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RESOLUTION LIMIT OF SMALL IMAGE SENSORS SIZE

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Abstract: Safety video surveillance systems have been relying on the technological achievements and developments of the consumer market in a number of respects from the very beginning. It is no different in the case of Ultra HD (4K). Although in spite of the fact that the market penetration of the ultra-high definition Broadcast technology is considerably slower than previously predicted, 4K-resolution slowly but surely infiltrates into the domain of video surveillance systems. More and more manufacturers include Ultra HD cameras in their portfolios. The question, however, is rather simple: is this sector really prepared to implement this technology? Does higher resolution actually provide more information? Have all the opportunities provided by full HD been fully exploited, or is there still room for improvement in this area?
Keywords: UHD, 4K, resolution, diffraction, limit of resolution

INTRODUCTION

We experience technological races in various fields of life. Be it the motor industry or the mobile phone market, we see more and more new technological developments in the given field. Manufacturers bid against one another to gain the largest possible market share, using various marketing tools. A pixel war is ongoing on the mobile front, while in television technology we have hardly been introduced to the 4K resolution when an advanced version of 8K was already displayed in exhibitions.

This trend did not leave the field of video surveillance systems untouched, either. More and more manufacturers include cameras with resolution exceeding Full HD in their portfolio. Many people think that the larger the number of pixels, the better the image quality and thereby the more details visible in the picture.

A declared objective of this article is to highlight that image quality does not only depend on the resolution of the imaging sensor. We have reached a level where we need to take into account such physical limitations that directly work against a more detailed image display.

CHANGES IN MARKET TRENDS IN THE LAST FEW YEARS

The statistics of camera sales in Hungary for Bosch, leading manufacturer in surveillance video systems, provides a good description of the technological advancements in this field.

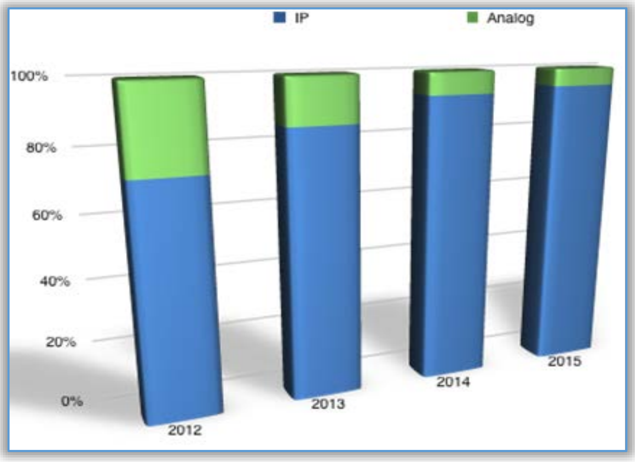

Figure 1: Statistics of Bosch camera sales in Hungary (source: own editing)

Analog camera sales keep shrinking, while sales of IP cameras are increasing at the same rate.[1] A further breakdown of sales statistics for HD and higher resolution cameras show that sales are more and more relevant for larger resolution equipment [1]. The higher the resolution of the camera we choose, the higher the chance that under some circumstances we will run into resolution limits.

[1] According to data by Attila Bárány, Head of Marketing at Bosch

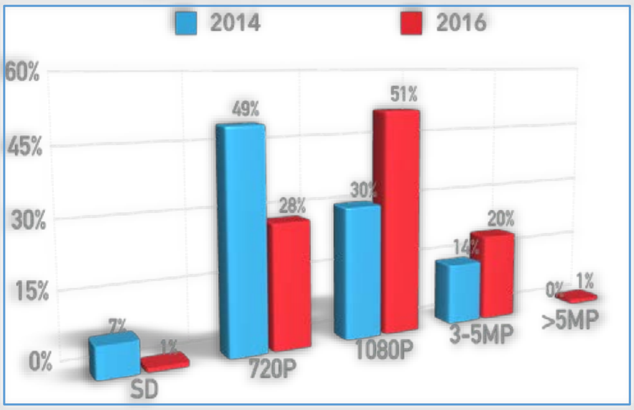

Figure 2: Camera sales according to resolution between 2014 and 2016 (source: own editing)

DIFFRACTION LIMIT

Diffraction as physical phenomenon is mostly relevant in wave optics. Projecting parallel light rays, incoming at a perpendicular angle, through a slit the size of which corresponds to the wave length of the light shows that light waves can reach areas of the receiving screen that are optically shaded if we assume a straight line of light propagation.

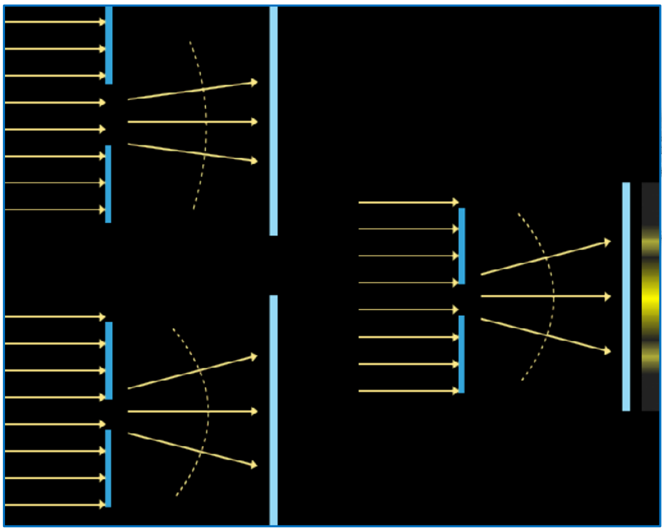

Figure 3: Correlation between diffraction and slit (source: own editing)

According to the Huygens-Fresnel principle, [2, pp. 413-414] elemental waves interfere in various ranges of the wave space, meaning that they either weaken or strengthen each other. This diffraction pattern is clearly visible in the receiving screen. The most intensive line of light is in line with the middle of the slit, and it gradually fades to the right and left up to the point of extinction. In case we consider the slit to be one-dimensional, the most intensive spot of light will be in the intersection of the screen and the line perpendicular to the screen, going through the middle of the slit. The intensity then decreases in both positive and negative directions until extinction. From here, we again see increasingly bright lanes, which again starts to fade after it reaches its maximum, until the second point of extinction (Figure 3, right side). The value of diffraction is proportional to the wavelength of the light, and inversely proportional to the size of the slit (Figure 3, left side).

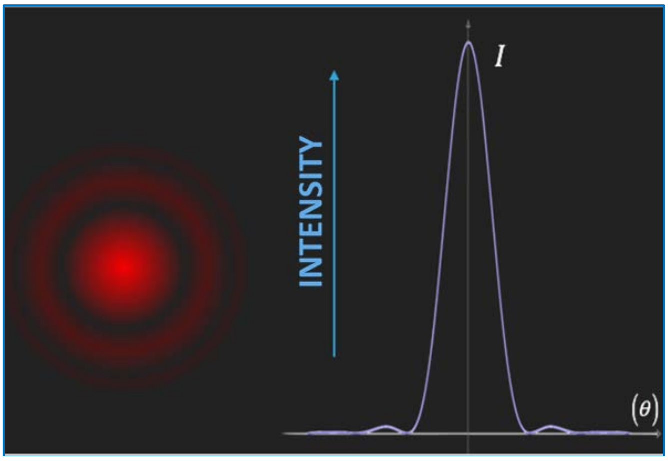

Figure 4: Airy disk and intensity function (source: own editing)

Through a round slit, light beams emanating from a single point will display as concentric, gradually fading circles with alternating brighter and darker light rings. The image thus produced is called the Airy[2] disk. (Figure 4). The intensity function beside the disk clearly shows that the second maximum value following the first, main minimum is only a fraction (1.75%) of the main maximum. Subsequent maximum values keep decreasing. The third maximum value is only 0.42% of the main maximum (these circles will only be visible with a very powerful light source).

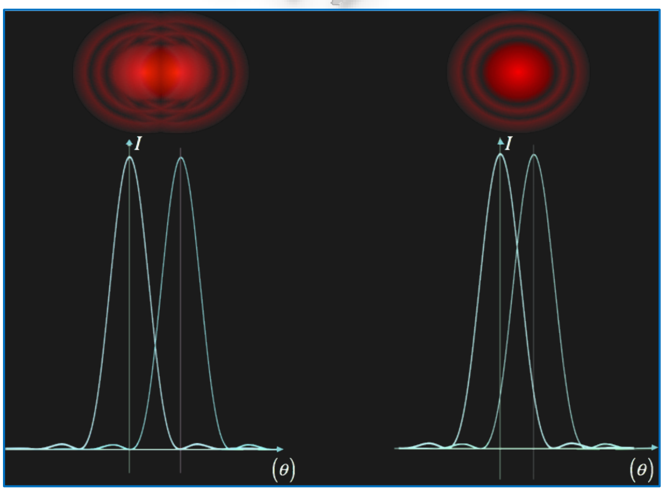

Figure 5: Rayleigh criterion (source: own editing)

When testing the resolution limit of an imaging equipment, an important concept id the Rayleigh[3] criterion. Let us examine the images displayed though a small round opening of two incoherent light disks that

[2] Sir George Biddell Airy (1801–1892) mathematician and astronomer

[3] Lord Rayleigh (1842-1919) physicist

are far from each other as compared to their diameters. Due to the diffraction, the displayed image of the two pointlike light sources will be an Airy disk.

In case the distance between the two pointlike light sources are comparable to the size of the slit, the image will be blurred and we will not be able to tell them apart [3, p. 149]. According to the Rayleigh criterion, the two pointlike spots will be just barely differentiated if on the displayed image the maximum of one Airy disk falls on the first minimum of the other Airy disk (Figure 5).

In order to calculate the first minimum of the Airy disk intensity function, we need to be able to compile the function itself. Assessing the resolution limits in an optical system [4, p. 117], and omitting a full mathematical deduction, for the direction corresponding to the first minimum of the function, the following relation can be stated:

$$\theta_0 = \arcsin\left(1{,}22\frac{\lambda}{D}\right) \tag{2.1}$$

where D is the diameter of the round aperture, and λ is the light's wave length. Consequently, the two points that are in α elongation from each other can be differentiated if:

$$\alpha \geq \theta_0 = 1{,}22\frac{\lambda}{D} \tag{2.2}$$

Since angles are very small in such close proximity of points, it will not be greatly misleading to state that:

$$\sin\theta_0 = \tan\theta_0 = \frac{r}{f} \tag{2.3}$$

where r is the radius of the first minimum circle, while f is the focal distance of the optic system (camera lens). Since the slit of a lens is (N),

$$N = \frac{f}{D} \tag{2.4}$$

where *D* in this case is the slit of the incoming pupil of the camera lens, thereby using this information as well as the equations 2.1 and 2.3, we can determine the radius of the first minimum of the Airy disk corresponding to various apertures:

$$r = 1{,}22 \cdot \lambda \cdot N \tag{2.5}$$

As per equation 2.5, the size of the Airy disk is proportional to the wavelength and the size of the aperture. At an aperture of F8.0, and taking the wavelength of green light (520 mm), the diameter of the Airy disk is

$$2r = 2{,}44 \cdot 5{,}2 \cdot 10^{-7} \cdot 8 = 10{,}15\ [\mu m] \tag{2.6}$$

The maximum aperture can be as high as F64 in some automatic iris lenses, which means an eight times larger Airy disk as compared to the result of equation 2.6.

CORRELATION BETWEEN DIFFRACTION BARRIER AND PIXEL SIZE

As technology in manufacturing develops, the elemental pixel size in CCD[4] and CMOS[5] image receivers keep decreasing. In the past twenty years or so, the elemental pixel size has shrunk to less than 1/100, while surface sensitivity per unit (mV/μm²) has increased in the same ratio. This is due to technological inventions such as OCML, OCCF and the tungsten shield, which has a 20-40% lower reflection than the previously used aluminium layer [5, pp. 27-30].

While the spectacular shrinking of mobile phones poses a certain expectation towards camera and lens manufacturers, this would not be a demand in video surveillance. Still, the size reduction for image receivers and lenses is ongoing. Image sensors used today with a resolution of 5 MP or higher mostly have a size of 1/1.8" (7.17 mm x 5.32 mm), or maybe 1/1.7" (7.6 mm · 5.7 mm) in better cases. On the contrary, the format for DSLR cameras keeps getting larger in parallel with resolution. The Canon PowerShot G1 X Mark II type DSLR camera has a nearly 13 megapixel (MP) image receiver with a size of 1.5"-os (18.7 mm x 14 mm) [6]. This is a 6.8 times larger surface than that of the 1/1.8" format.

When we compare the CMOS sensors of a Sony IMX185LQJ type Full HD [7] and a IMX226CQJ type 4K [8], we see that the elemental pixel size in the smaller resolution equipment is 3.75 μm x 3.75 μm, while the same value for 4K is 1.85 μm X 1.85 μm. since we are talking of small sizes, the difference does not seem large. Calculating, however, the surface size of the elemental pixel, the result for the former is 14.06(25) μm², while for the high-resolution latter equipment is barely its quarter at 3.42(25) μm².

Putting aside the Bayer filter used in the colour camera, and the fact that the colour information for these image receivers is compiled from 3 elemental pixels and these are not closely connected to each other, let us examine the effect of the Airy disk, caused by diffraction, on imaging.

Figure 6 shows that in case of low resolution, the Airy disk covers exactly one full pixel. Assuming an identical aperture, the light beam emanating from one point is spread over several pixels in a high-resolution equipment. This means that pixels close to each other will display identical information. In image receiving units with different sizes, the aperture value to limit maximum resolution will be different. Generally, we can state that at identical image sensory formats, higher-resolution elements will experience a deterioration in resolution at higher aperture values.

[4] Charged Couple Device

[5] Complementary Metal-Oxide Semiconductor

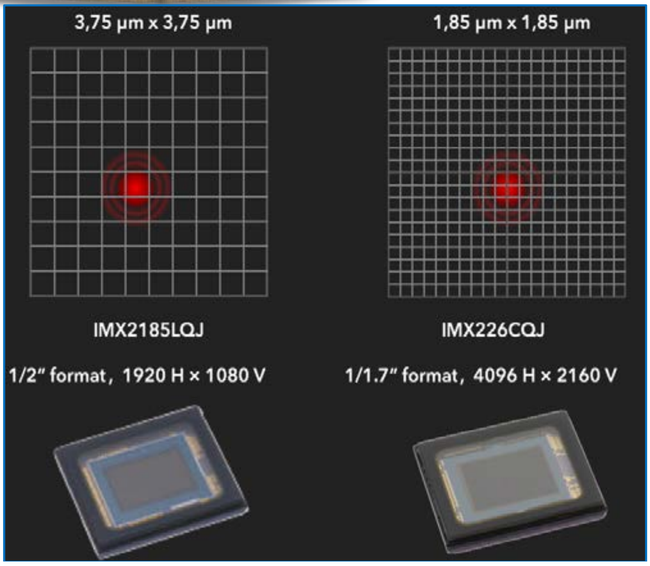

Figure 6: The influence of diffraction under high and low resolution (source: own editing)

CORRELATION OF SENSITIVITY AND PIXEL SIZE

Increasing the resolution of image receivers correlates with yet another issue, which is the decrease in sensitivity. It is easy to see that under identical lighting condition, a smaller elemental pixel size will receive a lower number of photons during a given time unit than a larger one. Consequently, the sensitivity and dynamic range of the equipment is worse. A lower number of received photons, assuming an identical quantum efficiency (QE) will result in less electrons. This decreased charge will in turn we comparable with the decoder noise and dark current noise produced by the image receiver. These together will also have a negative effect on resolution. [9, pp. 35-36]

The increases signal-noise relationship may result in further problems in image processing, transfer and storage as well. Processing a noisy image by software is more difficult, for example in motion detection the number of false alarms may increase, or contrarily: raising the threshold value may reduce the identification of real motion. Higher noise will also cause worse performance in compression, which in turn leads to a larger bandwidth for transferring and an increase in storage space demand.

TEST RESULTS

All of the above suggest that the physical limitations we have mentioned will considerably reduce image quality. I have verified the validity of theoretical calculations by measurements. When creating the appropriate test environment, I paid attention to Section 5.3 of the upcoming IEC 62676-5 standard, which provides a detailed prescription for the type of the test image, as well as the relative positioning of the camera, the illumination and the light meter. The test chart used for measurements is ISO 12233, as recommended in the standards.

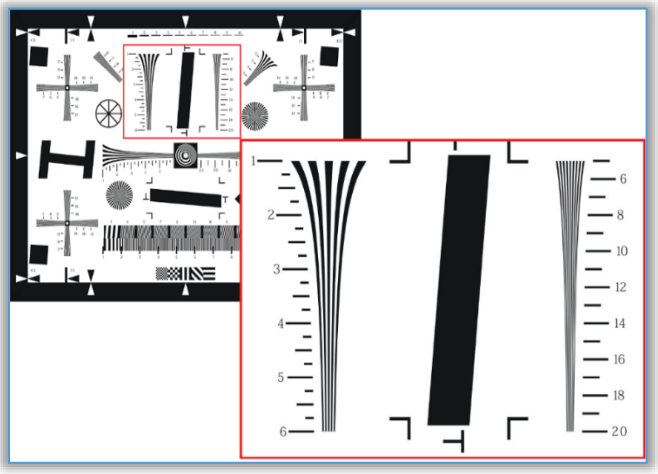

Figure 7: ISO 12233 test chart and enlarged wedge pattern (source: own editing)

The wedge pattern in the middle-top section of the test chart provides guidance for assessing horizontal resolution. The point where the increasingly frequent black and white lines can no longer be told apart (they merge) is called the camera's resolution limit. The corresponding line pair/millimetre (lp/mm) value can be read from the scale. To avoid any imprecisions of the reading, I have determined the resolution by using the Olympus HYRes 3.1 software.

When selecting cameras with differing resolutions, I aimed to choose from more or less the same (premium) category by leading manufacturers. The types I have examined according to resolution are: 2 MP (Full HD), 3 MP, 5 MP (3K) and 8 MP (4K). Manufacturers of the cameras tested are: Axis, Bosch, Hikvision and Samsung[6].

It is important to note that resolution was greatly influenced by the resolution limit of the lenses. Therefore, when selecting test camera lens, I took into consideration the manufacturers' recommendations, and I used the same 3 MP lens for both the 2 MP and 3 MP cameras.

The purpose of the testing was to determine how the richness in detail is influenced by various illumination values in cameras with varying resolutions.

Image 6 shows the results at an average lighting environment of 200 lx. At this lighting, the image quality corresponds with the resolution of the cameras.

Reducing the environmental illumination to 5 lux resulted in a drastic deterioration of resolution in 8 MP and 5 MP cameras. The reduction is 43% and 41%, respectively. The deterioration in resolution for equipment with a lower number of pixels is only 13% and 20% (Figure 7).

[6] Since this test does not aim at ranking the cameras, these measurement values intentionally do not include the type and manufacturer; the list is in alphabetical order, and does not in any way correspond to the rank of the test images.

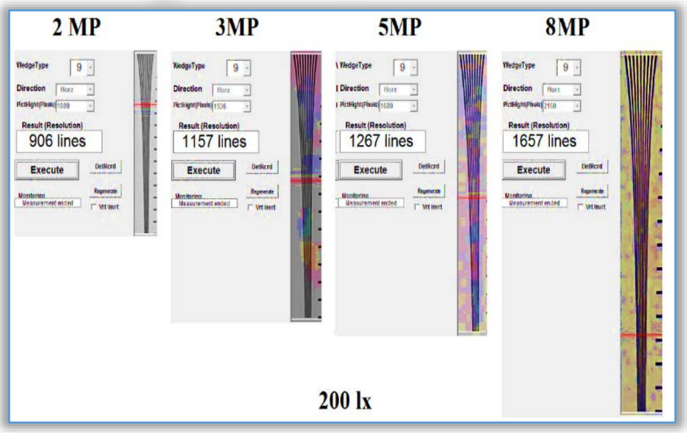

Figure 8: Resolution comparison at 200 lx environmental illumination (source: own editing)

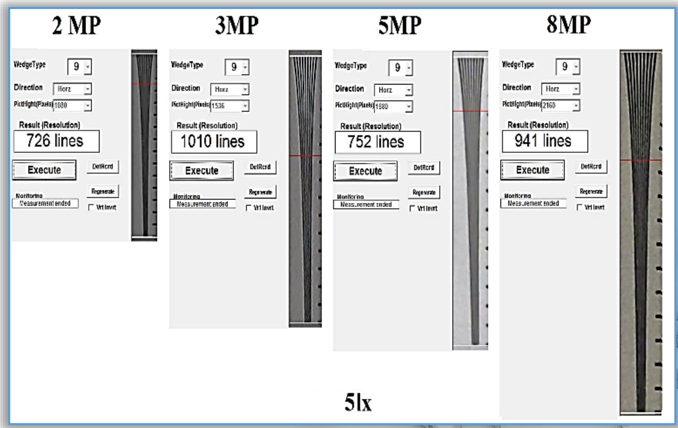

Figure 9: Resolution comparison at 5 lx environmental illumination (source: own editing)

Further reducing illumination resulted in further deterioration in resolution. 5 MP and 8 MP cameras both suffered a 54% reduction in resolution. The same value for the 3 MP equipment was only 18%. The resolution of the 5 MP camera at this level of lighting nearly equalled that of the Full HD equipment, while the 4K camera with the highest resolution produced a result lower than the 3 MP camera.

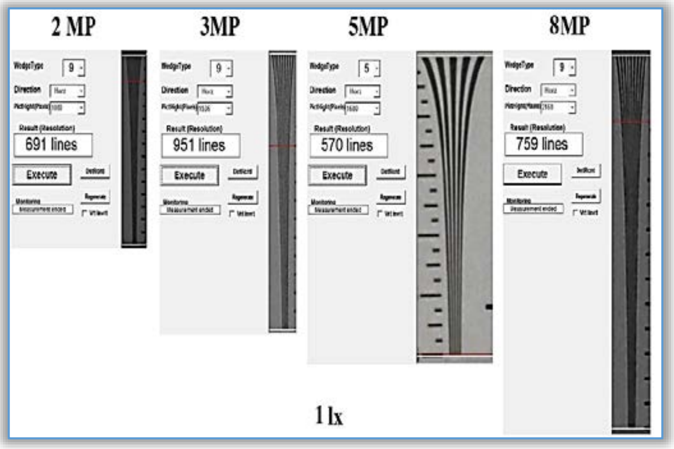

Figure 10: Resolution comparison at 1 lx environmental illumination (source: own editing)

The above measurements were conducted indoors with an artificial (2,700 K colour temperature) light source. However, to assess the influence of the diffraction barrier, I needed an environmental illumination of several thousands of lux, therefore further testing took place outdoors on a sunny late spring morning (on 20 May) at 11 a.m. The results in case of the 4K camera have verified my expectations: the equipment's resolution deteriorated by 41%, and the measured value was close to the resolution of a Full HD camera. Diffraction did not cause a decrease in resolution for the 5 MP, 3 MP and 2 MP cameras (Figure 11). For the latter two cameras this is acceptable, but the case of the 5 MP camera requires some explanation. The aperture for the lens used in this machine varied between F1.8 and F8. At an aperture of F8, no considerable diffraction effect can be measured in this 1/1.8" image receiver.

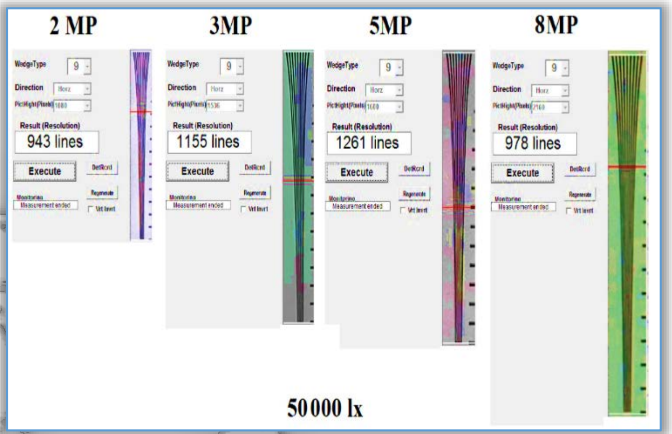

Figure 11: Resolution comparison at 50.000 lx environmental illumination (source: own editing)

CONCLUSIONS

Due to the development of manufacturing technologies, the size of CCD and CMOS image sensors have been decreasing in video surveillance cameras. Concurrently, there is a race of sorts between the manufacturers the produce cameras with ever-increasing resolution, and as statistic show, sales have moved in this direction as well. The consequence of the decrease in format and increase in resolution is that pixel element size is shrinking. This results in unwanted outcomes that counteract against producing images that are rich in detail and have a large resolution. The resolution of cameras with 4K or more pixels shrunk to a format of 1/1.7" will have both bottom and top limits regarding lighting environment. In poor illumination the signal-noise ratio deteriorates, and with it the resolution. The efficiency of compression for a noisy image is worse, thereby the image requires a larger bandwidth at transmission and more space for storage. In case of outdoors application, when in summer the illumination can reach up to100.000 lx, the diffraction caused by the contracting compartment of the automatic iris lens will result in poorer resolution. In the two extremes, the deterioration in quality can be so bad that even a good Full HD camera could produce an image that has less noisy and more details.

The above analysis does not mean that 4K cameras with such a small format are useless. At stable and sufficient illumination (ranging from a few hundred to a few thousand lux), it is recommended to trust the camera's auto shutter function to deal with brightness control, and use a manual aperture lens instead. The aperture should be at its maximum, although this may result in a decrease of depth of field. Under more extreme environmental lighting, the camera's auto shutter function will not be able to handle the huge light range. In this case, we should choose a lens where the aperture will not exceed F8, and use a supplementary light source in dusk. If worse comes to worst, we may also consider using several smaller resolution cameras.

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