Aperture and Digi scoping.

Thoughts on the value of the aperture of a scope – digital camera combination.

Before entering the heart of the matter, let's do a few reminders.

1. Entrance pupil.

It is the image of the diaphragm given by the forward part of the optical system located upstream of the diaphragm itself. For a lens at full aperture, this pupil of entry corresponds to the front lens of the optics. Its diameter is equal to that of this very same lens.

Entrance pupil at full aperture f/1.8

Entrance pupil at f/5.6

For a spotting scope without a diaphragm, it will always be the front lens. Its diameter is equal to the diameter of it.

2. Exit pupil.

It is the image of the diaphragm given by the aft part of the optical system located downstream of the diaphragm itself. For a lens at full aperture, this exit pupil is the image of the front lens given by the back lens.

Exit pupil at full aperture f/4

Exit pupil at f/16

For a spotting scope without a diaphragm, it is the image of the front lens given by the eyepiece. Remember that its diameter is defined by the ratio of the diameter of the front lens to magnification. For a scope which the front lens measures 80 mm of diameter and possessing an eyepiece with a zoom of25-50 x, the exit pupil measures 80/25 = 3.2 mm at 25 x and 80/50 = 1.6 mm at 50 x.

3. Diaphragm.

An optical system always has an aperture, whether a lens (or its mount) or an independent diaphragm.

On a spotting scope, the aim is to let a maximum amount of light through the instrument. Therefore, it will be built so that the diaphragm is the largest lens. It will be always the front lens. As it has a fixed size, the amount of light that passes through it is constant and cannot be modified by the user.

Let's take the example of the above scope. Using the formula for magnification, we can calculate the focal lengths equivalent to two extreme magnifications.

$G_{lens} = \frac{F}{50}$ or $F = G_{lens} \: x \: 50$ with F = focal length

So : at magnification of 25 x, the equivalent focal length is 25 x 50 = 1250 mm
at magnification of 50 x, the equivalent focal length is 50 x 50 = 2500 mm

Similarly, with the formula of lens aperture diameter, we can calculate the equivalent aperture at the two extreme magnifications.

$\Phi_{ouv\ diaph} = \frac{F}{f}$ ou $f = \frac{F}{\phi}$ with F = focal length
f = aperture

So : at magnification of 25 x the equivalent diaphragm is 1250/80 = 15.6 (f/16)
at magnification of 50 x, the equivalent diaphragm is 2500/80 = 31.25 (f/32)

In photography, the problem is different. The opening having an influence on the depth of field (Dof) and the exposure time, one wants to control it as a function of the desired effect. Therefore manufacturers place within the lens a physical diaphragm with an adjustable diameter which will serve as the aperture opening.

In the case of the camera lens, the diaphragm opening consists of an opaque plan with a hole formed by mobile slats (iris diaphragm). It is of variable size and makes it possible to modulate the amount of light that reaches the film or digital sensor. The aperture opening is the setting that allows varying the diameter of the diaphragm. The opening number (N) is a dimensionless number that is characterized by the ratio of the focal length f to the diameter of the entrance pupil d.

$N = \frac{f}{d}$

You will notice that the variables characterizing the focal length, aperture or f/number, and pupil of entry have changed to fit the language more commonly accepted in photography.

We see that at constant focal length, the diameter of the entrance pupil (or diaphragm) decreases if the aperture number increases and vice versa. Manufacturers always provide the maximum available aperture opening. It is also called smallest usable aperture.

f / 2.8 f / 4 f / 5.6 f / 8 f / 11

The diameter of the diaphragm opening has an influence on various more or less important phenomena for the photographer.

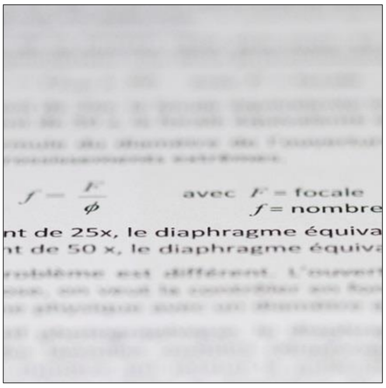
A. The depth of field (Dof)

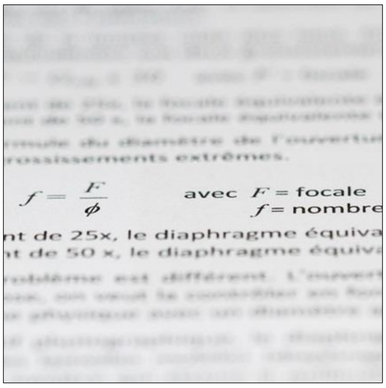
It is related to the opening of the diaphragm by

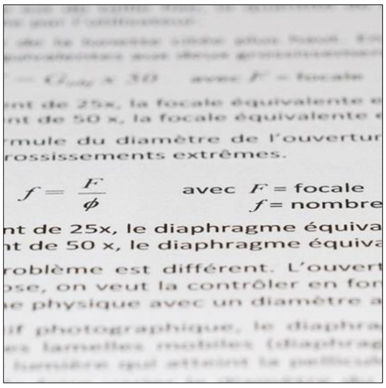
$$Dof = \frac{2 \cdot N \cdot c \cdot D^2}{f^2}$$

with
N = Aperture number
D = focusing distance
f = focal length
c = confusion circle

Therefore, at constant focal length and for a subject at same distance from the camera, depth of field increases as the diameter of the diaphragm decreases. Similarly, we can say that if the aperture number increases, the depth of field also increases.







These three pictures have been taken with the same lens (a fixed focal length of 150 mm), the same exposure time of 1/125 and at the same focusing distance. Only the aperture is modified

f/2.8 f/4 f/8

B. The vignetting.

It is the darkening of edges and especially photography angles. Usually just closing the diaphragm by one or two stops will correct this annoying effect.

C. Chromatic aberration.

It results from the variation of the refractive index of the material of construction of the lenses in function of the wavelength of the light that passes through. Yet the different colors that make up the light have different wavelengths. Chromatic aberration causes a loss of sharpness but by iridescent contours of different colors (blue, red or green in most cases) in the image.

Chromatic aberration causes green and red iridescent contours on the edges of the leaves.

The same picture on which chromatic aberration has been corrected

D. The sharpness.

Used in photography, it translates the quality of detail in an image. The higher the sharpness is, the more the photo will appear to be clear. One will often observe the following effects (be careful, these and particularly the aperture number values can vary depending on the optical characteristics of your lenses):

a. Sharpness is not optimal at full aperture.
b. It peaks at around f/5.6.
c. It goes down to the center but increases at the edges of the image at about f/8.
d. It continuously decreases beyond f/11.

In conclusion, remember that :

- Closing the diaphragm increases the depth of field.
- The vignetting is very marked (the quality is low) at the large openings. It is often negligible from f/4.
- Chromatic aberrations are reduced (the image quality is great) when closing the diaphragm.
- Sharpness is usually maximum 2 or 3 stops above of the largest opening. Before and after it drops.

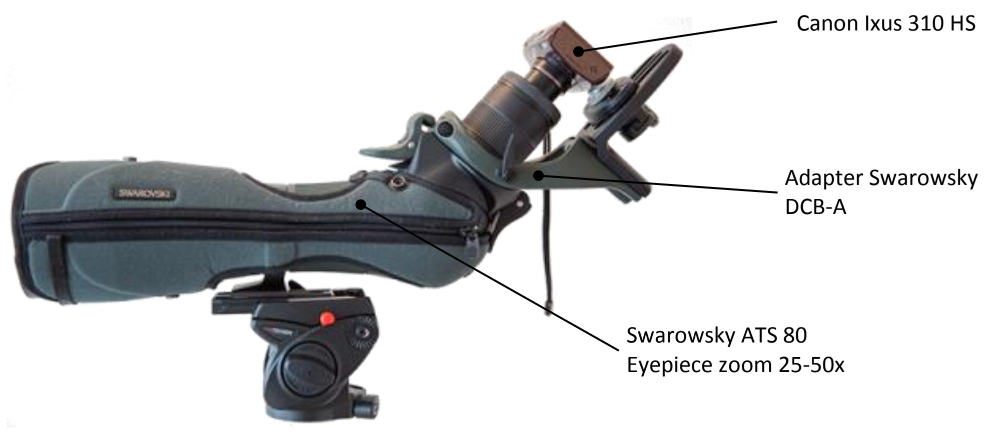
The scope associated to a digital camera.

1. A compact digital camera.

For example, an 80 mm diameter telescope equipped with an eyepiece 25-50 x zoom. Calculate the diameter of the exit pupil to different magnifications which will be used further in the rest of the discussion.

- Magnification 25 x, the diameter of the exit pupil is 80/25 = 3.2 mm
- Magnification 36x, the diameter of the exit pupil is 80/36 = 2.2 mm
- Magnification 40 x, the diameter of the exit pupil is 80/40 = 2.0 mm
- Magnification 50 x, the diameter of the exit pupil is 80/50 = 1.6 mm

We will add a compact digital camera, namely a Canon Ixus 310 HS. We will have to adjust it to its focal length equivalent to 50 mm on full format 24 x 36. How do we do it ?

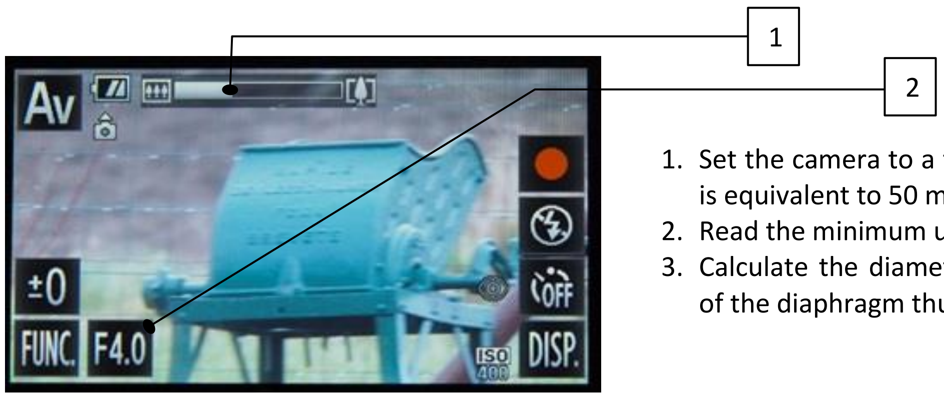


A. The manufacturer mentions the camera focal lengths equivalent to a full frame in the specifications: ***24 - 105 mm***

B. The manufacturer mentions the size of the sensor (1/2.3 "diagonal) and the actual focal lengths of the camera zoom (4.3 – 18.8 mm). Therefore, we need to calculate the correction factor inherent in the size of the sensor to determine the equivalent to full frame focal lengths.
Beware, the thumb ("") used is not a 'normal' inch of 25.4 mm but well of 16 mm (don't ask me why, I don't know). So the diagonal of the sensor measures 16 x 1/2.3 = *6.95 mm*. and the one of a full frame sensor $\sqrt{\left(24^2+36^2\right)}$= *43.26 mm*. Therefore, a correction factor of 43.26/6.95 = *6.22* needs to be applied. This allows us to evaluate focal lengths equivalent to a full frame from the actual focal length: 6.22 x 4.3 = ***26.74 mm*** and 6.22 x 18.8 = ***116.93 mm***. The result is still pretty inaccurate especially at higher focal length.

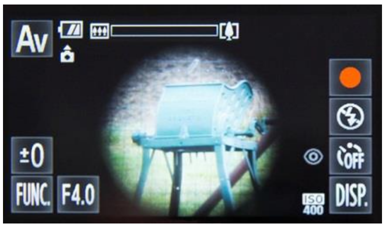
C. The manufacturer mentions the size of the sensor (L = 6.18 mm and l = 4.55 mm) and the actual focal lengths of the camera zoom (4.3 – 18.8 mm). The diagonal of the sensor than measures $\sqrt{\left(4.55^2+6.18^2\right)}$ = *7.67 mm*. A correction factor of 43.26/7.67 = *5.64* needs now to be taken into account. This allows us to evaluate focal lengths equivalent to a full frame from the actual focal lengths : 5.64 x 4.3 = ***24.25 mm*** and 5.64 x 18.8 = ***106.59 mm***. This result is much closer to the focal lengths reported by the manufacturer.

Once this is done, proceed as follows:



1. Set the camera to a focal length of 8.8 mm which is equivalent to 50 mm on a full frame (50/5.64
2. Read the minimum usable aperture number (f/4)
3. Calculate the diameter of the entrance pupil (or of the diaphragm thus) : 8.8/4 = 2.2mm

By comparing this entrance pupil to the exit pupil of the scope, we see that, at full opening, until the magnification of 36 x, the system is diaphragmed by the camera at f/4. Beyond 36 x, it's the scope that diaphragms the camera. The real opening is then 8.8/2 = f/4.5 at 40 x for example and 8.8/1.6 = F/5.6 at 50 x.



Setting the focal length to the equivalent of 50 mm full-frame has several advantages. It retains the magnification of the scope and avoids vignetting. At lower focal length, the magnification of the scope will be reduced by a factor worth its value divided by 50 (36 x will become 24 mm focal length 36 x (24/50) = 17.2 for example). Also, the field of view of the lens is so wide that we are seeing a significant vignetting that cannot be corrected even by closing the diaphragm. To a higher focal length, the diaphragm diameter will decrease so that the exposure time will increase significantly (causing motion induced out of focus) or you will have to increase the ISO (increase of still acceptable noise up to 400 ISO and difficult to treat beyond)

Up to 36 x magnification, the system is masked down by the camera at f/4. We see on the left side a photo taken with aperture (Av) priority at f/4 at 25 x magnification. We then get an exposure time of 1/125 of a second. On the right side the same photo this time at 36 x magnification, results in an exposure time of 1/160 second very close to 1/125 of the other image. This tends to prove that the diaphragm of the system does not change from one to the other.

Finally still the same picture but this time at 50 x magnification. The scope masks down the camera at f/5.6 increasing the exposure time to 1/40 of a second. We can eliminate camera shake out of focus with an increase in ISO with once again an increase in noise difficult or impossible to manage. Finally let's not forget that it is advisable to aim at an exposure time at least equal to the inverse of the focal length to avoid, precisely, out of focus images (at 25 x, the exposure time should be 1/1250 second and at 36x, 1/1800 !). This is very difficult to obtain, so let us aim for as short as possible exposure times.

2. A digital SLR.

For example, an 80 mm diameter telescope equipped with an eyepiece 25-50 x zoom. Calculate the diameter of the exit pupil to different magnifications which will be used further in the rest of the discussion.

- Magnification 25 x, the diameter of the exit pupil is 80/25 = 3.2 mm
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- Magnification 50 x, the diameter of the exit pupil is 80/50 = 1.6 mm

We will add a Canon EOS 600D. It is advisable to equip it with a 50 mm fixed focal length lens (again with its magnification of 1x, it will not affect the magnification of the scope) as bright as possible. Do not really look for an expensive very bright lens (a 50 mm f/1.2 for example). We use here the Canon EF 50 mm f/1: 1.4 (an f/1.8 will still perfectly do). It will be set in manual focus to infinity.

The diameters of the lens aperture are:

- at f/1.4 → 35.7 mm
- at f/2.8 → 17.8 mm
- at f/5.6 → 8.9 mm
- at f/8 → 6.2 mm
- at f/11 → 4.5 mm
- at f/16 → 3.1 mm
- at f/22 → 2.2 mm

So we see that, up to a camera aperture of f/16, the pupil of entry of the lens remains larger than the exit pupil of the scope. We can assume that this system will be always stopped down by the scope at constant aperture of the SLR up to f/16.

f/ SLR	Scope magnification	Exposure time	f/ scope SLR	f/ SLR	Scope magnification	Exposure time	f/ scope SLR
1.4	25x	1/80	16 → *19*	**2**	25x	1/40	*26*
	36x	1/60	22		36x	1/30	*32*
	50x	1/40	32		50x	1/15	*45*
2.8	25x	1/20	*36*	**4**	25x	1/10	*51*
	36x	1/15	*45*		36x	1/8	*63*
	50x	1/8	*63*		50x	1/4	*90*
5.6	25x	1/5	*73*	**8**	25x	1/25	*103*
	36x	1/4	*90*		36x	1/2	*125*
	50x	1/2	*125*		50x	1	*178*

1. Between the exposure time at 36x and 50x for all apertures of the camera, there is a difference of 1IL as expected. However between 25x and 36x, there is only a 0.5IL difference. This tends to indicate that f/16 is a bit too optimistic. It is closer to f/19 at 25 x magnification.
2. Every closing of the diaphragm by one stop obviously results in a reduction in overall telescope/camera of 1IL. This leads to diaphragms for the combination scope/SLR that will quickly complicate the exposure. This disadvantage can be compensated by a lengthening of the exposure time or an increase in the sensitivity of the sensor (higher ISO). The first solution has a bad influence on strong out of focus especially at large focal lengths. The second will significantly increase high ISO noise.
3. In terms of depth of field, it is assumed that the limiting factor will be the aperture number of the SLR. Indeed relatively small diaphragm diameters of the scope give a significant depth of field to start with.

In conclusion, it is better to work at full aperture in order not to get too long exposure time by keeping a maximum of 800 ISO. Resulting noise is still very well managed by the entry-level DSLRs. If the need arises to expand the depth of field, it is recommended not to close the diaphragm more of two stops.

3. Special case of the TLS APO of Swarowsky.

The TLS APO 30 mm lens was designed by Swarowsky to form a complete system with the new spotting scopes ATX/STX. It can also be used with the older scopes that are the ATS/STS with a supplied adapter.

It has no adjustable diaphragm. Its construction is such that its very small front lens stands almost exactly at the eye relief distance of the scope. Finally, his pupil of entry (or fixed diaphragm) has a diameter of about 3.5 mm. It remains in all cases of magnification larger than the exit pupil of the scope. Therefore, we can say that the SLR will always diaphragmed by the scope to values ranging from f/16 (or f/19) to f/32 depending on the magnification used.