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Specifying the visual optical system

B. H. Walker
Kollmorgen Corporation
Electro-Optical Division
Northampton, MA 01060

Abstract

This paper presents a cursory discussion of the visual optical system, its principal characteristics and the means by which they may be specified. A typical visual system will be discussed in detail, illustrating the required breakdown of its specification into two major areas, basic optical characteristics and system image quality. Consideration of the test procedures that will be precipitated by an unduly comprehensive specification leads to a discussion of those characteristics requiring actual testing vs. those that may be adequately proven by design calculations and documentation.

Introduction

Spec-i-fi-ca´-tion - A detailed and exact statement prescribing materials, dimensions, workmanship and performance.

This definition, taken from the American Heritage Dictionary, often leads to great difficulties when applied verbatim to the case of the visual optical system. This paper will deal with the various factors involved and what modifications may be appropriate to the above definition.

The intelligent, logical preparation of an optical system specification may be the most significant single step in the successful execution and management of a program. I believe this to be an accurate statement both in terms of final system performance as well as final system cost. In this case, unlike so many others, proper attention to the specification content will frequently yield improved performance and, simultaneously, reduced cost. While there is no reason to believe that this philosophy does not apply to all types of optical systems, because of my recent experiences as a lens designer I would like to address the particular area of visual optical systems.

The Visual System is Unique

Visual optical systems are unusual in that the final detector, or sensor, in the system is the visual portion of the human mind and body. This means that the detector will be a variable, not only from person to person depending on size, age, physical condition, sex, etc., but variations will also occur for each individual due to the inherent flexibility of the eye/mind combination. The eye is a dynamic detector in that it is constantly scanning the scene presented to it and adjusting its characteristics to suit. The iris of the eye will open and close over a range from 2 mm to 8 mm to compensate for dynamic changes in scene brightness. For longer duration brightness changes the sensitivity of the retina will be modified by an internal electro-chemical process. The internal eye lens will adjust its power (accommodate) to compensate for the apparent distance of the scene from the eye. The amount of accommodation possible will vary, with age primarily, from about 10 diopters at age 20 to 2 diopters or less at age 50. These are the principal characteristics of the eye that make the design and specification of a visual system somewhat unique. This important uniqueness should be kept in mind during the preparation of a specification for a visual optical system.

Contents of the Specification

Initially we must establish which characteristics of the system must be contained within the specification. The primary factor to be considered is of course the ultimate function of the system. Since detailing this function is not generally a practical or convenient way to specify the instrument, it is the responsibility of the individual preparing the specification to generate instead a family of descriptive characteristics (with tolerances) that will assure the satisfactory ultimate performance of the instrument.

As an example, let's look at a typical optical sighting device and consider those items that should be included in order to prepare a correct, complete and reasonable specification. The instrument shown in Figure 1 is similar to the auxiliary sight used in conjunction with the main weapons system on a modern tank. The sight consists of a well corrected objective lens which forms an image of the outside world at the reticle. This is followed by a pair of relay lenses that serves to transfer and erect the primary image. Finally, there is an eyepiece which allows us to view the final image and reticle, providing the desired field of view and magnification. Folding mirrors and/or prisms are included to suit the physical requirements of the overall system.

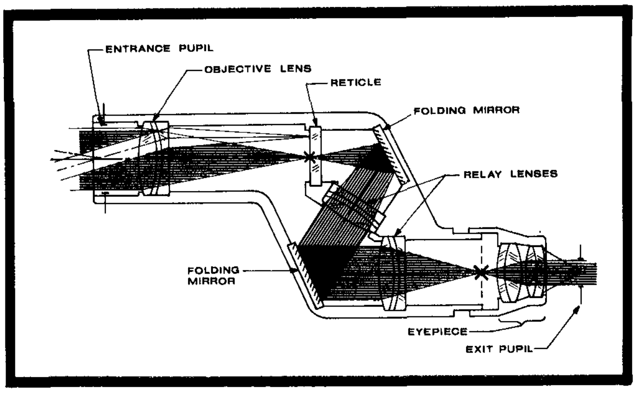


Fig. 1. A typical visual optical system and its basic components are shown.

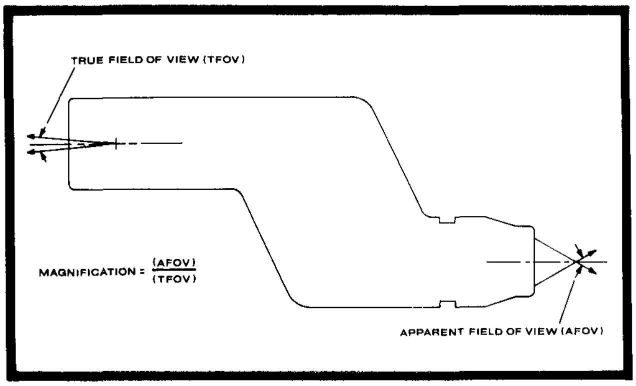


Fig. 2. The relationship between magnification and the apparent and true fields of view is illustrated here.

Basic Characteristics

A primary function of the specification is to define the instrument's basic optical characteristics; among these are:

Magnification - In this case we have an instrument with a basic magnification of 6X. In most noncritical cases a tolerance of ±3% on magnification would be considered reasonable.

Field of View - The true field of view, that is the field covered in object space, is 8° for the example being discussed. The 3% tolerance would again be appropriate. The apparent field of view, as seen through the eyepiece, is equal to the true field X the magnification, or 48° in this case. (See Figure 2.)

Entrance Pupil Diameter - This characteristic will affect image brightness on the one hand and cost on the other. Considering general tactical requirements plus mechanical restrictions, a value of 42.0 ± 0.5 mm was selected for the example being discussed.

Exit Pupil Diameter - In a relationship similar to that of the true and apparent FOV's, the exit pupil diameter will be determined by the entrance pupil divided by the magnification. This characteristic of pupil diameters is generally quite easy to confirm, as a result it is frequently used to verify system magnification. It is in areas such as this that one may simplify the specification greatly or, if not carefully thought out, one may overspecify the system, generating a number of conflicting requirements. When specifying pupil size, consideration should be given to the nature of the human eye, since the exit pupil of the instrument will be superimposed upon the entrance pupil of the eye. As a general rule, an exit pupil diameter of 4 mm will be quite comfortable to work with in normal daylight viewing systems. In cases where reduced illumination levels are anticipated, this may be increased to 7 or 8 mm. Since this pupil size will impact directly upon the size of many of the optical elements, it will affect final system cost significantly. In the case of our example, the 42 mm entrance pupil and 6X magnification will produce a nominal exit pupil diameter of 7 mm. These pupil characteristics are illustrated in Figure 3.

Eye Relief - Eye relief, or clear eye distance, is important to the user's comfort. A distance of from 25 to 30 mm from the last physical part of the instrument to the exit pupil, as shown in Figure 3, will generally be sufficient. Here again when eye relief is increased the diameter of some elements in the system will be affected. However, in this case we are dealing with the less precise and therefore less expensive eyepiece elements, so the cost tradeoff here will be less significant.

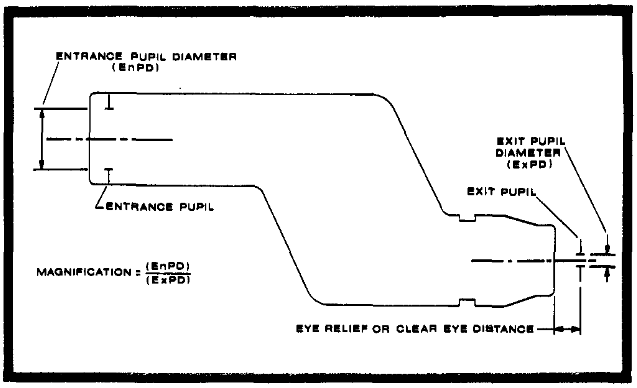


Fig. 3. The relationship between magnification and entrance and exit pupil diameters is shown. Also illustrated is the system eye relief or clear eye distance.

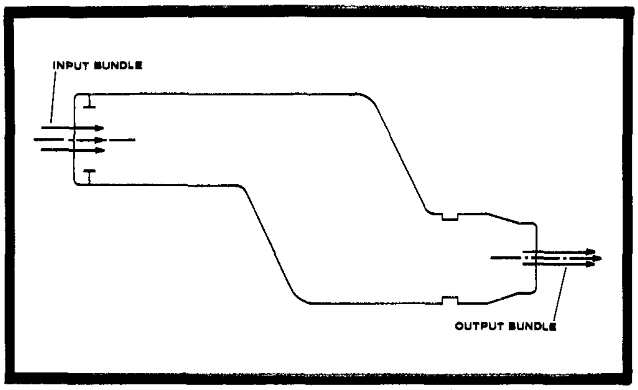


Fig. 4. System transmission deals with the amount of energy emerging from the system relative to the amount that enters. Note that the bundle must not be physically obscured during its passage through the system.

Transmission and Relative Illumination - It is at some risk of perpetuating a common error that I choose to discuss these two items simultaneously. They are really totally independent of one another. I hope to present them in such a way as to demonstrate this independence and in so doing eliminate any confusion which may exist. System transmission indicates the percentage of energy that will emerge through the system's exit pupil as compared with what entered through the entrance pupil. We reference a nearly axial bundle of light as shown in Figure 4, one which is in no way obstructed by system apertures as it passes through the system. The spectral region being considered must be specified. For a visual system we may specify transmission at a peak wavelength of .55µm or an average transmission value over a spectral range from .49 to .64 µm. The former method leads to more straightforward test procedures.

It is quite unreasonable to specify an exact transmission value prior to the establishment of a basic system design. Not knowing the number of lenses, prisms and mirrors involved makes it impossible to settle on a reasonable transmission value. Specifying an arbitrarily high transmission requirement can lead to exotic mirror and antireflection coatings. This again will significantly affect system cost. Here is another area where it is important to keep in mind the nature of the human eye. Should the image be somewhat less bright due to reduced system transmission, the characteristics of the eye will adjust to make the illumination level of the final retinal image satisfactory.

Once a basic system configuration has been settled upon, it becomes a simple matter to generate a reasonable target value for overall transmission. The principal elements affecting transmission in the case of our example are easily identified, they are eleven (11) optical elements and two (2) folding mirrors. Considering the minimum cost approach we would use standard single layer antireflection coatings on each lens and protected aluminum on the mirrors. This would lead to the following calculation:

$$T = (T_{\text{lenses}})\ (T_{\text{mirrors}}) \tag{1}$$

$$T = (.985^{20})\ (.86^{2}) = (.74)\ (.74) = .55 = 55\%$$

If this value were deemed unsatisfactory, we might consider first the use of enhanced aluminum on the mirror surfaces raising their reflectivity to about 93% with only a moderate increase in cost. This would increase the overall system transmission to about 64%. Frequently, it is possible to realize a substantial improvement in transmission by substituting prisms with total internal reflection for folding mirrors. In the example being considered a pair of prisms could be substituted that would transmit about 96% each. The gain in this case over the enhanced aluminum mirrors would not be worth the added cost. One final consideration would be the use of multilayer coatings on all air to glass surfaces. This, in conjunction with the use of enhanced aluminum on the mirrors, would produce the following version of Equation (1):

$$T = (.995^{20})\ (.93^{2}) = (.91)\ (.86) = .78 = 78\% \text{ trans.}$$

This would appear to be a cost vs. performance tradeoff worth further consideration.

Relative illumination deals with the size of the light beam that can be transmitted for off-axis image points relative to the on-axis beam size. Absolute transmission for both cases will be essentially equal but the off-axis beam is generally allowed to be smaller in cross section due to vignetting within the system. The "half lens" situation illustrated in Figure 5 will yield 40% relative illumination. This has been found to produce quite satisfactory system performance, and might qualify as the "standard" case for the visual optical system. Where dictated by other considerations, relative illumination levels as low as 15 to 20% have been found to be adequate. Some flexibility in specifying this area can lead to significant cost savings since both the size of the system and its optical complexity are being reduced simultaneously.

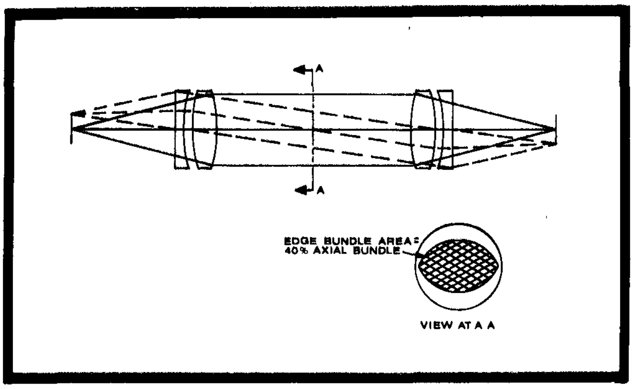
Image Quality, On-Axis

Having covered the basic optical characteristics of magnification, field of view, entrance/exit pupil, eye relief, transmission and relative illumination, let's now address the less definitive, more subjective area of image quality. Here we must take into account the function of the instrument as well as the more general requirement for a "crisp," "sharp," pleasant overall image indicative of a quality instrument.

The specification of image quality must be broken down into on-axis and off-axis criteria. For the on-axis case it is reasonable to ask that the system resolve, in object space, a pattern of equally spaced lines where each cycle, i.e., each line plus space, subtends an angle of 90 seconds divided by the system magnification. This will, theoretically, result in a system that is slightly better than the unaided human eye with normal visual acuity, which is generally considered to be 120 seconds/cycle. To many, the term "normal visual acuity" is not well defined. Most would agree that its quantitative value is one minute of arc, however, conversion of this angular acuity to a meaningful value, to be readily measured, frequently leads to some confusion. This would seem to be a situation similar to the often encountered TV-Photo resolution difference of lines vs. line pairs, or TV lines vs. cycles per millimeter. In terms of visual acuity, the basic question arises; just what is it that this 1 minute angle subtends? The answer to this question is basic and, for those of us involved with visual optical systems, it is well worth remembering. Standard visual acuity testing involves viewing block letters, such as the letter E, where the line width used to construct the letter is 1/5 the overall letter height. When a viewer can identify the letter at a distance where it subtends an overall angle of 5 minutes, that is when each stroke of the letter subtends an angle of 1 minute, the viewer is said to have "normal visual acuity." This situation is illustrated in Figure 6a.

When dealing with optical system resolution one is more likely to encounter the basic 3 bar pattern such as that found on the USAF-1951 test target. In order to relate this to the visual acuity concept, we may think of each 3 bar pattern as corresponding to the block letter and the viewer with normal visual acuity will resolve that 3 bar pattern which subtends a total angle of 5 minutes to the eye or each element of the 3 bar pattern subtends an angle of 1 minute (see Figure 6b). As we see in Figure 6c this basic acuity factor of 1 minute per element or 120 seconds per cycle, will be enhanced by the optical instrument.

There are some who prefer to use 60 seconds/cycle as a basic criterion for insturment resolution while another camp maintains that 120 seconds or 2 minutes/cycle is a more proper value. The 90 second value would seem to represent a reasonable compromise. Essentially, we are dealing here with the subtle difference between what might be termed a "good" system and one that might be termed "excellent."



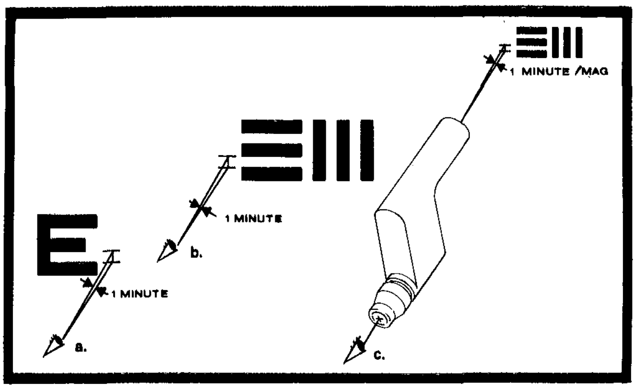


Fig. 5. Relative illumination refers to the size, in cross section, of an off-axis bundle relative to that of the axial bundle.

Fig. 6. a) Normal visual acuity: when the unaided eye resolves Snellen test letters with each element subtending an angle of 1 minute.
b) Corresponding case for standard 3-bar test pattern.
c) An optical instrument will enhance visual acuity by a factor equal to its magnification.

A second requirement of axial image quality, applicable to a sighting instrument such as this, is parallax error. Here we refer to the visual parallax existing between the sighting reticle and the image of the outside world. Parallax will occur due to aberrations of the optics forming the real world image at the reticle and also due to any out-of-focus condition which may exist at the reticle. It is most frequently specified as an angular error in object space. Parallax may be more easily envisioned if it is thought of as the angular subtense, in object space, of the blur circle formed by the objective lens at the reticle surface. (See Figure 7.) Accuracy of the related weapon will dictate the degree of parallax allowable, values of .1 to .25 milliradian are common. The parallax specification will apply over the useful field of the system's reticle, so it may extend into the region of off-axis image quality. Maximum allowable parallax should be specified for a particular object distance and should not neglect internal pressurization of the instrument.

Image Quality, Off-Axis

When we begin to consider off-axis image quality, we generally find we have drifted into an even more subjective region that is considerably more difficult to define than was the on-axis case. A basic understanding of the primary off-axis aberrations will be helpful in deciding on the best method of specifying off-axis performance. The off-axis aberrations of concern here are coma, astigmatism, field curvature, lateral color and distortion. Lateral color and distortion are generally not troublesome, being easily controlled by proper eyepiece design. When a specification value is felt to be necessary, lateral color is generally stated in terms of angular subtense to the eye. Distortion is specified in terms of maximum percentage allowable. Coma is probably the most objectionable of the off-axis aberrations. As with lateral color, it may be specified in terms of angular aberration at the exit pupil, i.e., the eye. Values in the range of 4-5 minutes for coma and lateral color, and 8% for distortion at the maximum field angle have been found to be reasonable when dealing with more or less cosmetic considerations such as these. Field curvature and astigmatism are closely linked and as a result should be specified together. It is common practice to specify the degree of field curvature allowable for the tangential and sagittal image surfaces, that is the image surface for lines oriented tangentially in the image and for lines oriented radially. The curvature of these image surfaces is specified in diopters, values less than 1 diopter indicating very good image quality across the field, 1 to 2 diopters being closer to average and 2-4 diopters representing about the maximum acceptable. Figure 8 shows typical field and distortion curves for a well corrected visual system. This is another of those areas where the nature of the eye becomes important. Under proper conditions the accommodation feature of the eye will compensate for several diopters of residual field curvature and astigmatism. Of course, systems having a wider apparent field of view will be much more troublesome in the area of off-axis image correction. A 30° apparent FOV proves to be quite economical and easily correctable while producing a somewhat undesirable "tunnel vision" effect. A system with a 48° apparent FOV, such as the example being considered, is found to represent a good compromise and yields comfortable viewing. Systems with considerably larger fields

(64°-75°) are frequently called for. Generally, the most severe design problems in such systems reside in the eyepiece. Resulting hardware will most likely be large, heavy and expensive, while the final performance characteristics will frequently be both disconcerting and disappointing.

How then do we cover this off-axis image quality portion of the specification? It is obviously difficult, if not impossible, to delineate all off-axis image quality factors precisely at the outset. My experience indicates that the best approach is to specify, in general terms, the quality level desired and then, through a series of "give and take" design reviews, settle on final values as the program and the design develop.

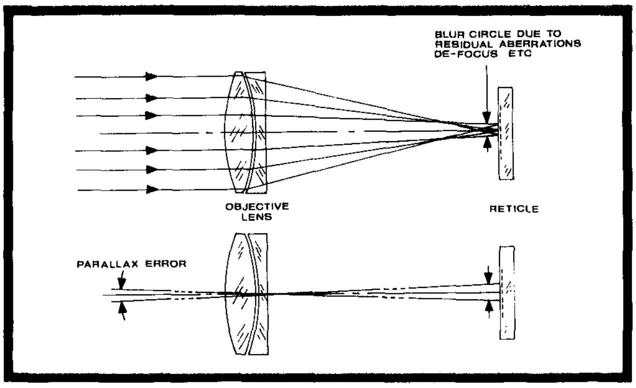


Fig. 7. Parallax error in object space is equal to the projected angle of the blur circle at the reticle.

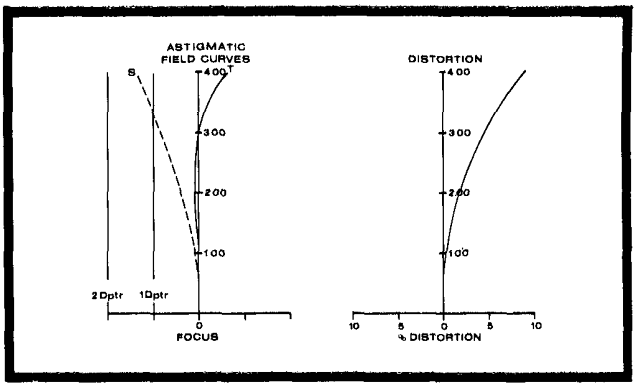


Fig. 8. Typical field curves and distortion data for a well corrected visual optical system.

The Value of Design Data

During the course of generating a system optical design, a great deal of valuable design data will be produced. It will benefit the total program greatly if portions of this design data are utilized as proof of performance in lieu of actual testing. Table 1 lists a reasonable breakdown into the two categories. Little risk of inadequate performance is introduced, while a considerable time and dollar saving will result through the implementation of such a breakdown.

Table 1

Prove compliance by:	Design Data	Testing
Axial Resolution		X
Parallax		X
Magnification		X
Field of View		X
Entrance Pupil		X
Eye Relief		X
Transmission - Peak Wavelength		X
Transmission - Spectral	X	
Relative Illumination	X	
Off-Axis Image Quality - General	X	
Astigmatism, Coma	X	
Distortion (Image, Pupil)	X	
Chromatic Aberrations	X	

The Importance of Cooperation

During the course of the earlier referenced design reviews it is important that a sense of cooperation and a common goal be developed between the two parties involved. Again in terms of the example being presented, we might have the case of prime contractor "A", responsible for building a sophisticated vehicle for the Government. "A" will then subcontract the sighting device to a smaller more specialized company "B".

The ideal scenario would have the cognizant system engineer at company "A" prepare a general specification covering in exact detail those items that are obviously critical to the success of the program while leaving other performance characteristics in a more flexible form, allowing them to become factors in a series of tradeoff studies. The design engineer at company "B" could then apply his expertise and his experience with similar systems to the preparation of a number of preliminary design concepts. A series of design review sessions between A & B at this point would lead to finalization of the formal specification. Realizing that this "ideal" approach may appear to contain some practical difficulties, it is presented here to counterbalance the prevalent although unreasonable theory that the initial specification must, at the outset, cover completely every detail of performance to the nth degree. It is essential that a spirit of cooperation be the goal of all involved, realizing that the closer we can come to full cooperation the greater will be the overall success of the program, with attendant benefits to all concerned.

Conclusion

In conclusion, then, I would offer the following expanded version of the definition introduced earlier:

Spec-i-fi-ca´-tion - A detailed and exact statement prescribing materials, dimensions, workmanship and performance, arrived at after careful and cooperative consideration of the system application and the realistic needs of the end user.

Questions from the Floor

Question 1: In your slide you showed the gap between two dark bars as the resolution. In the MIL specification, the resolution is defined by twice that amount. Would you care to comment on that?

Answer 1: This is in line with the 60-90 or 120 second question I discussed. This is frequently confusing and leads to overspecified and overdesigned systems.

Question 2: Considering the cost of the special glass, what is the acceptable level of secondary spectrum for a periscope system with many optical elements and relays?

Answer 2: For visual systems, 5 to 10 minutes at the eye. When photo and/or TV is anticipated this must be improved upon.

Question 3: In designing such systems, do you consider the effect on eye relief as required by persons wearing eye glasses?

Answer 3: Yes, generally this is required by our customer along with clearance for other apparatus such as helmets, etc.

Question 4: What is a reasonable range of eyepiece diopter adjustment?

Answer 4: +/- 4 diopters is more than adequate for most cases. Variation of this requirement will not generally not affect cost.