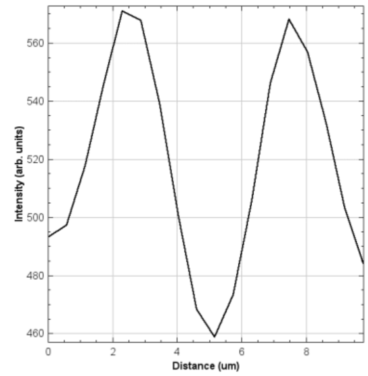


Figure 8. Line plot of Group 7, Element 5 of Figure 7. Maximum intensity is 571, minimum is 459. Contrast is 11%

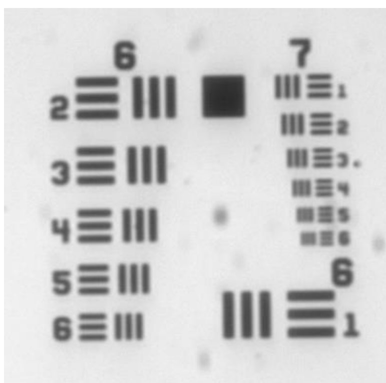


Figure 9. Resolution test target illuminated by Red Led (642nm). Exposure: 21ms. No gain. PCX lens orientated with planar surface facing resolution target

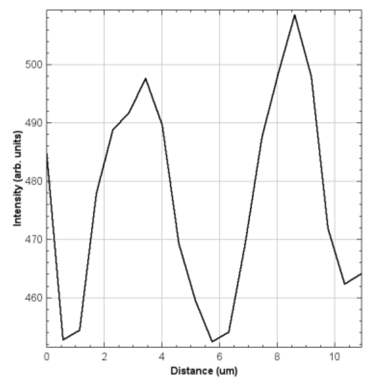


Figure 10. Line plot of Group 7, Element 4 of Figure 9. Maximum intensity is 550, minimum is 432. Contrast is 12%

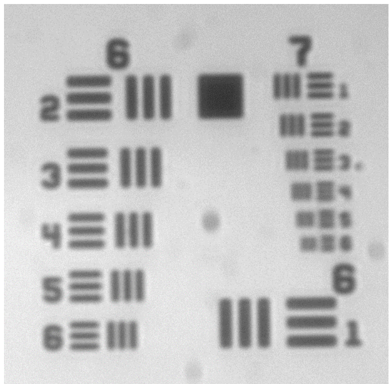


Figure 11. Resolution test target illuminated by IR Led (938nm). Exposure: 79ms. No gain. PCX lens orientated with planar surface facing resolution target.

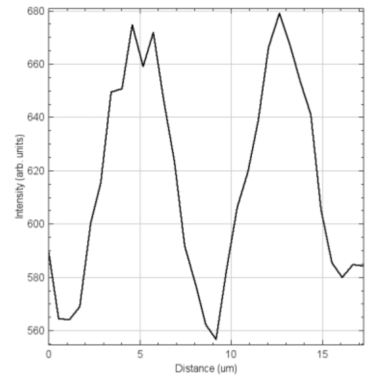


Figure 12 Line plot of Group 7, Element 1 of Figure 11. Maximum intensity is 679, minimym is 557. Contrast is 9.9%

The resolution measured for each wavelength of light is shown in Table 1. The Numerical aperture for the PCX lens, with a diameter of 25mm is determined by Equation 1 to be ½. The equivalent resolution given the minimum resolvable element is given by Equation 2.

Equation 1: $$NA \cong \frac{r}{f} = \frac{25mm/_2}{25mm} = {}^1/_2$$

Equation 2: $$resolution\ (um) = \ (10^3) \times 2^{-Group - \frac{(Element-1)}{6}}$$

Lamp Color	Lamp Wavelength (nm)	Lens NA	PCX Resolution (Group, Element)		Equivalent Resolution (um)
IR	938	0.5	7	1	7.81
Red	642	0.5	7	4	5.52
Green	526	0.5	7	5	4.92
Blue	404	0.5	7	6	4.38

Table 1. Imaging was best in the blue light spectrum, and became worse as the wavelength of light increased. This is shown by Equation 3, where as wavelength increase so does the minimum resolvable distance.

Table 2 Shows the relation between the measured resolution and the theoretical resolution given by Equation 3. As shown, there is a large difference between the measured resolution and the theoretical resolution. The explanation for the difference is the aberrations in the lenses. Although chromatic aberration is improved from using a black body source, as in Figure 1, the LEDs still emit a spectrum that will focus as multiple points. The PCX lens, being an approximation of an ideal lens will also have spherical aberrations.

Equation 3 $$\delta = \frac{0.61\lambda}{NA} = 1.22\lambda$$

Lamp Color	Lamp Wavelength (nm)	Measured Resolution (um)	Theoretical Resolution (um)	% difference

IR	938	7.81	1.14	149
Red	642	5.52	0.78	150
Green	526	4.92	0.64	154
Blue	404	4.38	0.49	160

Table 2. Comparison of measured resolution and the Theoretical resolution given by Equation 3. There is a significant difference between the theoretical and measured resolutions due to aberrations in the system.

The focal length of the lens changes as a function of the wavelength of light. The micrometer was used to adjust the sample stage to be in best focus for each wavelength of light. Lower wavelength of light moved the focus closer to the objective lens; such that the sample must be moved closer to the objective lens to be in focus.

Lamp Color	Lamp Wavelength, nm	Stage Micrometer Setting for PCX lens best focus
IR	938	3.049
Red	642	3.017
Green	526	2.545
Blue	404	2.508

Table 3. Positioning of the sample stage to focus the sample for each wavelength of light. Imaging with blue light required the sample to be closest to the objective, and infrared required the sample to be placed furthest away.

Narrowing the wave band of light emit by a lamp by using a filter is beneficial as you remove extraneous focal points for other wavelengths of light. This reduces the PSF of the image by reducing chromatic aberrations.

Chromatic Lens

The PCX lens was replacing with a achromatic lens for the objective. The focal length of the achromatic lens is 25mm. an aperture is also placed on the back of the lens to adjust the normal aperture of the lens. The aperture was set to be 2.5 mm in diameter. As with the PCX lens, 4 LEDs of different wavelengths were used to image the resolution test target.

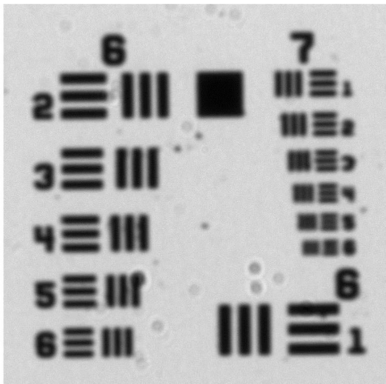


Figure 13. Resolution test target illuminated by Blue Led (404nm). Exposure: 23.2ms. No gain. Achromatic lens with aperture diameter of 2.5mm.

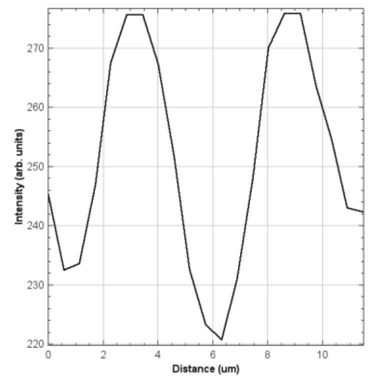


Figure 14. Line plot of Group 7, Element 4 of Figure 13. Maximum intensity is 276, minimum is 221. Contrast is 11.1%

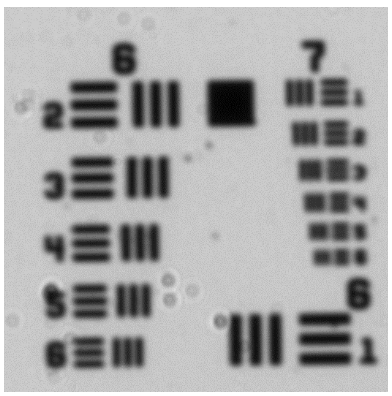


Figure 15. Resolution test target illuminated by Green Led (526nm). Exposure: 33.6ms. No gain. Achromatic lens with aperture diameter of 2.5mm.

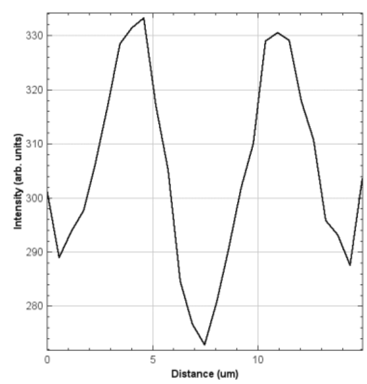


Figure 16. Line plot of Group 7, Element 2 of Figure 15. Maximum intensity is 333, minimum is 273. Contrast is 10%

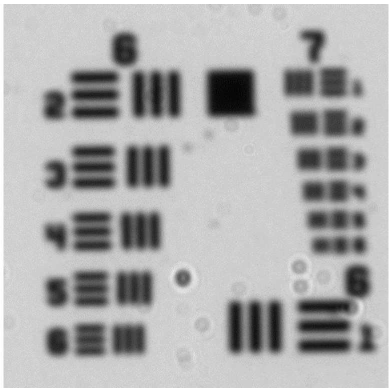


Figure 17. Resolution test target illuminated by Red Led (642nm). Exposure: 42ms. No gain. Achromatic lens with aperture diameter of 2.5mm.

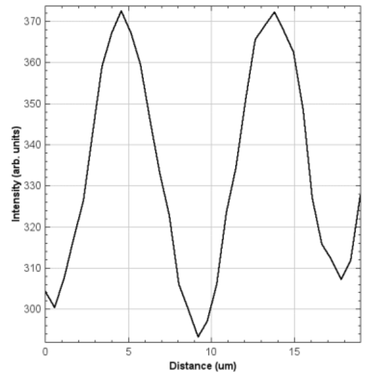


Figure 18. Line plot of Group 6, Element 6 of Figure 17. Maximum intensity is 372, minimum is 293. Contrast is 12%

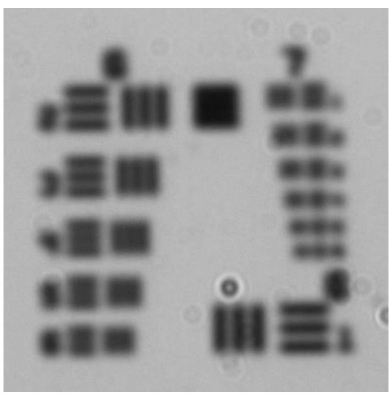


Figure 19. Resolution test target illuminated by Infrared Led (938nm). Exposure: 158ms. No gain. Achromatic lens with aperture diameter of 2.5mm.

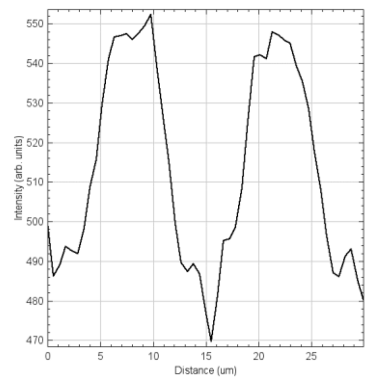


Figure 20. Line plot of Group 6, Element 1 of. Maximum intensity is 552, minimum is 470. Contrast is 8%

The resolution measured for each wavelength of light is shown in Table 4. The Numerical aperture for the achromatic lens, with an aperture diameter of 2.5mm is determined by to be 1/20 as shown by Equation 4. The equivalent resolution given the minimum resolvable element is given by Equation 2. The measured resolution is much closer to the expected Rayleigh resolution. Resolution is lower, per wavelength, compared to using a PCX, although increasing the Numerical Aperture by increasing the diameter of the iris would improve resolution.

Equation 4 $$NA \cong \frac{r}{f} = \frac{2.5mm/_2}{25mm} = {}^1/_{20}$$

Lamp Color	Lamp Wavelength (nm)	Stage micrometer setting (um)	PCX Resolution (Group, Element)	Resolution Based on Resolution Target, Achromat Objective, (um)	Expected Rayleigh Resolution for achromat objective (um)

IR	938	25	6	1	15.63	11.4436
Red	642	2	6	6	8.77	7.8324
Green	526	1	7	2	6.96	6.4172
Blue	404	0	7	4	5.52	4.9288

Table 4. Comparison of measured resolution and the Theoretical resolution using the achromatic lens.

Change in index of refraction.

Given that the index of refraction for red light is 1.51527, the index of refraction for blue light is calculated.

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \rightarrow \frac{1}{f(n-1)} = \left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

$$f_{red}(n_{red} - 1) = f_{blue}(n_{blue} - 1)$$

$$n_{blue} = \frac{f_{red}(n_{red} - 1)}{f_{blue}} + 1 = \frac{25mm(1.51527 - 1)}{25mm - 0.509mm} + 1 = 1.52598$$

Calculated change in focal length $1.51527 - 1.52598 = -0.0107$

Datasheet change $1.51527 - 1.5303 = -0.0150$

The difference between the calculated change and the change reported on the datasheet is 28%. There are several causes for this error. Foremost is the assumption that the red light had an index of refraction of exactly 1.51527; looking at the datasheet a wavelength of 642nm should have an index of refraction closer to 1.5148. Secondly, imprecision in measuring the foci of the red and blue lights would have a great effect on this result. Measuring the foci to more significant digits would likely decrease our error.

Pixel Spacing

The Ronchi line ruling with 30 line-pairs per mm was imaged in Figure 21, to measure the pixel spacing of an image. The length of 10 line-pairs was measured to be 581 pixels.

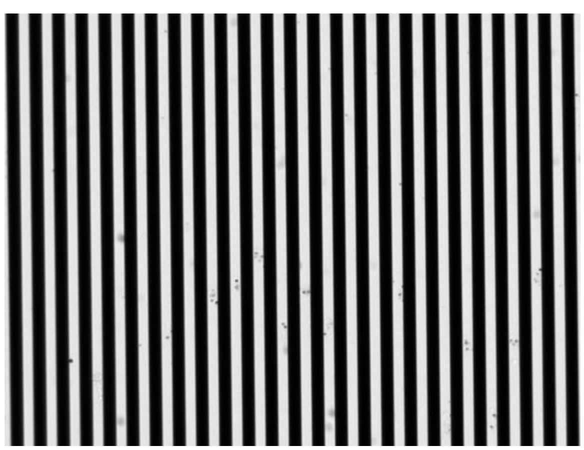


Figure 21. Ronchi ruling with 30 line-pairs per mm. Illuminated with a green LED (526nm). Objective is achromat with aperture 7mm in diameter.

$$\frac{\#lines}{pixels} \times \frac{1}{lp/mm} \times \frac{10^3 um}{mm} = \frac{10lp}{581px} \times \frac{1}{30lp/mm} \times \frac{10^3 um}{mm} = 0.574um/px$$

Given the pixel spacing of the camera used is 3.45um, the magnification of the system can be found by

$$M = \frac{Spacing_{camera}}{Spacing_{system}} = \frac{3.45um/px}{0.574um/px} = 6.01$$

The theoretical magnification of this system is known by

$$M = \frac{f_{tube}}{f_{objective}} = \frac{150mm}{25mm} = 6$$

As the error is 0.2%, The measured magnification agrees with what is expected.