The *Binocular Summation Factor* and its relevance for Deepsky Observing

Part 1, Scientific Background

by Arie Otte

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Abstract
Large-mirrored binoscopes are rare and amateur astronomers wonder about their benefits for deepsky observing. This often ends with one question only: *how large are the two mirrors of a binoscope in comparison with a single, larger mirror?* The theoretical answer to that question is partly dependent on the quantitative value of the so-called ***binocular summation factor***. In part 1 of this article I'll address historic and scientific aspects of this factor as well as controversies about its value. Both the factor and its value are often misinterpreted by amateur astronomers. From the scientific literature regularly a value of 1.4 emerges, which can be interpreted as if one should multiply the aperture of a single mirror (or lens) to obtain the equivalent aperture of a two-mirrored binoscope (or binocular). However, a popular view is that one must multiply the aperture of one mirror with a substantial lower factor of 1.19 to obtain the two-mirror equivalent. This discrepancy in interpretations is largely due to a complete lack of solid data. I have therefore directly compared a 2 x 13 inch binoscope with a 16 inch mono-mirrored telescope in order to directly determine the binocular summation factor. In part 2 of the article I'll describe the results. There, I'll discuss the relevance of the binocular summation factor in the context of other aspects of binocular vision.

Introduction

How can one compare a large-mirrored binoscope with a 'mono-telescope' that has a larger mirror? Binoscope owners may stress the increased signal to noise ratio you achieve by looking through a binoscope, resulting in an enhanced contrast of the images. This, however, appears not to provide a satisfactory answer. Instead, people, who have never looked through a binoscope, want to know how one can calculate the ***equivalent aperture*** of the two binoscope mirrors. So, for example, if you have two 13 inch mirrors, adding up the surface areas equals a single, ~18 inch mirror. But what if it were not the case that you see as much with this 2 x 13 inch binoscope as with a single 18 inch mirror? Why then bother and not simply buy an 18 inch mirror with which you can see ***more*** than with 2 x 13 inch mirrors? This is a fair concern, since a lot of money or building effort is involved.

A logical assumption would seem to be that 'one plus one equals two', meaning that you can see twice as much with two eyes than with one eye. A little reflection shows, however, that this cannot be true. When you close one eye during day light, it is obvious that you still see more than just 50% of before closing the one eye. Possibly you see with one eye even as much as with two eyes, except for the lack of depth, which is caused by parallax. It is only when light is dim and objects are visible at threshold levels that one start to note a difference between viewing with one or two eyes. This phenomenon has been the subject of a long history of vision research. This scientific research is in particular medical oriented. Naturally the question is of importance in cases of (partial) blindness to one eye, caused by accident or disease. Beside these practical, medical aspects, there is also a long standing interest into the theoretical aspects of 'binocular' vision versus 'monocular' vision. A lot of this research revolves about the question of how one could quantify the differences of viewing with one or two eyes. In a lot of quantitative models the ***binocular summation factor*** and its quantitative value plays a central role.

Binocular summation factor

Binocular summation is the process by which the brain combines the information that they get through incoming signals in the left and right eye. By means of binocular summation the threshold value for the detection of faint objects is lower with two eyes than with one eye. Statistically there is an advantage for the detection of a weak signal when two detectors are used instead of one detector. This advantage is √2, or 1.4, called the ***binocular summation factor***. On Bruce Sayre's website an excellent lecture given by dr. Thomas Salmon is quoted. In this lecture the theory is summarized.

Early experiments tried to pinpoint the advantage of binocular vision quantitatively (Pirenne, 1943). It was shown that with binocular detection a faint light signal is 1.4 times better observed than with monocular detection. The theory that was based on these early experiments is called the ***probability summation*** theory. To give an idea how such experiments were performed and interpreted, I'll summarize some of the findings. Pirenne used flashes of light with different brightness, for the duration of a few milliseconds. The observed frequency of seeing the flash of light were noted for the left eye only, for the right eye only and for both eyes. Here is one telling example (Pirenne, 1943):

Observed frequency of seeing

Left eye	25/125 = 0.198
Right eye	71/275 = 0.258
Both eyes	62/164 = **0.378** (this is a factor 1.66 better than the average of left/ right frequencies)

Now assuming that the probabilities of seeing signal with the left eye (P_l) or the right eye (P_r), are independent, one can predict the probability of seeing with both eyes (P_b). The definition of probability of detection this signal with both eyes is: $P_b = P_r + P_l – (P_r \times P_l)$. If the above observation for the left and right eyes are calculated, $P_b = 0.198 + 0.258 – (0.198 \times 0.258) =$ **0.405**. This is pretty close to the observed **0.378**. When the above and other experimental data are plotted, the figure below emerges. The B line is calculated from the observation values for the left (L) and right (R) eyes. At log brightness 1.0, the above explained example is plotted.

There are a couple of things to note. The observed frequencies with both eyes closely fit the predicted probabilities that were calculated with the formula above. Hence it was concluded that the increased probability of seeing with both eyes (the open circles in Fig. 1) can be explained with a statistic summation only and that no other, physiological fusion mechanism in the brain has to be responsible. Or, in other words, the two eyes are just seen as independent detectors. Here the term ***probability summation*** theory stems from.

A second point I want to stress is that the curves for the left and right eye differ significantly. Although this can be expected for two different eyes with different sensitivities etc., this point will come back later.

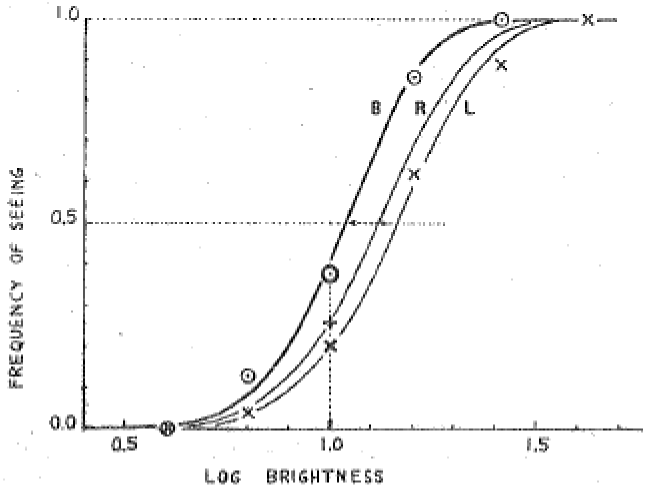

Figure 1. Pirenne's experimental data that fit the **predicted values** for the increased probability of seeing a light flash with two eyes (B), as compared with the **observed** frequency of seeing with the left (L) or right (R) eye only. The circles through which the B line runs, are the calculated Pb values.

Finally, the increased probability of seeing with both eyes depends highly on the brightness of the stimulus. In Salmon's notes, he arbitrarily used a probability of 0.6 of seeing with each eye. That means that the total probability for two eyes is 0.6 + 0.6 – (0.6 x 0.6) = 0.84. That is 1.4 times more than 0.6, so here we have the much quoted √2 or 1.4 large ***binocular summation factor***. However, the probability of detection could be anything, depending on what the person is looking at. If it is very difficult to see an object, the probability of detection would be very low, for example 0.1. If the object is easily visible, the probability would be nearly 1.0. In the introduction I referred in this context to binocular vision during daylight. If you look during daylight at a bright object, it won't matter much whether you look at it with one or two eyes. So the probability will be 1.0. That means that a total probability for seeing with both eyes is 1.0 too (namely 1.0 + 1.0 – (1.0 x 1.0) = 1.0). So it is only at increasingly dimmer lights that the probability for seeing with both eyes will become higher. For instance, when the probability for each eye is 0.3, the probability for seeing with both eyes is 0.3 + 0.3 – (0.3 x 0.3) = 0.51. This is a factor 1.7 larger than the probability of seeing with one eye only. These trends are also visible in figure 1.

Generally, when vision scientist conduct experiments to determine the threshold for detection, they often use a value of 0.5. Why? Since there is not a clear intensity level that you can call a "threshold," they **arbitrarily** define the threshold as the intensity at which you get a 50% probability of detection or 0.5. The probability that two eyes detect the signal is now 0.5 + 0.5 – (0.5 x 0.5) = 0.75. And now we have a 1.5 factor increase as compared to the 0.5 probability of seeing with one eye only.

So the much quoted 1.4 binocular summation factor is in fact largely dependent on how dim the observed objects are. This value coincides exactly with the increase in aperture diameter of two mirrors. Take for instance my two mirrors with a diameter of 13 inch each. The surface of each mirror is or $\pi(1/2d)^2$, or ~132.6 inch^2. The combined surface of the two mirrors is thus ~265.3 inch^2. And this is equivalent to one mirror with a diameter of ~18.4 inch. And that is exactly a factor √2 or 1.41 larger than my 13 inch mirror diameter. Hence the following formula could be used to determine the equivalent aperture of a larger mono-mirror, in comparison with two smaller mirrors in a binoscope.

$$\sqrt{(A^2 \times 2)}$$

Here, the A stand stands for the aperture or diameter of the mirror.

Binocular summation, binocular facilitation and other aspects of binocular vision

It is known that many visual cortical neurones are binocularly connected in higher primates. Since there exist functional and physical interactions between visual neurones from the two eyes it is hard to believe that statistics and probability are the only explanation for binocular summation. So while the probability summation theory is still perceived in the scientific literature as a valid approach, there are additional factors that influence the value of the binocular summation factor. For instance, there are conditions, in which the increase in binocular sensitivity is greater than could be explained by probability summation alone. Optimal summation occurs when 1) corresponding points on the two retinas are stimulated with like targets or stimuli, and 2) when the stimuli are presented to the two eye simultaneously, or at least within ~100 msec of each other. In these cases the activity of the brain is enhanced more than the sum of both brain activities that are provoked by each one eye separately. If there is any advantage ***above*** the mentioned binocular summation factor of 1.4, this is attributed to this mechanism, which is called ***binocular facilitation*** or ***neural summation***.

Furthermore, Campbell and Green (1965) provided another explanation of why binocular summation should lower the visual threshold by a factor of 1.4. They argue that by combining the input from two eyes, neural signals would be added while background neural noise (assumed to be random and uncorrelated) should partially cancel. They predicted and measured that this process alone would cause binocular thresholds to be lower by a factor of √2 or 1.4 (Figure 2).

Therefore, the often recurring 1.4-fold improvement in visual function could be explained by either ***probability summation***, an ***increase in signal-to-noise ratio*** or ***neural summation***. Any improvement by more than this 1.4 fold would indicate that neural summation or some other form of physiological summation is involved.

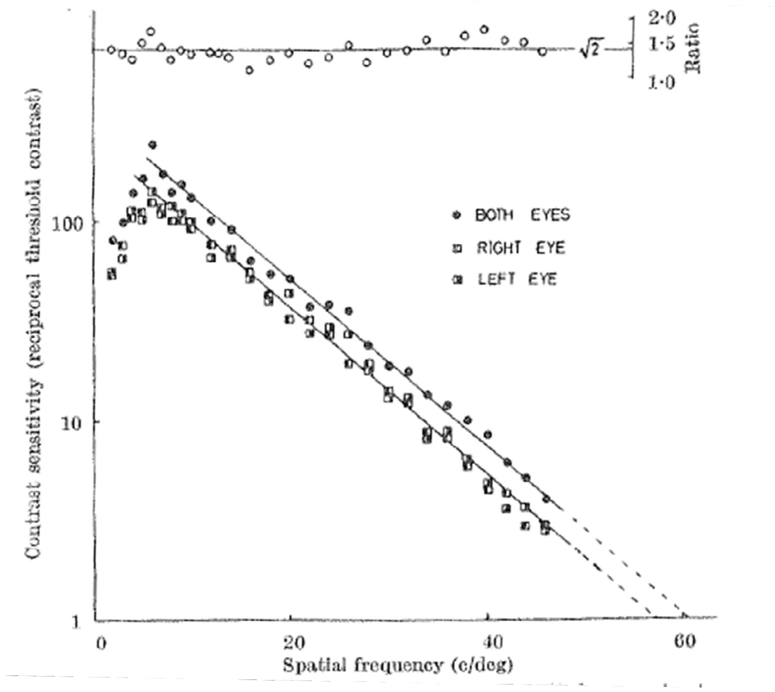

Figure 2. Campbell and Green (1965) contrast sensitivity tests. The open circles at the top represent the binocular/ (mean) monocular sensitivities. The straight horizontal line is the average of these ratios at different spatial frequencies, which is √2! (In fact 1.418 ± 0.021 for three experiments with two different people).

Since these landmark studies, a lot of scientific research has been conducted concerning binocular versus monocular vision. At least five different models have been proposed (Meese et al, 2006) to explain binocular summation. Sometimes experiments are conducted that show that binocular summation exceeds the factor √2 (Meese et al, 2006) But as far as I can tell, no simple interpretation has come forward as yet. There are a number of reasons for that.

1. Methodologies range widely, signifying that it is not an easy task to design experiments that unequivocally address and resolve the issue properly. One experiment might have let subject dark adapt for 30 minutes, but another might have dark adapted for only 10 minutes. In one experiment, the dim light may have been presented for just 1 second, but in another, for 5 seconds. All these variables can affect results and the protocols used are far from standardized. In my case of estimating limiting magnitudes (see below) it is of importance that my eyes have to be well dark-adapted in order to detect the weakest star possible. This usually takes at least 15 to 30 minutes.
2. Aspects of vision such as the detection of threshold levels of light, contrast or resolution benefit to a different extent by binocular vision. A point source would be perceived only by a small area of the retina, but a larger source would include areas of the retina that might respond differently. For example, the physiology of the central 1° of vision is very different from that a few degrees peripherally. This makes 'fixing' one single binocular summation factor for all these aspects also a difficult affair.
3. Our two eyes are rarely identical, this can already be seen in the 1943 Pirenne data. The 1.41 factor may only be valid when both eyes are equally sensitive and optimal. But it will in the extreme decrease to 1 when one eye has no sensitivity at all (Nelson-Quigg et al., 2000).
4. In a number of studies large differences are reported between individuals. The spread is so large that one study concludes that there may be not a single binocular summation constant at all (Frisen and Lindblom, 1988). They also concluded that the degree of binocular summation is related to the complexity of the visual task. For instance, they found that the binocular summation factor was significantly smaller in resolution tests than in detection tests. Similarly, when a parameter such as contrast is taken as read-out, the resulting binocular summation factor is higher than the often quoted 1.4 (Meese et al, 2006).
5. It is telling that some scientific papers use more accurately phrases such as "the √2 ratio of binocular to monocular **contrast** sensitivity" (Anderson and Movskon, 1989). Or "the binocular summation (the ratio of binocular to monocular **contrast** sensitivities at threshold) is ~1.7" (Meese et al., 2006). In these statements, the read-out, being resolution, detection or contrast sensitivity, is directly coupled to the 'type' of binocular summation factor that is referred to.

Interpretations of the binocular summation factor by amateur astronomers

How has the √2 value for the binocular summation factor been perceived by the amateur astronomy community? In most instances the reasoning is simple: just add the two areas of the mirrors, so the binocular summation factor is √2 or 1.41. But others say no, this is not the way things work. For instance Ed Zarenski on Cloudy Nights (Zarenski, 2006) states this: *"these factors are applied on the aperture delivering light to each eye, not the total area of the two apertures delivering light to both eyes. What I mean is this; you would not add the area of two 70mm lenses to get 4900 + 4900 = 9800, then take the √9800 to find total light delivered from a total 99mm aperture. The light is delivered from a 70mm aperture to each eye. The binocular summation factors are applied to that 70mm aperture".* Thereby he implies that two 70 mm lenses are not equivalent to $\sqrt{(\mathbf{A^2 \times 2})} = \sqrt{(70^2 \times 2)} = \sqrt{(4900 \times 2)} =$ 99 mm but to $\sqrt{(\mathbf{A^2 \times 1.41})} = \sqrt{(70^2 \times 1.41)} = \sqrt{(4900 \times 1.41)} = 83.2$ mm. So instead of multiplying the diameter of the mirror by √2, the diameter is multiplied with a factor of √1.41 or 1.19. This would imply that my 2 x 13 inch mirrors are equivalent to a ~15.5 inch mono telescope instead of ~18.3 inch. Unfortunately Zarenski does not provide any background information for his claims. He simply states over and over again that other interpretations are wrong.

This interpretation is restricted to the rather small audience that visit internet forums such as Cloudy Nights. Unfortunately, it has been taken to a wider audience by Phil Harrington in his book Cosmic Challenges (Harrington, 2011). He takes over Zarenski's interpretation and uses the formula

$$\sqrt{(A^2 \times 1.41)}$$

He uses this formula to calculate the equivalent telescope aperture of a number of binoculars and simply multiplies the aperture of one lens with 1.19 instead of 1.4. Also in this book no explanation on the background of the formula is given, it just is there.

Conclusions

Scientific research into the relevance and the value of the binocular summation factor has a long history. It is clear from the extensive literature that it is very hard to assign an exact and single value to this factor. This may not be surprising given that binocular vision involves many different aspects. Not only the physical components of the eyes, but also complex neural processes play key roles in binocular vision. Therefore, one single binocular summation factor is probably not sufficient to cover all aspects of binocular vision. Furthermore, there is an amazing range in how different individuals perceive aspects of binocular vision. Therefore utmost care must be taken with generalizing conclusions. In particular sweeping statements and simple formulae to compare binoculars (or two binoscope mirrors for that matter!) to one larger mirror are almost certainly misleading at best. This, however, appears to be the unsatisfactory status in amateur astronomy. One way out of this could be to directly compare a large binoscope with a large mono-telescope. At least for point light sources, i.e. stars, one can determine the limiting magnitudes and from that calculate the binocular summation factor for that specific situation. In part 2 of the article I'll present such direct measurements. In part 2 I'll also address the relevance of the binocular summation factor for deepsky observing, in comparison to other factors that favour binocular viewing.

Acknowledgements

A number of people commented on the questions that I sent them. Those questions concerned the binocular summation factor and its relevance for visual observations of deepsky objects. I want to thank them for their time to write me back and share their views and insights with me. In alphabetic order those are Phil Harrington, Bruce Sayre, Gary Seronik and Mark Suchting. I am particularly indebted to Mel Bartels, Jan van Gastel and Dr. Thomas Salmon. They were very supportive and encouraged me to continue searching the literature and their comments eventually shaped the contents of this article. Mel Bartels also suggested to directly measure the limiting magnitudes and allowed me to cite his results.

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The *Binocular Summation Factor* and its relevance for Deepsky Observing

Part 2, Measurements to determine the Value of the Factor

by Arie Otte

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Abstract
Large-mirrored binoscopes are rare and amateur astronomers wonder about their benefits for deepsky observing. This often ends with one question: *how large are the two mirrors of a binoscope in comparison with a single and larger mirror?* The theoretical answer to that question is partly dependent on the quantitative value of the so-called ***binocular summation factor***. In part 1 of this article I addressed historic and scientific aspects of this factor as well as controversies about its value. Both the factor and its value are often misinterpreted by amateur astronomers. This is largely due to a complete lack of solid data. I have therefore directly compared a 2 x 13 inch binoscope with a 16 inch mono-mirrored telescope in order to determine their respective limiting magnitudes. Here, in part 2 of the article I describe the results. These allowed me to calculate that the binocular summation factor, specifically for point light sources such as stars, ranges between 1.4 and 1.5. However, on extended objects, such as galaxies, the factor is larger, may be as high as 1.8. I further discuss the binocular summation factor in the context of other aspects of binocular vision.

Introduction
How can one compare a large-mirrored binoscope with a ‘mono-telescope’ that has a larger mirror? As explained in Part 1 of the article, the ***binocular summation factor*** and its quantitative value plays a central role in how to compare the two mirrors to one larger mirror. The scientific literature is very careful in assigning a single value to the binocular summation factor and its interpretation. In the amateur astronomy community a prevailing view is put forward by Zarenski (2006) on Cloudy Nights and Phil Harrington in his book Cosmic Challenges (Harrington, 2011). They assign a simple formula to the comparison between two mirrors compared to one larger one. Their formula is $\sqrt{(A^2 \times 1.41)}$. Here, A stands for the aperture of one binocular lens (or binoscope mirror). This, in short, says that one must multiply the diameter of one lens/ mirror with a factor 1.19 to obtain the diameter of a comparable single lens/mirror. This 1.19 in fact represents the value of the binocular summation factor and this is at odds with most of the values that have been assigned to the binocular summation factor in the scientific literature. These go back as far as 1943 (Pirenne, 1943) and 1965 (Campbell and Green, 1965) and they commonly range between 1.4 and 1.7.

One way to address this controversy is to directly compare a large binoscope with a large mono-telescope. At least for point light sources, i.e. stars, one can determine the limiting magnitudes and from that calculate the binocular summation factor for that specific situation. Here I present such direct measurements. Finally, I also address the relevance of the binocular summation factor for deepsky observing, in comparison to other factors that favour binocular viewing.

Measuring the value of the binocular summation factor with stars as object
So the question is: how does the size of two binoscope mirrors compare to one larger mirror. One way to test this is to determine limiting magnitudes of stars under equal observation conditions and compare these for both a binoscope and a comparably larger single mirror telescope. To determine

the limiting magnitude one simply determines the faintest star one can still see with either the binoscope or the comparable one, larger mirror. The resulting differences in limiting magnitude are thereby an indirect measure for the value of the binocular summation factor. In a mail exchange with Mel Bartels, he proposed that he would directly compare a binoscope and an equivalent mono-mirrored Dobsonian telescope to determine the limiting magnitudes of either instrument. I followed up his suggestion.
To compare the 2 x 13 inch mirrors of the binoscope I Ideally should have taken a mono-Dobsonian telescope with a **$\sqrt{(A^2 \times 2)}$** or 1.41 times larger, 18.4 inch mirror. Unfortunately, I don't own a 18 inch mono-Dobsonian telescope. However, I do own a 16 inch mono-Dobsonian, and this comes close to a 1.19 factor difference in mirror aperture. If Zarenski's formula is valid, I could expect the 2 x 13 inch binoscope to be equivalent with a **$\sqrt{(A^2 \times 1.41)}$** or 15.5 inch mono-mirror. So in theory I would see less with the 2 x 13 inch binoscope than with the 16 inch mono-Dobsonian telescope. I therefore set out to compare the 2 x 13 inch binoscope and the 16 inch mono-Dobsonian for determination of limiting magnitudes (see Figure 1).

The mirrors of the 2 x 13 inch binoscope are f/5.0, giving a focal length of 1650 mm. The 16 inch mirror is f/4.5, but I use a Paracorr coma corrector, which transforms the mirror into a f/5.2, and an effective focal length of 2080 mm. When using the same eyepieces, the respective focal ratios of f/5 and f/5.2 provide exit pupils that resemble each other closely. So, for example, when using 10 mm Ethos eyepieces, the exit pupil with the binoscope is 10/ 5 = 2, while the exit pupil with the 16 inch 10/ 5.2 = 1. 92. These exit pupils are almost the same. This is important, since when viewing point light sources such as stars, the exit pupil determines the degree of background 'blackness'. By coincidence the background darkness in each telescope is thus more or less the same, allowing a proper comparison. Only the magnification in each telescope will differ because of the different focal length.

I determined the limiting magnitude for each telescope during two nights. The first night had almost perfect conditions, with an SQM of approaching 22.0 (a naked limiting magnitude of 7.0) and a very high level of transparency. I chose a star field close to Polaris. The second night conditions were somewhat less, with a SQM of 21.5 (a naked eye limiting magnitude of 6.6). Transparency was good. I chose two star fields, surrounding NGC 7448 and NGC 7678 in Pegasus.

Figure 1. At the left my 16 inch f/4.5 mono-Dobsonian telescope and at the right the 2 x 13 inch f/5.0 binoscope. For more pictures of these instruments see my website (http://arieotte-binoscopes.nl/Binoscopes.htm)

The results are shown in Table 1. The limiting magnitudes were determined in the respective star fields with the 2 x 13 inch binoscope (column 2 x 13) and the 16 inch mono-mirrored Dobsonian telescope (column 16). As can be expected, the limiting magnitudes from the second session are somewhat lower than during the first session, due to the lower sky blackness. Also, with a smaller exit pupil (higher blackness of the background sky) the binocular summation factor appears to become somewhat larger. The main conclusion is though that, when taken as a whole, the binocular summation factor seems to range between 1.4 and 1.5.

					Observed limiting magnitudes			
					Aperture (inch)			
Date	SQM	Eyepieces	Exit pupil[1]	Magnification[2]	16	2 x 13	1 x 13[3]	Δ factor with 13 inch[4]
1-5-2013	22.0	27 mm Panoptic	5.4	61 - 77	15.5	**15.8**	15,1	1,39
		10 mm Ethos	2.0	165 - 207	15.9	**16.4**	15,5	1,53
1-8-2013	21.5	27 mm Panoptics	5.4	61 - 77	14.4	14.9	14.0	1.51
		10 mm Ethos	2.0	165 - 207	15.5	16.0	15.1	1.51
		6 mm Ethos	1.2	275 - 345	15.8	16.4	15.4	1.58

1. Calculated for the f/5.0 binoscope. With a Paracorr the 16 inch f/4.5 telescope has a f/5.2 ratio, the exit pupils are corrected for that.
2. The first magnification is for the 2 x 13 inch, the second for the 16 inch f/4.5, with Paracorr
3. To calculate the limiting magnitude for a single 13 inch mirror, in comparison to the 16 inch mirror, the following formula is used: M-5*log(aperture 400/aperture330). For instance for 10 mm Ethos at 1-5-2013: 15.9 - 5*log (400/330) = 15.9 - 5*0.0834 = 15.9 - 0.417 = 15.48 (15.5 is written down!)
4. To calculate the **increase** of the **two** 13 inch mirrors as compared to the **one** 13 inch mirror **(i.e this is the binocular summation factor!!**), the following formula is used: 10^(1/5*(M_bino-M_mono)). For instance for 10 mm Ethos at 1-5-2013: 10^1/5*(16.4 - 15.48) = 10^0.184 = 1.53.

Table 1. Results that show the limiting magnitudes when using either the 2 x 13 inch binoscope or the 16 inch mono-mirrored Dobsonian telescope. See the text for explanations.

During the same period Mel Bartels and some experienced observers compared a 2 x 8 inch binoscope with either a 12 or 13 inch mono-mirrored Dobsonian telescope. The difference in equivalent apertures between the 2 x 8 inch and the 12 or 13 inch is 1.5 and 1.62, respectively. They concluded that in terms of limiting magnitudes the binoscope was ´just a tad less´ than the mono-mirrored telescopes (Mel Bartels, personal communication). Combining their set of data with mine, **it appears safe to place the binocular summation factor between 1.4 and 1.5.** More specifically stated, this is for point light sources such as stars and within the set-up of comparing a large-mirrored binoscope with a larger mirrored mono-telescope. Importantly, in either case the binoscopes see more than the 1.19 Zarenski factor and in reality more in the range of 1.4 to 1.5. This invalidates the 1.19 Zarenski factor.

The value of the binocular summation factor with extended objects as test object

While the above is concerned with point light sources only, a different picture emerges with extended objects, such as nebulae and galaxies. The problem is that differences on extended objects are much harder to quantify accurately. However, Mel Bartels continues to say that "but the nebulosity was equal or better in raw detail and ***every single observer*** there agreed that aesthetically the 8" binos were better on extended objects" (Mel Bartels, personal communication).

I myself can confirm that extended objects benefit the most from binocular viewing. For instance, with a 20 inch telescope I probably saw M51 as slightly brighter. But with the 2 x 13 inch binoscope I see much more details and contrast within the arms and halo of M51 than with the 20 inch. This observation does not stand on its own. Similarly, I saw the very faint arms of M81 much more pronounced and extended with the binoscope than with the 20 inch. And even more dramatic are views of M31, the Andromeda nebula. The extremely large and faint halo is readily visible in both the 2 x 13 inch binoscope and in the 20 inch. But, with the binoscope a sharp transition between the edge of the halo and the space beyond is visible. In other words, with the binoscope one sees better where the M31 halo ends. This is easily observed when one scans at low speed through the halo. All these observations are the result of the highly increased contrast that can be gained with a binoscope. Below in Figure 2, I give an impression of how I observed the M27 Dumbbell nebula through either a 20 inch f/4.0 mono-telescope and the 2 x 13 inch binoscope. The image of M27 is overall not at all brighter than when observed with the 20 inch telescope. What stands out, however, is the highly increased contrast in details such as filaments.

Figure 2. At the left a drawing of the M27 Dumbbell nebula with a 20 inch f/4 mono-Dobsonian telescope and at the right a drawing the Dumbbell nebula seen through the 2 x 13 inch f/5.0 binoscope.

I share these findings with others. During the 2014 Oregon Star Party Telescope Walkabout, Jerry Oltion demonstrated his 2 x 12.5 inch during three nights (http://www.bbastrodesigns.com/osp14/osp14.html#Jerry_Oltion). Observers judged that “the scope performed equal to that of a 18 inch to 24 inch scope, depending on object”. That’s a factor 1.44 to 1.9 difference, in line with what I describe in this article. Furthermore, “the Dumbbell Nebula was quite striking - one of the best objects in the scope”. Or, “one object that stood out better in Jerry's binoscope than any other scope regardless of size was M31, the Andromeda Galaxy. The dark dust lanes were very striking”.

Why is there such a difference when it comes to observing stars versus extended objects? As pointed out in part 1, it is probably not valid to assign a single binocular summation factor to all facets of binocular vision. It seems that a different value is found experimentally when different read-outs such as resolution, detection or contrast sensitivity is used. One study that uses contrast sensitivity as read-out claims a 1.7 value for binocular summation (the ratio of binocular to monocular **contrast** sensitivities at threshold) (Meese et al., 2006). Possibly the improved signal to noise ratio that is achieved by viewing with two eyes plays a role here. This may translate as a difference in the **contrast gain** of a binoscope versus a large single mirror telescope. The resulting improved contrast is critical for the increased possibilities to observe faint details in halos and arms of galaxies.

In conclusion, in agreement with many previous studies, we find that assigning a value of the binocular summation factor is in fact highly dependent on the type of read-out, in our case being stars or extended objects. It appears that the binocular summation factor is larger when extended objects are used as test object, concomitant with an increased contrast. But even though the increases in contrast in a binoscope are very obvious at the eyepiece, it remains to be repeated that quantitative measurements on extended objects are much harder than on point light sources.

The binocular summation factor in comparison to other factors that favour binocular viewing

Assuming that the binocular summation factor on point light sources such as stars ranges between 1.4 and 1.5, what is its real impact for deepsky observing? The value of 1.4 to 1.5 is approximately equivalent to a doubling of the mirror aperture. So, as calculated before, the 2 x 13 inch binoscope would be equivalent to a 18.4 inch mono-mirror. As shown in Figure 4, this doubling in light-gathering area of a mirror results on average in an increased limiting magnitude of ~0.7 (Bartels, 2012).

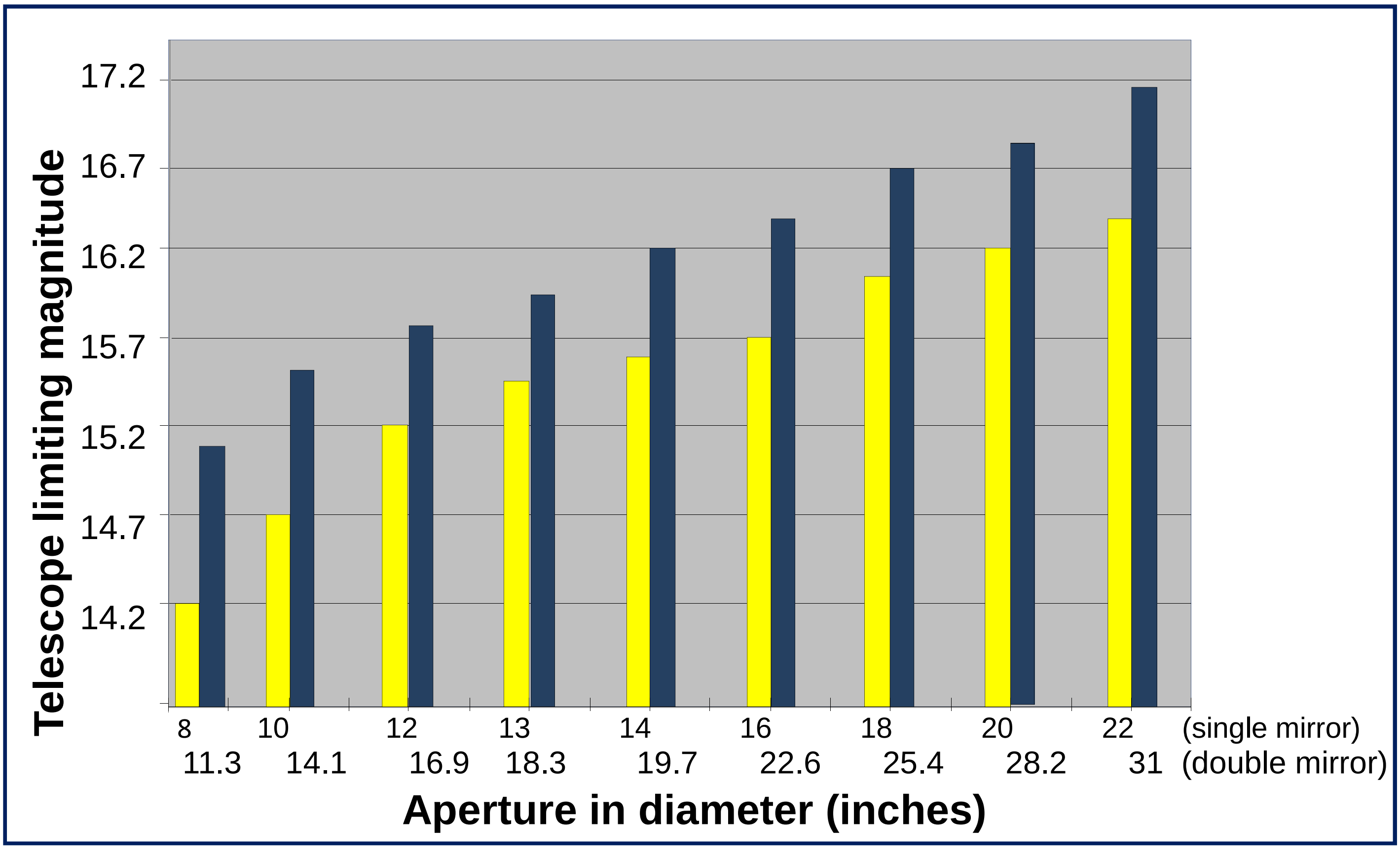

Figure 3. Limiting magnitudes that correspond with different aperture mirrors. In yellow the apertures in inches diameter are given, indicated by the upper row of numbers. In bleu are double apertures (double surface areas), calculated in aperture diameters, indicated by the lower row of numbers. Note that the difference between the yellow and blue bars I consistently ~0.7 magnitudes. Also an increase from 12 inch to 16 inch (approximately a doubling in aperture) results in an 0.7 increase in limiting magnitude. The numbers are derived from Mel Bartels (Bartels, 2012).

To put this number into perspective: when I am in my hometown I achieve a deplorable limiting magnitude of 4.7, if I'm lucky. In rural France a limiting magnitude of 6.7 is easily within reach. This gain in 2 full magnitudes dwarfs the at most 0.7 increase in limiting magnitude that can be achieved by changing from an equivalent mirrored mono telescope to a binoscope. Or, if the binocular summation factor in terms of light gathering capacity is the only argument to go for a binoscope, my advice would be: 'don't bother'.

What then would be the principal factors that determine the benefits of binoscope over a large-mirrored mono-telescope?

1. The most important factor is the better signal to noise ratio that leads to the perception of a darker sky background. This is the single most important factor that favours a binoscope in comparison to a large mirror single telescope. What does this mean? A stimulus that is not originating from an astronomical object (for instance 'light noise' from light pollution) could be interpreted by one eye as a bona fide signal. But the chance that such random noise signals hit two eyes simultaneously and reach the brains is very small indeed. In other words, when looking with two eyes, the brains do have to suppress much less background noise created by light pollution. And this automatically translates itself into a darker sky background, even in my light-polluted hometown. This phenomenon is in particular relevant for the observation of very faint galaxy halo's or arms. Within these faint, extended objects many more details become visible and the contrast within the objects is greatly enhanced. ***Neural summation*** is probably responsible for this phenomenon. As stated above, this is possibly underlying a binocular summation factor in the range of 1.8, specifically when extended objects are the observation objects!

   Here also a binoscope has an distinctive advantage above a binoviewer that simply splits ONE light signal into two. With a binoviewer the reduction in the random noise signal principally cannot take place!

2. ***Stereopsis*** is the ability see depth. Because of the different positions of the eyes, an object is viewed by each eye from a slightly different angle (parallax). This creates a spatial 3D effect. How closer the object is, the larger the angle and how greater the 3D effect. But unfortunately, astronomical objects are so distant that there is no such thing as parallax there and consequently no 'real' stereopsis. But, there is a related phenomenon called chromatic stereopsis or chromostereopsis. This is caused by the slightly different breaking in the eye lens of for instance red versus blue light. As a consequence red and blue light focus in a slightly different place on the retina. This effect is different for each eye and it therefore appears as if red stars stand a bit closer than blue stars. When looking through a binoscope, chromostereopsis hereby creates an illusion of depth, although this is completely artificial.

3. The principally wider field of view that can be achieved with a binoscope can hardly be achieved with a large mono-telescope, a point which is often stressed by Mel Bartels. Indeed, looking through a binoscope, this is a beautiful effect that is immediately obvious. But why is that? If you take the example of my 2 x 13 inch binoscope, with f/5.0 mirrors, the use of two 10 mm Televue Ethosses delivers a 165 x magnification and a 0.61 degree true field. Suppose this binoscope has an approximate equivalent of a 18 inch mono-telescope, also being f/5.0. Now the 10 mm Ethos would deliver a 225 x magnification and a 0.45 degree true field, which is only half of the true field you see with the binoscope. To achieve a 165 x magnification and a 0.61 degree true field, the 18" needs to be f/3.7. And since this creates massive coma, a coma-reducing Paracorr will be needed. As a consequence, the mirror needs to be even f/3.2 for these same magnification and true field (with thanks to the Televue Eyepiece Calculator!). Now consider what will be the costs of such a steep mirror!

There is another aspect here that is rarely addressed. In humans, the horizontal binocular visual field is 120 degrees. But there is an additional 45 degrees monocular field on each side of the binocular field. So, there is a total of a 90 degrees field that is non-binocular, but that is seen by looking with two eyes. By looking with one eye only, this is just a mere 45 degrees of the one eye. And even though you cannot encompass the entire 120 plus 90 degrees at one glance, you will observe it peripherally and it adds to the feeling of being present in the picture. Of course, the choice of eyepieces is important here: with two 50 degree apparent field of view eyepieces, you will just see the field stops. But the effects are very obvious when two Ethos eyepieces with a 100 degree apparent field of view are used.

4. The sheer comfort of observing with two eyes. There is also the 'ordinary' effect of the increased comfort by looking with two eyes instead of with one eye, and another squeezed eye. Sustained and concentrated viewing at faint details with two eyes, without the strain of looking with one eye only, is more pleasant and more relaxing.

5. The gain in limiting magnitude of stars, which is almost exclusively translated as **THE** gain in aperture in order to make a binoscope comparable with a larger mono-telescope. This is the main topic of this article. Unfortunately, as explained, this aspect gets most of the attention, while the gain in aperture should be specifically coupled to the type of observed objects, being point light sources such as stars or extended objects.

Conclusions

Speculations about the value of the binocular summation factor and in its direct implications for how one should compare two binoscope mirrors to a single larger one are misleading at best. First of all, assigning one single value when different classes of observed objects are either point light sources such as stars or extended objects such as nebula and galaxies is most likely completely wrong. The binocular summation factor is very dependent on the context in which it is determined.

In the second place, the only proper way to determine the binocular summation factor is by direct measurements. Results shown here indicate that for a binoscope versus a large-mirrored mono-telescope the binocular summation factor ranges between 1.4 and 1.5. That is: when stars are used as object of observation!! This ~1.4 value is in fact in rather close agreement with what has been proposed and measured for decades. It is, however, vital to understand that the direct measurements shown here concern point light sources. When extended objects are used as study object, a higher value of the binocular summation factor, between 1.6 and 1.8, is probably more accurate. This translates to a large **gain in contrast** when it comes to observing extended objects with a binoscope. This effect is one of the most prominent effects that is readily seen when a binoscope is used. It explains why a binoscope has a larger beneficial effect when extended objects are observed than when stars are observed.

A final conclusion is that the $\sqrt{(A^2 \times 1.41)}$ formula to which Zarenski (and Harrington) adhere, is invalid. In the first place, there is no scientific basis for this formula. In the second place, the data presented here show otherwise. Their claims of a meagre and overall 1.19 x improvement of a binoscope (or binocular) on all types of objects in comparison to a single mirror/ lens probably puts of many potential users/ builders of binoscopes. This is regrettable, to say the least.

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