The secrets of higher sensitivity CCTV cameras

***Nikolai Uvarov**, a Russian CCTV expert from Bezopasnost, Moscow, uses CCD theoretical calculations to prove that minimum illumination specifications as written by some camera manufacturers are not only misleading and incorrect, but also impossible with the current technology. An understanding of basic high school mathematics is required in order to follow his presentation.*

Text Nikolai Uvarov, illustrations Vlado Damjanovski

It is no secret that the colour television cameras of different manufacturers differ in terms of sensitivity. There is however very little ground for them to differ significantly: silicon, even from Africa – has a quantum efficiency similar to silicon from anywhere else; all cameras work in the same spectral range – i.e. visible light, otherwise colours will be incorrect if they are to be reproduced on any monitor. And of course, even the evaluation of various video cameras is based on the same important factor – the presence of light and colour. If there is no colour how can there be colour cameras? For colour cameras, where light is split on the chip further into primary colours, there must be sufficient illumination in order to produce a proper video signal. Light illuminations might be sufficient to form a luminance signal, but it may be insufficient to produce colour. Therefore, in the specifications of colour television cameras, as a rule, sensitivity for the signal of -6 dB or lower is given very rarely. But for a complete video signal, depending on the size of the CCD sensor, minimum illumination on the object (sensitivity under standard measurement conditions - with lens f/1,2 and 75% object reflectivity) is usually said to be between 1,5~8 luxes [1].

Table 1 *- Parameters of some colour video cameras*

MANUFACTURER camera model	PARAMETERS		
	CCD size	Pixels	Min.illum. (lux)
Hitachi VK-C317E	1/4 "	752 X 582	6.9
Sony SSC-DC593	1/3 "	752 X 582	2.9
Philips LTC0455	1/3 "	752 X 582	2.6
Vista NCL735CK	1/3 "	752 X 582	3.1
JVC TK-C1480E	½ "	752 X 582	1.3

It is a different matter with black and white (monochrome) video cameras.

I never cease to be amazed by advertising tricks with respect to the parameters of sensitivity and minimum illumination, published in different sources, for monochrome CCTV cameras.

I will give you a clear example of extremism - an advertisement from a Russian company “Armo-group”, found in issue №33 of “Security systems, links and telecommunications" (2000). There, it is asserted that the specialised camera LCL902HS (WATEC America Corp.) with a 1/2” CCD sensor and pixel size of 8um X 8um possesses sensitivity of 0,00015 lux, with a lens @F1,4.

An average customer may not understand the real meaning of such claims, as stated in the advertising literature, so I am going to do some basic calculations the way they are done in the science of light engineering - photometry.

There is a well-known formula that describes the number of photons, which participate in the formation of charge packets in the cycle of accumulation on the element (pixel) of the CCD sensor, which is defined as:

$$N_{\phi} = E \cdot S \cdot t \cdot \eta / W_{\phi} \qquad (1)$$

where:

E = illumination, in W/m^2,
S = picture element surface, in m^2,
t = accumulation time, in s,
$W_{\phi} = h\nu$ - photon energy, in J,
$h = 6{,}626 \cdot 10^{-34}$ Js – Planck's constant
$\nu = c/\lambda$ light frequency, in Hz,
$c = 3 \cdot 10^{8}$ m/s speed of light,
λ = light wavelength, in m,
η = quantum efficiency

Let's calculate the illumination energy at the object of observation.

Firstly, let's note that 1 W = 1 J/s. Secondly, 1 W of power of luminous radiation from the source of white light with uniform energy distribution (for example the sun), in the visible spectrum corresponds to the luminance flux of 220 lumens [2]. Hence the conclusion that 1 W/m^2 = 220 lumens.

In other words, two luxes (which is a typical number for minimum illumination at the object, for colour CCTV cameras) correspond to illumination of 9.1×10^{-3} W/m^2.

Such an illumination, which is quantified as 2 luxes, can be detected with a special instrument – called luxmeter, which has spectral sensitivity similar to the human eye's spectral sensitivity (i.e. visible light).

When such an image is projected on the CCD sensor the light energy will be attenuated. The attenuation factor of the photons, after being reflected from the object and projected onto the focusing plane, is derived from the following expression:

$$E_{CCD} = (4 \cdot F^2)^{-1} \cdot E_{object} \cdot \rho \cdot \tau \qquad (2)$$

where,

ρ = reflection factor of object
τ = lens objective transmission factor,
F = lens aperture

For standard measurement conditions of television cameras, the following are typical numbers: the reflection coefficient ρ is approximately = 0.75; transmission τ = 0.85; aperture F = 1.2.

If we replace all the above numbers in (3), under standard conditions, the illumination attenuation when the image of an object is projected onto the CCD imaging plane becomes:

$$E_{object} / E_{CCD} = 4 \cdot (1.2)^2/(0.7 \cdot 0.85) = 9 \text{ times.}$$

Thus, when we have 2 luxes at the object this becomes approximately 10^{-3} W/m^2 at the CCD plane.

Let's now return to the initial formula (1), and let us determine the number of photoelectrons accumulated on the element of the CCD sensor during the standard accumulation time of $t = 0.02$ s (for PAL) with the light energy of $E = 10^{-3}$ W/m^2.

$$N_e = E \cdot S \cdot t \cdot \eta / W_{\phi} \qquad (3)$$

S = is the pixel area of the ½" CCD sensor, which is 8.6 μm X 8.3 μm = 70 □m^2 or $70 \cdot 10^{-12}$ m^2.

The average value of quantum efficiency η for CCD sensor in the visible spectrum is η = 0.7 [3]. The average photon energy in the same spectral range can be determined from the expression:

$$W_\phi = h \cdot 2c \ / (\lambda_{max}+\lambda_{min}) = 6.626 \cdot 10^{-34} \cdot 2 \ \cdot 3 \ \cdot 10^8 / (0.72 + 0.40) \cdot 10^{-6} = 3.54 \cdot 10^{-19} \ Joules$$

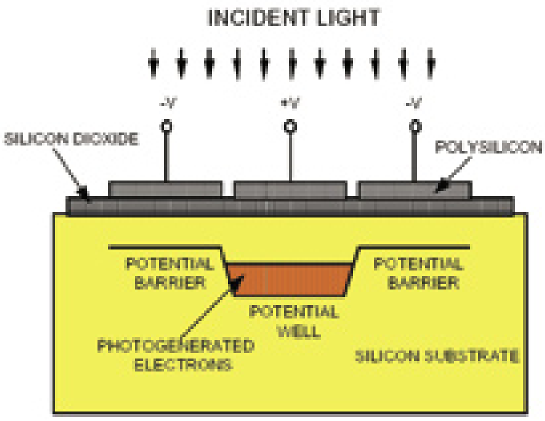
Thus, the average value of the number of electrons in the potential well of the CCD pixels becomes:

$$N_e = E \ \cdot S \ \cdot t \ \cdot \eta \ / \ W_\phi = 10^{-3} \cdot 70 \ \cdot 10^{-12} \cdot 0.02 \cdot 0.7 / 3.54 \cdot 10^{-19} = 2768 \ electrons$$

Let us now compare these calculations with the practice through the analysis of signal-to-noise (S/N) ratio of the output video signal of a camera.

During the photoelectric conversion of the image into electrical signal, the noise is inherent and appears naturally.

Firstly, there is photon noise and secondly, there is inherent noise of the video electronic circuit. The photon noise is a consequence of the discrete nature of light. Any digital process obeys the statistical law of Poisson. The flow of photons also follows these statistics, and according to it the photon noise is equal to the square root of the number of photons. Thus, the S/N ratio in the flow of photons falling onto the CCD pixels, will also be equal to the square root of the number of photons. Consequently, the noise component of charge packets will also be equal to the square root of the average value of the number of electrons in the CCD pixel's potential well [4].



Potential Well and Barriers

In our case, using the previous equation, the number of noise electrons

$$N_{e\_noise} = SQRT(2768) = 52 \ electrons.$$

The noise that is inherent in the CCD is caused by many factors: thermal noise in the semiconductor, noise of charge transfers, the end device noise due to the conversion of charge packets into the voltage at the output stage of the CCD, etc.

In practice, most of the contemporary high-quality CCD sensors, which are widely used in the industrial and applied television, have electron noise quantity of approximately 15 ~ 25 [3].

These are typical numbers and are valid for all CCD crystals, using the CCD technology of converting light energy into voltage.

Let us add this inherent CCD electron noise of 20 units into the Poisson noise of charge packet, and we will get:

$$N_{e\_noise} = SQRT(52^2 + 20^2) = 56$$

It is now possible to calculate the S/N ratio according to the formula:

$$S/N = 20 \log (U_S / U_N)$$

where:
U_S = the signal amplitude,
U_N = the RMS (root mean square) value of the noise.

In our case, U_S = 2768 electrons, and U_N = 56 electrons, i.e., the calculated S/N ratio will be S/N = 34 dB.

Usually, the measurement of the RMS value of the noise is made with the *weighing filter*, which immitates the visual perception of fluctuation interferences, which depends on the energy distribution of interferences across the spectrum. The weighing filter seemingly equalises the power of interferences on the monitor screen, as seen by the human eye. It is experimentally established that the use of the weighing filter is accurate when S/N are higher than 26 ~ 30 dB. This rule is not so accurate with smaller S/N values.

For the uniform spectrum of fluctuation, the attenuation imposed by the weighing filter is 9.2 dB [5].

This means, if the measurements of the RMS noise value are made without the filter, then to the calculated value of S/N one should add 9.2 dB.

In our case, since the calculation of the weighing filter was not considered we should take its influence into account and that will give us:

$$S/N = 34 + 9.2 = 43.2\ dB$$

Now let's go back to the "Philips CSI" catalogue, "CCTV products 2002". One of the highest quality monochrome CCTV cameras we can see there is LTC 0500. The CCD chip is size 1/2", and the number of active picture elements is 752 X 582 pixels; while the S/N (AGC switched off) is 50 dB, with 0.25 luxes on the CCD sensor (with the weighing according to CCIR 576).

From the previous calculations, for analogue CCD sensors we get for the illumination on the chip itself:

$$E_{CCD} = E_{object} / 9 = 2\ lux / 9 = 0.22\ lux$$

where 9 is the attenuating factor of the photon flow when the object image is projected onto the focusing plane of the CCD chip, as calculated in expression (2).

Thus, we obtain the S/N value of 43.2 dB.

So the accurate translation of the 0.25 luxes of illumination produces S/N of 44 dB. This result differs from the practical measurements, given in the catalogue by -6 dB.

Where did we lose the 6 dB during calculations?

In order to find the answer to this, let's solve the inverse problem.

Let's determine the necessary number of photoelectrons in the pixel potential well, which produces signal-to-noise ratio S/N = of 50 dB.

Let us first deduct all additions from the S/N value, i.e. additions which were introduced by the weighing filter:

$$50\ dB - 9.2\ dB = 40.8\ dB$$

Now let's find out what is the ratio that produces 40.8 dB?

By using the formula for S/N we determine this to be a ratio of 110 times. If we square it, we will obtain the number of photoelectrons in the potential well, which produces S/N = 50 dB, and that is 12100 electrons. According to our calculations with the illumination of 2.5 luxes the number of photoelectrons corresponds to 3025.

As we can see, in practice there are four times more electrons.

So where do they come from?

An important fact is that the calculation was made for photons which belong to the visible spectrum.

I should also point out that this is the spectral region of the luxmeter sensitivity as well.

In practice, the spectral characteristic of CCD sensitivity is considerably wider than the eye's sensitivity curve and it is substantially extended in the infrared (IR) region (see fig. 1).

It is a fact that much larger number of photons participates in the formation of the charge packets than was accepted in our calculations. And in our calculations we could not limit the illumination spectrum to the eye sensitivity curve only. However, the calculations were produced for the spectral range where the photometric units of the flux radiation are clearly determined – lumens; and in practice, there is an objective means of measurement of such an illumination – with the use of a luxmeter. Calculating the same for the wider spectrum of radiation is more complicated, and we don't really need to do it to prove our point.

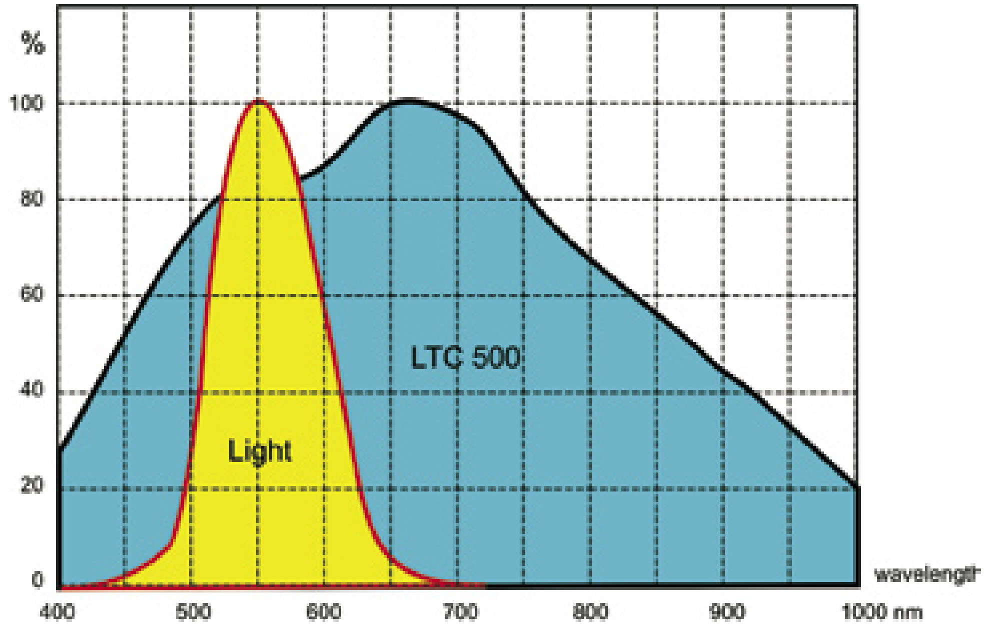


Fig.1 The spectral response of the Philips LTC 500 CCTV camera

Let's now try to determine the additional photoelectrons in the pixel's potential well when the spectral range is extended into the IR range.

Firstly, based on the previous formulas the photon energy falls with the increase in the wavelength λ. Their number increases per unit of power emission with the increase of λ.

Or, more correctly, when there is uniform distribution of spectrum energy of the initial light source it can be interpreted as an increase in the number of photons in the spectrum unit interval.

Secondly, as it follows from the spectral characteristics, an increase in the number of photons with the increase of λ reduces the quantum efficiency with the same increase in the emission wavelength.

Complex calculations and theoretical studies have shown that the number of photoelectrons (with the uniform spectral energy of the light source) in the potential well will increase proportionally to the area under the spectral sensitivity curve of the CCD sensor [6].

Judging by the relation of the area under the normalised eye sensitivity curve and the standardised spectral characteristics of the television camera LTC 0500 sensitivity (Fig. 1), we can see that the area under the spectral characteristic is composed of approximately 39 sections, whilst under the eye sensitivity curve there are approximately 10 sections.

This means the illumination of a uniform energy source and the luxmeter measurements of 2.5 lux illumination will have a ratio of 4:1.

Based on the above it is possible to draw the following important conclusions:

1. The given calculations agree well with the practice.
2. The sensitivity of a black and white (monochrome) CCTV camera with a normalised (corrected) spectral characteristic (which is done with an optical infra red cut filter on the CCD chip) has an inferior sensitivity to a video camera without a filter.
3. The difference in the sensitivity of the video cameras listed in Table 1 depends substantially on the distribution of the spectral density of the original light course.

Let's now perform some simple calculations for the number of photoelectrons in the potential well of the pixels for a 1/2" CCD chip (752 X 582), with and without the IR cut filter. Let's calculate the signal-to-noise ratio with and without the weighed filter, having in mind that the addition of the weighing filter is used when the calculated S/N is higher than 26 ~ 30 dB.

The results are given in Table 2, where the numerator of the fractions is for the video cameras with the standardised spectral characteristic, and the denominator - for the cameras without one.

Table 2

Illumination in lux:	2.0	0.2	0.02	0.002	0.0002
Number of electrons in the potential well	2768 / 11072	277 / 1107	28 / 111	3 / 11	0 / 1
S/N ratio without weighing filter, dB	34 / 39	17.8 / 26.4	1.0 / 11.3	- / -	
S/N ratio with weighing filter, dB	43.2 / 48.2	- / 35.6	- / -		

Let's now return again to the advertisement of the previously mentioned company, in which it is claimed that the specialised camera LCL902HS (by WATEC America Corp.) with a 1/2" CCD sensor and pixel size of 8.6 µm X 8.3 µm works under a minimum illumination of 0.00015 lux, when lens with F/1.4 is used.

From *Table 2* it can be concluded that even if such a video camera possesses such an incredible sensitivity without IR cut filter, in the pixels there will be, at best, **one photoelectron**!

Clearly, there could be no discussion of a video signal in such a case.

Even with the highest level of AGC of the video camera, one electron can not be reproduced as any meaningful information, but rather it will be masked by the inherent noise.

If we were to use Table 2 for further conclusions, we can say that the practical possibilities of typical CCD cameras are limited to the minimum illumination at the object of around 0.15 luxes, where the S/N is approximately 24 dB. **This is the theoretical masking noise limiting value**, above which we can only reproduce and see the so-called "acceptable image" on the monitor.

A further increase of the sensitivity of the video camera is only possible by implementing the technology of photoelectron accumulation, also known as frame integration. It is obvious though that in such a case the time-spatial characteristics of the video camera will be worsened. The camera resolution will be lowered and mobile objects will appear blurred.

This always needs to be considered since in CCTV security systems the time-spatial characteristics are the most important for determining the operator's capabilities to successfully recognise and identify objects.

The process of time-spatial integration of charges in the CCD sensors is effective only if special techniques of sensor noise reduction are implemented. This, for example, can be made by Peltier cooling of the CCD crystal by thermoelectric refrigerating. This is however an expensive and technically complicated task, hardly practical for CCTV surveillance applications.

The moral from all of the above calculations is that in general, in an advertisement it is possible to write almost anything.

However, if somebody is trying to demonstrate high sensitivity of a video camera, one must understand what is practically possible, as well as what could be an error in the measurement.

I will give you one practical example.

It should be known that the light measurement of low levels of illumination (less than 1 lux) is not an easy task.

Modern luxmeters are made of selenium element with conversion factor of millivolt for each 100 luxes.

This means, in the best case, only a minimum illumination of 1 lux can be read. Only with the help of neutral density filters can lower illumination be simulated and measured.

Here is how such a measurement can be done.

A television test chart is placed in front of the camera, for example TITUS 0249.

Then, the chart is illuminated with an incandescent lamp, i.e., by a source of the type “A”. Let’s assume we are measuring 10 luxes illumination from the test chart. The projected test chart onto the CCD sensor is displayed on a monitor, where all camera variables are fixed. Next, the lens objective is shut with ND filters with the coefficients of transmission 0.1; 0.01 and 0.001 (made up of two together). The image projected on the CCD sensor will therefore be equal to 1 lux, 0,1 luxes, 0,01 luxes (using the three different ND filters).

In accordance with the previous calculations above (in Table 2), we should expect that with illumination of 0.01 lux we will see some noise on the monitor. So the video camera should produce images in accordance with Table 2.

And where is the problem?

Back in 2000 I was told about a demonstration of camera sensitivity based on Sony CCD chip ICX055AL. Analysing the spectral sensitivity of a luxmeter and comparing it with the ICX055AL spectral response I was almost convinced that the energy relationships for CCD and luxmeter differ 5 ~ 6 times (Fig. 2)

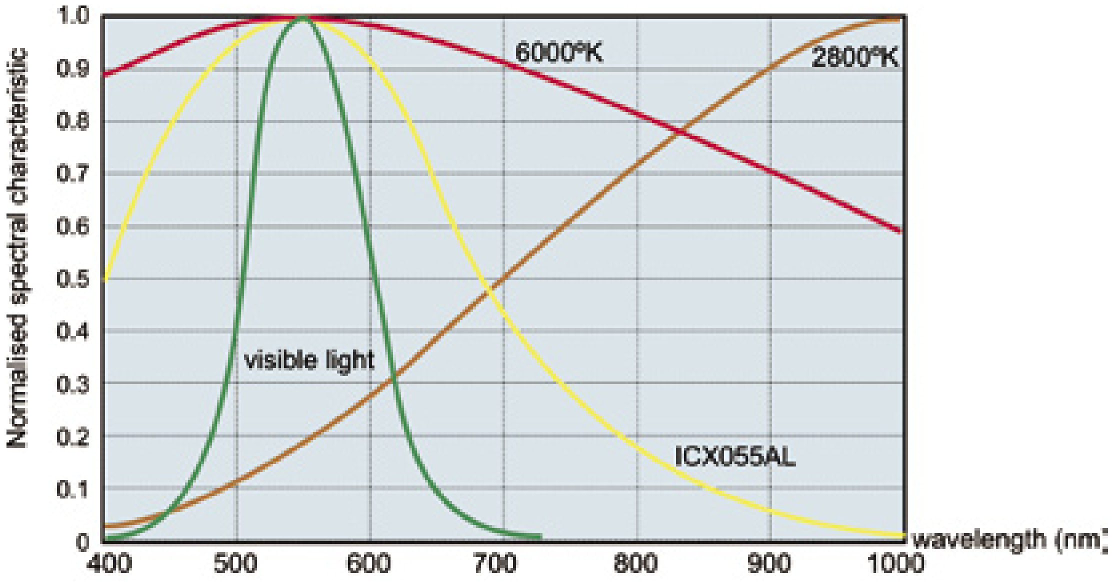


Fig.2 - Spectral characteristics of the sensor and light sources

In other words the spectral characteristics area of the standard light source “A” (the brown curve, @2800° K), has a maximum emission according to the known formula:

$$\lambda_{max} = 2896/T = 1\mu m \ (= 1000 \text{ nm}),$$

When compared to the luxmeter area (the eye sensitivity green curve) the brown curve area (of the CCD sensor ICX055AL) should be around 5 times the surface area of the source “A.”

This would occur as a result of the expanded CCD spectral sensitivity and the linear increase with the increase of wavelength λ, from 400 nm (when the normalised spectral characteristic is 0.05) to 1000 nm (when the normalised spectral characteristic is 1).

I was however being convinced that the video camera has higher sensitivity of more than 5 times.

But, when I checked the spectral characteristics of the neutral filters, everything came into place [7].

Figure 3 represents the spectral characteristics of the neutral filters NC2, NC3 and TC10, with thickness of 4 mm (GOST 9411-91 “Optical coloured glass”).

Filters are intended for work in the visible spectrum and they do reduce the luminous flux in accordance with the specified rating: NC2 - 10 times; NC3 and TC10 - 100 times, in the visible spectrum.

In the other parts of the spectrum (Ultra Violet and Infra Red) ND filters light attenuation is not normalised, and these values can be completely arbitrary.

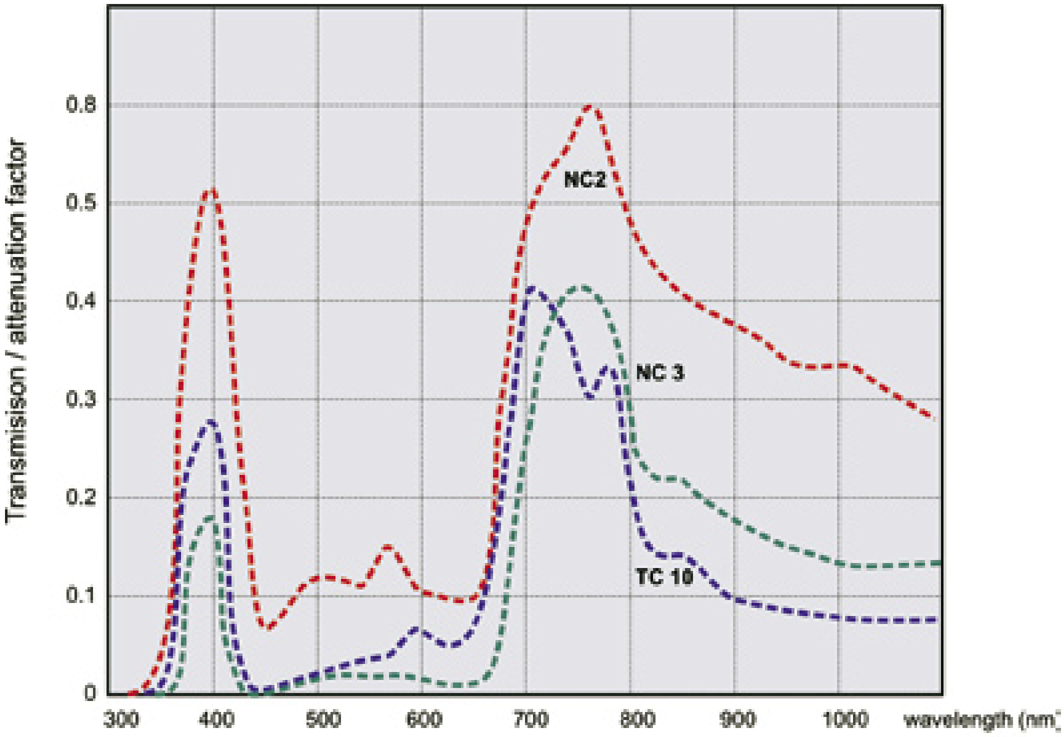


Fig.3 - Spectral characteristics of ND filters

Thus, at 700 nm, where the CCD sensor has maximum sensitivity (see Fig.1), the coefficient of transmission is equal to 0.5 for NC2, which means the luminous flux is attenuated only 2, not 10 times.

But for NC3 the coefficient of transmission is equal to 0.3 and the luminous flux is attenuated 3.3.

When adding ND filters, the expected 1000 times attenuation of the luminous does occur only in the visible spectrum. Outside this range the attenuation of luminous flux is significantly less, so at wavelengths of around 700 nm the attenuation is 6 -7 times.

The above proved that the experimenters that were telling me about this measurement of the above mentioned chip unknowingly introduced an error in their experiment and consequently "proved" the very low sensitivity of the CCTV camera.

In conclusion, I can say that the secrets of the "impossibly" high sensitivity in CCTV cameras are practically always connected to either unconscientious advertising or experimental measuring errors.

I hope that this article will help you become more aware about sales people trying to grab your attention by very low lux numbers on their cameras. [•]

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