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# Measurement of eyepiece diopter of direct view imagers

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**Abstract**

This paper presents a detailed review on a present confused situation related to defining and measurement of the eyepiece diopter range of optical/electro-optical devices to be used for a direct observation by human observers. On the basis of this review three precise definitions of a direct view imagers eyepiece diopter are presented. One of these definitions is determined as optimal fit to describe the perception of human observers. Further on, design and measurement uncertainties of diopter meters are discussed and rules of accurate measurements are formulated. Finally, recommendations for the maximum acceptable errors of the diopter scale of eyepieces of classic types of direct view imagers are presented, as well.

## 1. Introduction

Diopter (English spelling 'dioptre') is formally a name of a measurement unit of the lens optical power which is equal to the reciprocal of the focal length measured in meters. The definition of a diopter as a unit of optical power can be found in most optical encyclopedias/vocabularies [1-4]. Optical power of optimal corrective glasses to be used by humans is measured by ophthalmologists using an optical device called a phoropter [5]. Because of a significant fraction of humans who use corrective glasses, the term 'diopter' understood as a unit of the optical power measurement is commonly known. However, there is also a parameter commonly called 'eyepiece diopter' (sometimes other names are used) that is used to describe the optimal tuning of eyepieces of direct view imagers (binoculars, optical sights, nigh vision devices, classical microscopes, classical photo-cameras) for humans having eyes with a focusing disorder.

There is a series of meters for the measurement of the eyepiece diopter offered on international market [6-10]. There is also a series of military standards that outlines requirements for eyepiece diopter of two important types of military direct view imagers: night vision devices and telescopic sights [11-14]. There are also three standards issued by civilian international organizations [15-17]. Some of these standards give some recommendations regarding the measurement methods of this parameter, as well [11,12,16]. However, it can be surprising but none of these earlier listed optical encyclopedias/vocabularies or test standards present any precise definition of the eyepiece diopter parameter or any discussion about measurement methods.

In such a situation, a review of this confused situation related to defining and measurement of the eyepiece diopter of direct view optical/electro-optical devices has been carried out in this paper. Solutions that clarify this situation are proposed.

## 2. Importance of the eyepiece diopter parameter

Eyepiece diopter is used to describe the optimal tuning of eyepieces direct view imagers to a human observer. These imagers are of a critical importance for military and are also used in civilian applications. In detail, direct view imagers are commonly used as portable sights (telescopic sights, night vision sights, thermal sights), as portable surveillance devices (binoculars, night vision goggles/monoculars, thermal binoculars), classic microscopes and classic photo cameras. Specifications of programs on modern direct view imagers typically present requirements for an eyepiece diopter [18,19]. There is also a series of scientific papers that confirms importance of an eyepiece

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diopter proper setting to achieve the optimum performance of night vision devices to be used by human operators [20-24]. This optimal tuning of the eyepiece-human eye is extremely important because a successful performance of some military tasks is largely dependent on visual performance of a night vision goggle [24,25]. Therefore, it can be concluded that both listed earlier test standards and specialized literature show clearly the eyepiece diopter importance for a direct imaging technology. However, the same conclusion is not valid for terminology and test method.

## 3. Terminology review

A short review of literature listed in the previous section shows clearly that a series of different terms is used for the parameter name describing the eyepiece dioptre ability to tune a direct view imager to a human with an eye disorder at a different level (Table 1).

Standards are commonly considered to be documents prepared logically and in order. Therefore, the data shown in Table 1 is surprising, since it shows that standards issued by the same organizations propose different names for the same parameter.

US military MIL standards propose at least three different terms: eyepiece diopter, diopter focus or diopter setting. It should be noted that all these standards refer to the same type of direct view imagers: night vision devices.

Next, we have a situation when two different standards issued by ISO organization propose again different terms: dioptre scale or collimation. It is correct that these two standards talk on parameters of two different types of direct view imagers: night vision devices and telescopic sights. However, an eyepiece of nigh vision sight works in the same way as an eyepiece in telescopic sight and the ability to use both types of devices by people having eye disorders should be described by the same parameter.

Scientific papers only increase chaos in terminology created by standards. However, this chaotic terminology situation is not the biggest problem when testing direct view imagers. More important problem is lack of a precise definition of the parameter most commonly called an eyepiece diopter and a method to measure this parameter in both standards and scientific papers. For example, the standard of ISO 14490-1 presents no definition of this parameter but only advice to use a dioptric tester with no discussion regarding requirements for this tester or conditions for using this tester. The papers treat the eyepiece diopter as a simple commonly known parameter that does not need to be discussed.

## 4. Equipment for the eyepiece diopter measurement

On the international market there are at least five manufacturers who offer a product to measure the eyepiece diopter of direct view imagers [6-10]. After reading the previous section, it is not surprising that the products used for measuring practically the same parameter are called by different names: diopter tester, diopter meter, diopter telescope, dioptometer, diopter power meter. In detail, the author being CEO (Chief Executive Officer) of one of these manufacturers can partially blame himself for increasing the terminology confusion by adding another name to the already mentioned.

Different names for measuring a tool used by the manufacturers for the eyepiece diopter measurement are annoying, but still can be tolerated. All these manufacturers claim delivering a measuring tool to measure the eyepiece regulation range of lenses in diopter. The problem is that the author has received a report from one of its customers (company with decades of experience in manufacturing direct view imagers) that measurement results of an eyepiece diopter done using tools from different manufactures generate slightly different measurement results and the measurement results depend on a position of the meter relative to the tested direct view imager eyepiece. The latter effect has been considered as an important defect of diopter meters. The customer report has initiated a

Table 1:
Terms used to describe ability of humans with eye disorders to use direct view imagers.

| Document name | Recommended term |
|---|---|
| MIL-A-49425 (CR), Aviator's night vision imaging system AN/AVS-6(V) 1, AN/AVS/6(V)2, 1989 [11] | Eyepiece diopter |
| MIL-D-49313(CR), Goggles, Night vision AN-PVS-7B, 1989 [12] | Diopter focus |
| MIL-PRF-49064E, Performance specification: Night vision sight, Crew served weapon AN/TVS-5, 1999 [13] | Eyepiece diopter focus |
| MIL-PRF-49147D(CR), Lens assembly, Eyepiece viewer, Driver night vision, AN/VVS-2V, 1992 [14] | Diopter setting |
| RTCA DO-275, Minimum operational performance standards for integrated night vision imaging system equipment, 2001 [15] | Eyepiece diopter |
| ISO 21094 Optics and photonics — Telescopic systems — Specifications for night vision devices, 2008 [16] | Dioptre scale |
| ISO 14490-1 Optics and optical instruments — Test methods for telescopic systems —Part 1: Test methods for basic characteristics, 2005 [17] | Collimation |
| Scientific papers [18,20] | Eyepiece focus (diopter) |
| Scientific papers [21,22] | Eyepiece focus |
| Scientific paper [23] | Eyepiece focus settings |
| Scientific papers [24,25] | Diopter adjustment |

deeper work on this subject that has grown to a form of this scientific paper due to a complexity of the problem of defining and measurement of the eyepiece diopter.

## 5. Determination of optimal corrective glasses

Users of direct view imagers with eye disorders typically have tendency to set an eyepiece diopter to the value equal to the optical power of corrective glasses prescribed by a doctor. Therefore, in order to present a precise definition and measurement method of the eyepiece diopter, it is necessary to understand the role of corrective glasses and how optimal corrective glasses are chosen by doctors.

Optimal corrective glasses for a human are determined by using a device called 'phoropter' [5]. The device looks sophisticated, but, practically, it is a simple device that rotates a series of lenses of different optical power in front of eyes of a human observer looking for a target located at some distance o (typically 6 m) through the corrective lens (Fig. 1).

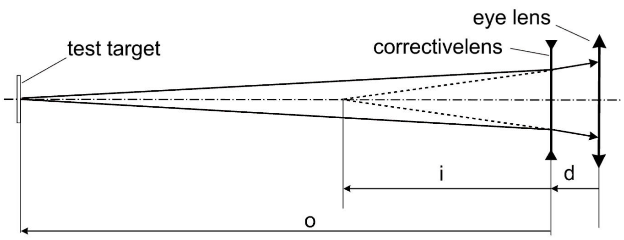


**Fig. 1.** Diagram of the ophthalmology test.

The lens creates a target image at the distance *i* that depends on the corrective lens optical power. The relationship between the distances *o*, *i* and the focal length *f'* is described by the thin lens equation:

$$\frac{1}{i} = \frac{1}{o} + \frac{1}{f} \quad \text{or} \quad i = \frac{o \cdot f}{o+f}. \tag{1}$$

Analysis of the diagram of an ophthalmology test shown in Fig. 1 can bring us to a conclusion that the corrective lens changes the distance to a perceived target. Shorter the distance to a simulated target means more powerful corrective lens. Therefore, let us define effective optical power (*EOP*) of a corrective lens used during the ophthalmology test as the reciprocal of the perceived distance (sum of *i* and *d*):

$$EOP = \frac{1}{i+d}, \tag{2}$$

where distance *d* equals 0.02 m.

*EOP* represents true optical power of corrective lens used during the ophthalmology test but this term is a novelty introduced in this paper. Nominal optical power (*NOP*) defined as equal to the reciprocal of the focal length measured in meters is typically used to describe corrective lenses optical power. *NOP* can be treated as a special case of *EOP* when distance *o* is equal to infinity and distance *d* equals zero:

$$NOP = \frac{1}{i(o=\infty)} = \frac{1}{f}. \tag{3}$$

*EOP* differs from *NOP* because of two factors. First, ophthalmology tests are carried out using a target located at a distance of 6 m and not at infinity. Second, the corrective lens used during the ophthalmology tests is located at a distance of about 15 mm in front of the eye (or of about the distance *d* from the centre of the corrective lens to the centre of the eye lens equal to 20 mm). The relationship between *EOP* and *NOP* can be presented in the equation below:

$$EOP = \frac{1}{\frac{o \cdot f}{o+f} + d} = \frac{1}{\frac{o}{o \cdot NOP+1} + d}. \tag{4}$$

Finally, let us name the difference between *EOP* and *NOP* as a medical correction (*MedCor*) as it represents a certain correction of *NOP* to determine *EOP*:

$$MedCor = EOP - NOP = \frac{1}{\frac{o}{o \cdot NOP+1} + d} - NOP. \tag{5}$$

As can be seen in Fig. 2, the values of *MedCor* are not high but still are noticeable, especially, for the case of corrective lenses of a negative nominal optical power.

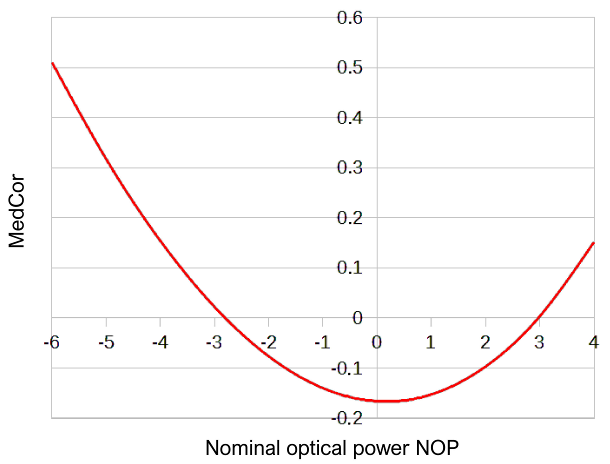


**Fig. 2.** Relationship between medical correction *MedCor* and nominal optical power *NOP* of corrective glasses.

Understanding subtle differences between *EOP* and *NOP* is needed to allow discussion on defining the eyepiece diopter of direct view imagers.

## 6. Defining the eyepiece diopter

As it was mentioned in Section 3, all manufacturers of devices for measuring the eyepiece diopter claim that they deliver meters to measure the eyepiece regulation range expressed in a diopter unit. However, they do not present any precise definition of the eyepiece diopter. Therefore, let us analyse possible definitions of this parameter.

Eyepieces typically work as image projectors projecting image created by an objective (telescopic sights), screen image of the image intensifier tube (night vision device), or image of display (thermal sights) towards a human eye. In all these cases by adjusting eyepieces, a distance to image plane of a projected target can be changed. This distance should be used in defining the eyepiece diopter.

Analysis of the work of such eyepieces shows that these optical systems can be characterized in different ways and that at least three definitions of an eyepiece diopter can be formulated:

1. Raw eyepiece diopter,
2. Perceived eyepiece diopter,
3. Medical eyepiece diopter.

Raw eyepiece diopter (*RawED*) is a power of the eyepiece lens equal to the reciprocal of the imaging distance *i* measured in meters. The imaging distance *i* is equal to a distance between the plane of an image created by the eyepiece and the principal plane of the eyepiece lens. By sign convention, distance *i* is negative for the case shown in Fig. 3.

$$RawED = \frac{1}{i} \quad (6)$$

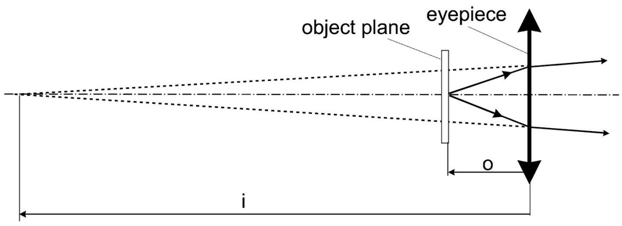


**Fig. 3.** Graphical interpretation of a *RawED* concept.

Perceived eyepiece diopter (*PerceivedED*) is a power of the eyepiece lens equal to the reciprocal of the distance from eye lens to an image created by the eyepiece. In detail, it is equal to the reciprocal of the sum of the imaging distance *i* and the separation distance *e* between eyepiece and eye equal typically to the eye relief distance.

It should be noted that for a situation shown in Fig. 4, the reference plane is a plane of eye lens and the distances *x, e, i* are all negative. According to this convention *e* is always negative but *x* and *i* can be either negative or positive depending on *RawED*. *PerceivedED* can be calculated as below:

$$PerceivedED = \frac{1}{x} = \frac{1}{e+i} = \frac{RawED}{e \cdot RawED+1} \quad (7)$$

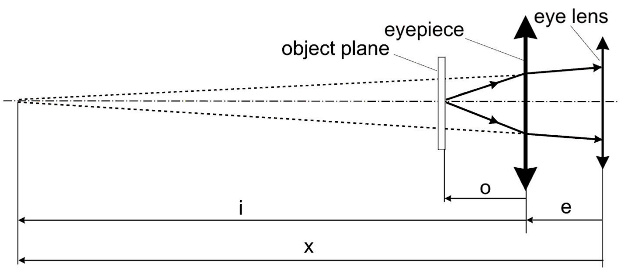


**Fig. 4.** Graphical interpretation of a *PerceivedED* concept

Figure 5 shows the variation between *RawED* and *PerceivedED* in a typical range of the eye relief of direct view imagers (range from about 10 mm to about 110 mm) and for a typical range of eye disorders (from -6D to +4D) can be over 2D.

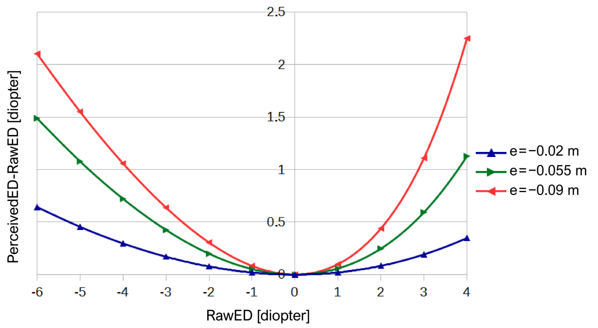


**Fig. 5.** Difference between *PerceivedED* and *RawED*.

Next, *PerceivedED* depends on the separation distance *e*. Data from Fig. 5 show that <u>*PerceivedED*</u> can vary as much as almost 2D when the distance *e* varies from 20 mm to 90 mm (typical range met in many direct view imagers). The conclusion is that *PerceivedED* should be measured for the distance *e* where a human eye is supposed to be (typically the exit pupil position or other distance specified by a manufacturer).

Finally, medical eyepiece diopter (*MedicalED)* is equal to *NOP* of a corrective lens that simulates the same image distance for a human observer during the ophthalmology test as an eyepiece when using a direct view imager. *MedicalED* can be calculated as a difference of *PerceivedED* and *MedCor* calculated using Eq. (4):

$$MedicalED = PerceivedED - MedCor \quad (8)$$

If an eyepiece diopter, calibrated using *MedicalED* definition, is set to *X* dioptre, then a human observer should perceive the same image sharpness as perceived during ophthalmology tests when the corrective lens of the optical power *X* diopter was used.

## 7. Choosing the best definition

It is obvious that *RawED* does not take into account influence of the separation distance *e* on a distance to the target perceived by the user of direct view imagers in a situation when this influence can be significant (Fig. 5). Therefore, only *PerceivedED* and *MedicalED* can be seriously considered as quantities to be used to calibrate eyepieces of direct view imagers.

Simplicity of a definition and a direct connection to a distance from an eye to a simulated target is an advantage of *PerceivedED*.

However, a direct view imager having the eyepiece diopter set to *X* according to the *Perceived* scale shall generate images at a slightly different distance comparing to a distance perceived during ophthalmology tests when looking through a corrective lens of the nominal optical power equal to *X*. Practically, it means that eyepieces calibrated using *PerceivedED* concept simulate a slightly different distance to the virtual target compared to the expected distance. Therefore, *MedicalED* should be treated as the best definition of the eyepiece diopter.

Differences between *PerceivedED* and *MedicalED* are rather small. What is even more important, the relationship between these two quantities is known [Eq. (5)]. Therefore, it is possible to measure *PerceivedED* and, next, to calculate *MedicalED*.

The author is CEO of the company manufacturing eyepiece diopter meters calibrated to measure directly *PerceivedED*, but in new models manuals a table enabling the conversion to *MedicalED* is presented. As it was earlier mentioned, it is not clear how other manufacturers define and measure the eyepiece diopter. However, it can be expected that all meters offered on the market do measure *PerceivedED*. Differences in a generated measurement result probably from a different position of the reference plane of these meters during measurements. In such a situation, it seems that the solution of a direct measurement of *PerceiveED* and the calculation of *MedicalED* can be accepted by the market of eyepiece diopter meters because it is easy to implement.

## 8. Measurement of the eyepiece diopter

Meters of eyepiece diopter (dioptometers) are typically built as wide range refocusable telescopes or electronic cameras [6-10]. In order to simplify the work diagram, let us assume that these meters work as refocusable imaging cameras as shown in Fig. 6. The meters typically have a precisely defined position of a reference mechanical plane. From the functional point of view, the eyepiece diopter meter is a meter calibrated to measure the distance from the meter reference plane to the image plane created by the tested eyepiece.

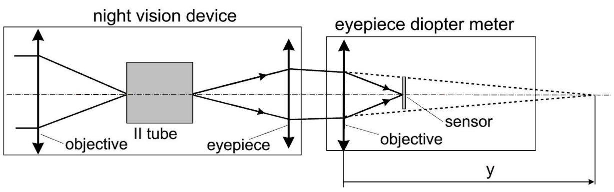


**Fig. 6.** Concept of the work of an eyepiece diopter meter.

As discussed in the previous section, these meters enable the measurement of *PerceivedED* of the tested direct view imagers eyepieces. *PerceivedED* depends on the distance of eyepiece-eye. Therefore, it is critical that the eyepiece diopter meter reference plane is located exactly at the imager exit pupil plane (if there is an exit pupil) or at a distance specified by the imager manufacturer. Disregard of this basic rule can bring eyepiece diopter significant measurement errors (see Fig. 5).

As discussed in Section 6, only *MedicalED* measurement can give truly accurate information on the eyepiece ability to enable a comfortable vision for humans with eye defects related to the diopter power of corrective glasses used by a human observer. At present, the eyepiece diopter meters offer typically the measurement of *PerceivedED*. However, in future it can be expected that the meters can be calibrated to indicate *MedicalED* or at least to the present in manuals conversion table from *PerceivedED* to *MedicalED*.

## 9. Uncertainty of the eyepiece dioptre measurement

The uncertainties of the eyepiece diopter measurement can be divided into two groups: method uncertainties and meter uncertainties. The total uncertainty of the eyepiece diopter measurement can be calculated using this equation:

$$Total = \sqrt{Method^2 + Meter^2}. \tag{9}$$

The *Method* uncertainties are uncertainties that exist even in case of a perfect eyepiece diopter meter due to:

1. difference between *MedicalED* (ideal result) and *PerceivedED* (typical meter result),
2. difference between the position of the meter reference plane and the position of the tested imager exit pupil (or other position recommended by the imager manufacturer).

It should be emphasized that the *Method* uncertainties can be eliminated or at least kept at a low level. Influence of the first factor can be eliminated using a proper conversion table in the meter manual (if there is such a table) or using directly Eq. (5). Influence of the second factor can be eliminated by following the basic rule that the eyepiece diopter meter reference plane is to be located at the same position where the eye is intended to be. However, this rule is often disregarded and such situation can lead to high measurement errors at the level over 2D. For example, such a situation can occur while measuring an eyepiece diopter of a telescopic sight having the exit pupil located at a distance of 90 mm from the eyepiece using the meter with its reference plane positioned at a distance of about 10 mm from the eyepiece.

The *Meter* uncertainties are uncertainties that are generated by factors related to a non-perfect design of eyepiece diopter meters like limited calibration accuracy, limited measurement resolution, non-perfect determination of a position of the meter reference plane. If uncertainties of the eyepiece diopter meter are to be negligible, then two conditions must be fulfilled:

1. the meter must be sensitive enough to detect small changes of the tested eyepiece optical power (resolution below 0.1 diopter),
2. the meter must be calibrated with high accuracy (precise relationship of focusing position and distance from the reference plane to the plane of the simulated image).

If the eyepiece diopter meter resolution below 0.1D is to be achieved, then bright objectives of F number below 1.5 of a narrow depth focus are recommended. Therefore, meters based on the imaging camera concept are recommended over meters based on the optical telescope using objectives of a high F number (typically over F4) of a wide depth focus.

Calibration of eyepiece diopter meters is of a crucial importance to achieve high accuracy of these meters. A series of possible methods can be used. Author prefers to use a method that can be called the reference eyepiece of a regulated eyepiece diopter. In detail, it is an image projector (a set of light source, target, reference objective of precisely known positions of cardinal planes and effective focal length) of a precisely regulated distance target to an objective input cardinal plane. In such a case it is possible to predict theoretically what is the eyepiece diopter (distance to the image of the target) of the projector for a specified target position and a specified position of the observer's eye.

## 10. Tolerances on eyepiece diopter scale

Users of direct view imagers can regulate the eyepiece diopter if they are not comfortable with present settings. Therefore, theoretically even significant errors on a diopter scale of eyepieces seem to be unimportant as long as the user can finally find a proper setting for himself. The problem with this logic is that a human under stress can set a wrong diopter setting but will start feeling wrong effect only after some time of work. The second problem is that users of direct view imagers typically trust the diopter scale and set the eyepiece diopter for *X* diopter if they use corrective glasses of *NOP* equal to *X* diopter.

In such a situation, it is important to find answers to two questions related to tolerances of eyepiece diopter scales on eyepieces of direct view imagers.

First, what is acceptable maximal error of diopter scale in eyepieces of typical direct vision imagers? Secondly, what is acceptable measurement uncertainty of eyepiece diopter meters?

The answer to question no. 1 depends on a direct view imager type. There are direct view imagers needed for a relatively short time observation (telescopic sight, night vision sight, thermal sight) and the user can tolerate even a relatively significant error of the eyepiece dioptre setting. Author's personal experience shows that a human at short observation tolerates quite well a unperfect fit of the eyepiece dioptre, if the difference is not bigger than ± 1D. This conclusion correlates well with the recommendation of the ISO 21094 standard that specifies acceptable deviations of a zero-setting error of the dioptre scale at the level of ± 1D.

Binocular night vision goggles for airborne applications represent another extreme. They are used for a long time observation and a comfort of helicopter pilots visual observation is extremely important. Pilots have the right to trust the diopter scale on their goggles. In such a situation, it can be logically expected that the acceptable error of the diopter scale of binocular night vision goggles should be at least two times lower than it is for sights. Which means that the maximum acceptable error of the diopter scale of the binocular night vision goggles should be of ± 0.5D.This conclusion is also in a good agreement with the available specialized literature saying that an aircrew could accommodate an unperfect setting of eyepiece diopter as high as ± 0.5D [11].

There is no literature recommendations for the acceptable measurement uncertainty of eyepiece dioptre meters. However, it can be logically expected that the meter uncertainty should be at least four times lower than the acceptable tolerance for the eyepiece diopter of tested direct view imagers:

- 0.125D when testing binocular night vision goggles,
- 0.25D when testing optical/night vision/thermal sights.

These uncertainty limits can be met in case of well-designed eyepiece diopter meters.

## 11. Conclusions

This paper presents a detailed review on a present confused situation related to defining and measurement of the eyepiece diopter range of optical/electro-optical devices to be used for a direct observation by human observers. On the basis of this review three precise definitions of a direct view imagers eyepiece diopter are presented. One of these definitions is determined as the optimal fit to describe the perception of human observers. Further on, design and measurement uncertainties of diopter meters are discussed and rules of accurate measurements are formulated.

Finally, recommendations for the maximum acceptable errors of the diopter scale of eyepieces of classic types of direct view imagers are presented, as well.

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